Searching for High Energy Neutrino counterpart signals; The case of the Fermi Bubbles signal and of Dark Matter annihilation in the inner Galaxy

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The recent uncovering of the Fermi Bubbles/haze in the Fermi \(\gamma\)-ray data has generated theoretical work to explain such a signal of hard \(\gamma\)-rays in combination with the WMAP haze signal. Many of these theoretical models can have distinctively different implications with regards to the production of high energy neutrinos. We discuss the neutrino signals from different models proposed for the explanation of the Fermi Bubbles/haze, more explicitly, from Dark Matter annihilation in the galactic halo with conditions of preferential CR diffusion, from recent AGN jet activity, from periodic diffusive shock acceleration, from stochastic 2nd order Fermi acceleration and from long time-scale star formation in the galactic center in combination with strong galactic winds. We find that some of these models will be probed by the IceCube DeepCore detector. Moreover, with a km\(^3\) telescope located at the north hemisphere, we will be able to discriminate between the hadronic, leptonic and the DM models. Additionally using the reconstructed neutrino spectra we will probe annihilation of TeV scale dark matter towards the galactic center.

I. INTRODUCTION

Using the first year of Fermi LAT \(\gamma\)-ray full sky data,\textsuperscript{1} revealed the presence of a diffuse component towards the galactic center that extends up to 50° in latitude. That component has a spectrum significantly harder than elsewhere in the Galaxy\textsuperscript{2,3} and a morphology elongated in latitude to longitude, that depending on the exact template analysis used for its extraction from the full sky data, is either well defined within 2 bubbles with distinct edges both at high and low latitudes\textsuperscript{2} known as the "Fermi Bubbles", or is slightly more diffuse (the "Fermi haze") with a latitude to longitude axis ratio of \(\simeq 2\) but still confined within \(|l| \lesssim 20^\circ\) and \(|b| \lesssim 50^\circ\) and with the "edges" seen only at the higher latitudes\textsuperscript{3}.

That signal of hard \(\gamma\)-rays together with the WMAP haze\textsuperscript{1,2} may indicate the presence of a hard component of Cosmic Ray (CR) electrons, that through their up-scattering of low energy photons produce the hard spectrum of (Inverse Compton) \(\gamma\)-rays and through their synchrotron radiation the hard observed spectrum at microwaves. Various authors have suggested mechanisms for the origin of these CR electrons. Among them, possible scenarios include recent (1-3 Myr ago) AGN jet activity in the galactic center\textsuperscript{3,7}; TeV scale Dark Matter (DM) annihilating to leptons\textsuperscript{3,8}, within conditions of preferential diffusion perpendicular to the plane\textsuperscript{3}; stochastic 2nd order Fermi acceleration by large scale turbulence in magneto-sonic waves\textsuperscript{3}, or periodic injection of hot plasma causing diffusive shock acceleration (1st order Fermi acc.) in the halo\textsuperscript{10}.

Alternatively, CR protons associated with long time scale (\~{}Gyr) star formation in the galactic center, transferred by strong winds into the Fermi Bubbles region have been suggested by\textsuperscript{11}. Finally, a combination of DM and millisecond pulsars in the galactic halo adding up to the signals at \(\gamma\)-rays and microwaves has been discussed in\textsuperscript{12}.

The detection or lack of high energy neutrinos from km\(^3\) neutrino telescopes could help discriminate between the leptonic\textsuperscript{3,6,7,9,10} and the hadronic\textsuperscript{11} scenarios, since the leptonic scenarios would not produce any, or a few and up to the TeV scale neutrinos while the hadronic explanation of\textsuperscript{11} would produce abundant neutrinos up to the PeV scale\textsuperscript{13,14} (see also discussion in\textsuperscript{15}).

In addition to discriminating among different models for the Fermi haze/Bubbles via searching for their neutrino counterpart, such searches can be used as an other channel of indirect DM searches.

DM composes approximately 85\% of the matter density of the universe, yet its particle physics properties still remain unknown. Measurements of cosmic rays (CR)\textsuperscript{16,22} have generated new model building\textsuperscript{3,23,34} and have helped place new constraints on dark matter properties\textsuperscript{33,35}. Since many of these models and constraints are placed at the TeV mass scale and suggest/refer to enhanced (boosted) annihilation cross-sections with hard spectra for the Standard Model (SM) particle annihilation products, neutrino signals from the galactic center (GC)\textsuperscript{40} from the Sun\textsuperscript{11} or the Earth\textsuperscript{42} can be considered of interest.

IceCube in the South Pole\textsuperscript{43,44} has already presented some early (pre-DeepCore) results\textsuperscript{45,47} and is expected with its DeepCore update to better probe the region that is sensitive for DM searches and has \(<\sim 100\) GeV in neutrino energy. ANTARES located in the Mediterranean is also collecting data\textsuperscript{48,51} and due to its location probes significantly better the GC than the IceCube, but because of its small size has still low number of statistics. Finally a future km\(^3\) telescope located
in the Mediterranean as KM3NeT \cite{122, 51, 52} will combine the virtues of IceCube and ANTARES providing a good neutrino telescope for searches of DM annihilation towards the GC.

In this paper, in section \[\text{II}\] we will discuss the neutrino signals of various DM models that could explain the Fermi haze and WMAP haze signals as presented in \cite{3}, for both IceCube and a future km$^3$ telescope located in the northern hemisphere (using the Mediterranean as the Earth’s latitude of reference), presenting also search strategies for those signals. We use simulated performance information published for the KM3NeT \cite{51, 52}.

We will extend in section \[\text{III}\] the discussion of searching for signals in neutrinos towards the GC from more generic DM models. In section \[\text{IV}\] we will describe the neutrino predictions of the hadronic model of \cite{11} for the Fermi Bubbles that if true should soon be seen. In section \[\text{V}\] we discuss why we don’t expect any significant signal in neutrinos from the non-DM leptonic models of \cite{3, 4, 6, 11} presented for the Bubbles and conclude in section \[\text{VI}\].

In this work we will discuss the upward going $\nu_\mu$ s flux expected to be measured at the ongoing and future telescopes. For a comparison of the upward going muon events rate and the rate of fully contained muons produced by neutrinos inside the detector see discussion in \cite{53}.

\section{II. EXCITING DARK MATTER ANNIHILATION, CONNECTING TO THE FERMI HAZE AND THE WMAP HAZE}

In the context of DM annihilating to leptons, \cite{3} invoked preferential (anisotropic) diffusion of CR electrons perpendicular to the galactic disk due to ordered magnetic fields in the same direction. Such conditions could explain the Fermi haze spectrum and morphology in combination with the WMAP haze spectrum and angular profile (see Figs. 7 and 8 of \cite{3}).

In that case, eXciting Dark Matter (XDM) \cite{3} was considered where DM particles with mass $m_\chi = 1.2$ TeV annihilate into a pair of scalar bosons $\phi$ that then decay to a pair of $e^\pm$ due to kinematic suppression for the case of $m_\phi < 2m_\mu$. In such a case the energy released by the DM annihilation goes to $e^\pm$ that have a hard enough spectrum to explain the haze signals \cite{3, 6}.

Also in an XDM scenario as has been shown in \cite{23}, the annihilation cross-section can be enhanced up to $O(10^3)$ to motivate the necessary boost (BF) on the annihilation rates that have been invoked to explain the CR positron fraction and $e^- + e^+$ flux excesses \cite{24, 52, 56}. Thus the magnitude of the annihilation rate needed to explain the Fermi and WMAP haze signals (BF$\simeq 30$), is naturally explained within the context of an XDM annihilating to final state SM leptons. Finally, since from Cold Dark Matter (CDM) cosmological simulations \cite{57, 58} the DM halo profiles are typically triaxial, a prolate DM profile has been used in \cite{3}, with its axis perpendicular to the galactic disk. Observations of the spatial distribution of Milky-Way satellites suggest a prolated DM halo with its major axis perpendicular to the stellar disk \cite{60, 61}, in agreement with suggestions by hydrodynamic simulations of galaxies with stellar disks \cite{61}.

For the case when the SM leptons from the $\phi$ decay are $e^\pm$ ($m_\phi < 2m_\mu$), no neutrinos are produced thus the presence of a possible “Neutrino haze” is excluded. Alternatively, for $m_\phi > 2m_\mu$ the decay to $\mu^\pm$ is allowed and a neutrino haze can exist. To maximize the possible neutrino haze signal and also to explain the Fermi and WMAP signals we will consider the case where $m_\chi = 2.5$ TeV particles annihilate to a pair of $\phi$s that decay with a BR$=1$ to $\mu^\pm$ \cite{123}. The mass of 2.5 TeV is chosen to produce -after the muons decay- $e^\pm$ which during propagation will give similar synchrotron and IC signals. The necessary enhancement in the annihilation rate is $BF\simeq 150$ to produce the same total injected energy in high energy $e^\pm$ (see for instance Fig. 6 k & 7 of \cite{53}).

Since neutrinos do not diffuse or loose energy, the neutrino signal from the DM halo will be identical to the annihilation rate profile $\sim f_\nu(\sigma v)\rho_d^2 d\Omega$; with $l$ being the line of sight, $\Omega$ the angle of observation, $\rho_d$ the DM density and $\langle \sigma v \rangle$ the velocity averaged annihilation cross-section (more accurately written as $\langle \sigma | v | \rangle$). Since in the Sommerfeld enhancement case, the $\langle \sigma v \rangle$ depends on the velocity dispersion \cite{23, 62, 63}, it also may have a profile within the main halo (see for instance \cite{63}). That is ignoring effects of substructure that may make the position dependence of the averaged (after integration) $\langle \sigma v \rangle$ over the galaxy even more evident \cite{60}.

In Fig. 4 we show the case of $3 \times 10^4$ neutrino simulated events for a prolate DM Einasto profile described by:

$$\rho(z, R) = \rho_0 \exp \left[ \frac{2 R_c^2}{R} - \frac{2}{\alpha} \left( \frac{R^2}{R_c^2} + \frac{z^2}{Z_c^2} \right)^{\alpha/2} \right]$$

with $\rho_0 = 0.4$ GeV cm$^{-3}$ the local DM density \cite{67, 68}, $\alpha = 0.17$, $Z_c/R_c = 2$ and $Z_c = 27$ kpc (giving a total amount of DM within the inner $\sim 100$ kpc as is for a spherically symmetric case of $Z_c = R_c = 25$ kpc) \cite{69}.

The cases of a homogeneous $\langle \sigma v \rangle$ Fig. 4 (left) and of $\langle \sigma v \rangle \propto r^{1/4}$ in Fig. 4 (right), (with $r$ the galactocentric distance) are shown. The latter dependence can be the case for the Sommerfeld models \cite{3}, as cosmological simulations with DM and baryons have suggested a profile of increasing velocity dispersion towards the GC (compared to the local values) and up to the inner 1 kpc \cite{71, 72}. The profile with the $\propto r^{1/4}$ cross section is slightly more diffuse and less elongated. Since the exact DM profile in the inner 5$^\circ$ of the galactic center is very uncertain we will derive our conclusions ignoring that part of the DM halo. Additionally, TeV neutrino sources either point or diffuse (from inelastic collisions of CR nuclei with dense ISM gas) are concentrated along the galactic disk. The thin galactic disk where continuous star formation takes place, has a characteristic (for exponentially decreasing)
scale high of 0.3 kpc \( [73] \). This scale height is indicative of the majority of the TeV neutrino sources \( [124] \). The HI ISM gas has also a scale height that towards the GC is \( \approx 0.15 \) kpc and increasing up to 0.3 kpc at the solar ring \( [70, 72] \), while the H2 gas a scale height of 0.1 kpc \( [73, 75] \). These scale heights are indicative for the galactic diffuse TeV neutrino flux \( [122] \) (see also work of \( [80] \)). Thus we will avoid the entire inner 5° in \( | \beta | \).

The neutrino flux at Earth due to DM annihilation from an angle \( d\Omega \) ignoring oscillation (\( \phi^0_{\nu_i} \)) is described by \( [126] \):

\[
\frac{d\phi^0_{\nu_i}}{dE_{\nu_i}} = \int d\Omega \int_{l.o.s.} d\ell(\ell, \theta) \frac{\rho_{DM}^2(\sigma v)(\ell, \theta)}{8\pi m^2_\chi} dN_{\nu_i} \tag{2}
\]

where we have left \( \langle \sigma v \rangle(\ell, \theta) \) to depend on the position in the Galaxy for the most generic case. A boost factor is absorbed in either \( \rho_{DM}^2 \) or/and the \( \langle \sigma v \rangle \). The \( dN_{\nu_i}/dE_{\nu_i} \) is the neutrino spectrum of the species \( \nu_i \). The multiplicity \( M^i \) of \( \nu_i \)s per annihilation event is absorbed in \( dN_{\nu_i}/dE_{\nu_i} \) giving:

\[
\int_0^{M^i} dN_{\nu_i}/dE_{\nu_i} dE = M^i. \tag{3}
\]

In this work we discuss only the upward going \( \nu_i \)s flux. The \( A_{\text{eff}} \) of \( \nu_e \) upward for both the IceCube DeepCore (not optimally placed for the GC searches) \( [14] \) and the KM3NeT \( [81] \), is smaller for \( \nu_i \)s by at least a factor of 2 at all energies of interest. For simplicity we are going to ignore their contribution.

The observed \( \nu_\mu \) flux at Earth after oscillations is given by \( [47, 82, 83] \):

\[
\phi_{\nu_\mu} \simeq \frac{1}{2} \left( \phi^0_{\nu_\mu} + \phi^0_{\nu_e} \right) + \frac{1}{8} s_2 \text{ with } \\
\phi^0_{\nu_\mu} = \sin^2 2\Theta_{12} \left( 2\phi^0_{\nu_e} - \phi^0_{\nu_\mu} - \phi^0_{\nu_\tau} \right) \tag{4}
\]

\[
sin^2 2\Theta_{12} = 0.86,
\]

where \( \phi^0_{\nu_i} \) is the flux at injection of flavor species \( \nu_i \).

For specific experiments one has to include the strong dependence of the telescopes effective area with angle and energy. Within an angle \( d\Omega \) and an energy range \( E - E + \Delta E \) the total number of upward going \( \nu_\mu + \bar{\nu}_\mu \) events is \( [125] \):

\[
N_{\nu_\mu,\bar{\nu}_\mu}(E, d\Omega) = \int_{E'}^{E'} dE' \int d\ell \int_{l.o.s.} d\ell(\theta) \frac{\rho_{DM}^2(\sigma v)}{8\pi m^2_\chi} A_{\text{eff}}(E', \theta) \frac{dN_{\nu_\mu,\bar{\nu}_\mu}}{dE_{\nu_\mu,\bar{\nu}_\mu}}, \tag{5}
\]

where,

\[
\frac{dN_{\nu_\mu,\bar{\nu}_\mu}}{dE_{\nu_\mu,\bar{\nu}_\mu}} = \frac{1}{2} \left( \frac{dN_{\nu_\mu,\bar{\nu}_\mu}}{dE_{\nu_e,\bar{\nu}_e}} + \frac{dN_{\nu_\tau,\bar{\nu}_\tau}}{dE_{\nu_e,\bar{\nu}_e}} \right) \tag{6}
\]

\[
+ \frac{1}{8} s_2 \left( \frac{dN_{\nu_\mu,\bar{\nu}_\mu}}{dE_{\nu_e,\bar{\nu}_e}} - \frac{dN_{\nu_\tau,\bar{\nu}_\tau}}{dE_{\nu_e,\bar{\nu}_e}} \right).
\]

For the \( dN_{\nu_\mu,\bar{\nu}_\mu}/d\Omega \) originating from the 2.5 TeV XDM to muons case, the injection spectra of \( \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e \) (there are no \( \nu_\tau \)s) are practically identical to those of the injected \( e^\pm \) given in appendix A of \( [83] \). Per annihilation event there are 2 neutrinos (and 2 antineutrinos) for each flavor.

Having excluded the \( | \beta | < 5^\circ \) region, the basic remaining background is that of the atmospheric upward neutrinos. The atmospheric background flux is isotropic after averaging for the many different directions of the neutrino telescopes axis within long timescales. For the atmospheric \( \nu_\mu \) and \( \bar{\nu}_\mu \) spectra and fluxes above 10 GeV and up to 10 TeV we used the tables of Appendix B of \( [83] \), extrapolating to higher energies with a spectral power law of 3.7 for the differential spectrum \( [40] \).

In Fig. 2 we give in galactic coordinates 10 yr mock maps for \( \nu_\mu + \bar{\nu}_\mu \) upward events with energy between
360 and 2160 GeV. The energy range has been chosen to optimize the detection of a DM signal for the specific 2.5 TeV XDM case.

The atmospheric background $\nu_e + \bar{\nu}_e$ events that are shown in the top left of Fig. 2 are 152784; while the DM events for the prolate Einasto are 424 and 332 for the case of $\langle \sigma v \rangle \propto r^{1/4}$ for the entire sky. Those numbers of DM events are smaller than the 1 $\sigma$ deviation (for the entire sky). Since the morphology of the DM signal is much different than that of the atmospheric background, one can expect to see a signal increase of events towards the GC (see the bottom row of Fig. 2) where we show the inner 60° × 60°. Including the | $b$ | < 5° mask for the TeV sources (point and diffuse) for the galactic center and disk most of this dim DM contribution is hidden. In fact since for IceCube the neutrino events are minimally enhanced in the GC and TeV neutrino point sources and the diffuse galactic neutrinos are also expected to contribute in that region of the sky, a claim for DM can not be made. Thus for the IceCube DeepCore the sensitivity towards the GC is still too low and the angular resolution (not accounted for the IceCube DeepCore) the sensitivity towards the GC region of the sky, a claim for DM can not be made. Thus one can expect to see a signal increase of events towards the GC (see the bottom row of Fig. 2).

TABLE I: The time-scale to observe 100 $\nu_e + \bar{\nu}_e$ upward events associated to signals of interest in IceCube (with online filter) and in KM3NeT (assuming the HOURS simulation). In all the DM cases (XDM $\mu^\pm$, $\chi \rightarrow \mu^+ \mu^-$ and $\chi \rightarrow W^+ W^-$), we use the same sky region of interest: 5° < | $b$ | < 15°, | $l$ | < 5° (see main text for motivation) and an energy range of 1.0-1.3 TeV, around which these neutrino (observed) spectra peak. For the XDM $\mu^\pm$ case we show results for an Einasto prolate DM profile without (with) $r^{1/4}$ velocity induced suppression to the DM annihilation cross-section. The same Einasto prolate profile for a homogeneous DM annihilation cross-section is used for $\chi \rightarrow \mu^+ \mu^-$ and $\chi \rightarrow W^+ W^-$ with a spherical Einasto profile assumed in the results shown in the parentheses. For the Fermi Bubbles we use the entire region of the Bubbles and an energy range of 100 TeV to 1 PeV (100-130 TeV in parentheses).

| Signal of Interest | IceCube (yr) | KM3NeT (yr) |
|--------------------|--------------|--------------|
| XDM $\mu^\pm$ 2.5 TeV | 158 (294) | 3.4 (5.8) |
| $\chi \rightarrow \mu^+ \mu^-$ 1.5 TeV | 38 (168) | 0.76 (3.3) |
| $\chi \rightarrow W^+ W^-$ 2.0 TeV | 44 (193) | 0.86 (3.8) |
| Fermi Bubbles | 9.0 (58) | 0.11 (0.54) |

For a km$^3$ telescope in the North Hemisphere the situation can be very different. In Fig. 3 we give the expected 3 yr mock maps of reconstructed events using the HOURS simulation for KM3NeT. In that case by comparing Fig. 3 top left where only the atmospheric background simulated events with Fig. 3 top right (for combined DM Einasto prolate and the atmospheric background), and middle (for the prolate Einasto with $\langle \sigma v \rangle \propto r^{1/4}$ plus atmospheric), one can see a clear indication of a signal from the 2.5 TeV XDM to muons model used to explain the combination of Fermi and WMAP haze signals. Concentrating in the inner 60° × 60° window for the case of simple Einasto profile the signal will be very clear even in the total counts. Known TeV $\gamma$-ray sources such as the H.E.S.S. J1745-290, Sgr A8 are also expected to contribute in this region. Yet, the angular resolution of KM3NeT at ~1 TeV is expected to be below 1°. Thus given the already precise known location of these sources (from $\gamma$-rays) it will be easy to account for their contribution, as has been done with $\gamma$-rays H.E.S.S. data

With 10 years of data with KM3NeT the excess towards the GC will be very evident. About 8 × 10$^3$ DM events for the case of an Einasto prolate profile and 5 × 10$^3$ for the Einasto prolate profile with $\langle \sigma v \rangle \propto r^{1/4}$ will be detected.

In Fig. 2 we show the $\nu_e + \bar{\nu}_e$ reconstructed spectra from atmospheric and from XDM to muons after 3 yrs of observations in KM3NeT, from a window of 5° < | $b$ | < 15° and | $l$ | < 5°, which was chosen to be optimal for a search of a signal from DM annihilation.

For an alternative comparison to those of Fig. 3 and 4 we also give in Table II the time-scale in years for either IceCube or a telescope such as KM3NeT to observe 100 events from DM annihilation from the selected window of 5° < | $b$ | < 15°, | $l$ | < 5° and energy range of 1.0 - 1.3 TeV around which the neutrino spectrum of DM origin peaks. It is clear that a signal from XDM $\mu^\pm$ can not be probed by IceCube in any reasonable time-scale. Yet, a counter-part experiment in the northern hemisphere, with characteristics as those of the proposed KM3NeT, can detect such a signal within a few years.

The uncertainty in the atmospheric neutrino flux due to uncertainties in the p-p collisions production cross-sections through the decay of $\pi$, $K$ and $\sigma$ mesons is expected to be up to ~30% at TeV energies. Yet, this uncertainty can not explain a change in the power law that would appear direction dependent in the galactic sky. For the case in Fig. 2 right ($\langle \sigma v \rangle \propto r^{1/4}$) the DM signal is too small to be detected. For the case of the Einasto prolate of Fig. 2 left, the break at ~2 TeV is not going to be very strong, even in that window. Yet, a gradual hardening of the total events spectra decreasing from high | $b$ | towards the galactic disk (excluding the | $b$ | < 5° region), will be an indication of a signal from DM annihilation in the main DM halo. We expect that the power law of total reconstructed $\nu_e, \bar{\nu}_e$ events with energy between 300 GeV and 1.5 TeV will become harder by 0.3 from the window of | $b$ | > 50°, | $l$ | < 5° to that of 5° < | $b$ | < 15°, | $l$ | < 5°.

III. DARK MATTER ANNIHILATION TOWARDS THE GC, OTHER CHANNELS

Apart from the question on explaining the Fermi and WMAP haze signals via DM annihilation, the general connection of DM searches in neutrinos has received some attention in the recent years either from annihilation towards the GC 40, 45, 53 or from the DM annihilation captured in the Sun 41, 43, 91, 92.
FIG. 2: IceCube DeepCore $\nu_\mu + \bar{\nu}_\mu$ events after 10 years of data collected with “online filter” \[44\] with energy between 360-2160 GeV. For the calculations we use the angular dependence for $A_{\text{eff}}$ of \[43\]. Top left: Just atmospheric background, 152784 $\nu_\mu + \bar{\nu}_\mu$ events. Top right: atmospheric background (152784 $\nu_\mu + \bar{\nu}_\mu$ events) and DM annihilation contribution (424 $\nu_\mu + \bar{\nu}_\mu$ events) from prolate Einasto profile with homogeneous annihilation cross-section enhancement. Middle: atmospheric background (152784 $\nu_\mu + \bar{\nu}_\mu$ events) and DM annihilation contribution (332 $\nu_\mu + \bar{\nu}_\mu$ events) from prolate Einasto profile with $\propto r^{1/4}$ annihilation cross-section enhancement. Numbers refer to the entire sky. We mask out the $|b| < 5^\circ$ to account for neutrinos from point sources concentrated on the disk and from galactic diffuse concentrated also on the disk (see text for more details). Bottom left: inner $60^\circ \times 60^\circ$ for the atmospheric and the XDM prolate profile case. Bottom right: same region as in bottom left for the case of atmospheric background and XDM prolate Einasto with radial dependence. The neutrinos from the GC are minimally enhanced.

The Fermi and HESS $e^- + e^+$ CR flux \[19, 21\] and PAMELA positron \[16\] excesses apart from the XDM models discussed in \[11\] can be explained by a variety of other phenomenological channels \[55, 93, 94\]. For standard phenomenological models $\chi \chi \rightarrow W^+ W^-$, $\chi \chi \rightarrow b \bar{b}$ strong limits have been placed using SUPER-K and IceCube observations towards the Sun (see for example some recent works of \[11, 91, 92\]).
FIG. 3: KM3NeT $\nu_\mu + \bar{\nu}_\mu$ events after 3 years of data reconstructed by the HOURS package with energy in the range of 360-2160 GeV. We use for KM3NeT the same angular dependence of $A_{\text{eff}}$ as for ANTARES due to their expected similar geographic latitude location. Top left: Just atmospheric background, 212446 $\nu_\mu + \bar{\nu}_\mu$ events. Top right: Atmospheric background (212446 $\nu_\mu + \bar{\nu}_\mu$ events) and DM annihilation contribution (2412 $\nu_\mu + \bar{\nu}_\mu$ events) from prolate Einasto profile with homogeneous annihilation cross-section enhancement. Middle: Atmospheric background (212446 $\nu_\mu + \bar{\nu}_\mu$ events) and DM annihilation contribution (1579 $\nu_\mu + \bar{\nu}_\mu$ events) from prolate Einasto profile with $\propto r^{1/4}$ annihilation cross-section enhancement. As in Fig. 2 events numbers refer to the entire sky and we use the same mask of $|b| < 5^\circ$. Bottom left and bottom right: As the bottom plots of Fig. 2 for the case of atmospheric background and XDM prolate Einasto without (left) and with (right) radial dependence. Due to its high sensitivity towards the GC and its good angular resolution KM3NeT would observe a clear signal from these models.

Among the many models we choose to show results for the phenomenological models of DM annihilating directly to muons ($\chi\chi \to \mu^+\mu^-$) or directly to W bosons ($\chi\chi \to W^+W^-$), where electroweak corrections -especially important for the former channel- have been included [97, 98]. These two channels are distinct between each other since for the one annihilating to muons high energy neutrinos come from the decay of the boosted
muons, while for the $\chi\chi \rightarrow W^+W^-$ neutrinos are produced with a softer overall spectrum but at significantly higher multiplicity.

In Fig. 4 we show for the window of $5^\circ < |b| < 15^\circ$, $|l| < 5^\circ$ the expected reconstructed upward fluxes in IceCube DeepCore of $\nu_\mu + \overline{\nu}_\mu$, for $\chi\chi \rightarrow \mu^+\mu^-$ with $m_\chi = 1.5$ TeV (left) and for $\chi\chi \rightarrow W^+W^-$ with $m_\chi = 2.0$ TeV (right).

The masses and annihilation cross-sections are chosen to fit the Fermi, HESS and PAMELA leptonic excesses given in [55]. We show results for two cases of DM profiles, the Einasto prolate profile of eq. (44) (red lines) and the spherical Einasto profile (green lines). As can be seen for the more optimistic (to give a clear DM signal) prolate profile, a signal can be seen in IceCube DeepCore within 3 yrs of data for both channels. For the less optimistic spherical Einasto profile only in the case of $\chi\chi \rightarrow W^+W^-$ a weak break at $\sim 2$ TeV may be seen.

Yet, in KM3NeT -that is near to optimal for searching for such a signal- after 3 yr of data the reconstructed spectra in the same window will be measured with much greater statistics as is shown in Fig. 5. Apart from the case of $\chi\chi \rightarrow \mu^+\mu^-$ with a spherical Einasto profile, all other cases give a clear break at the respective mass of the DM particle. For the case of $\chi\chi \rightarrow \mu^+\mu^-$ in the spherical Einasto an indication of a signal will be the smooth hardening of the spectrum as one moves (using the same longitude range) from the high $|b|$ towards the disk as discussed in section II. In the specific case at $|b| > 40^\circ$ the power law is going to be $\sim 4.0$ while at the $5^\circ < |b| < 15^\circ$ it is going to be $\sim 3.2$ between energies of 300 GeV and 1.0 TeV. For a more cored profile the difference in the power law between the $|b| > 40^\circ$ region and the $5^\circ < |b| < 15^\circ$ region of the sky, is going to be only by 0.2.

An alternative indication of how much better a km$^3$ telescope in the North Hemisphere is going to be compared to IceCube DeepCore for that type of searches,
is given in Fig. 7. In Fig. 7 we show the reconstructed \( \nu_p + \bar{\nu}_p \) within 500 GeV and 1.5 TeV for the \( m_\chi = 1.5 \) TeV, \( \chi\chi \rightarrow \mu^+\mu^- \) case. For the IceCube DeepCore (left) and the KM3NeT (right) using the reconstructed HOURS simulation [51]. For the entire DM halo (ignoring substructure) we show 368 \( \nu_p + \bar{\nu}_p \) events (3 yr) in IceCube DeepCore and 6482 for KM3NeT (3yr), with the equivalent background events to be 2.2 \times 10^4 and 1.4 \times 10^5. In Table 1 we also give for both the \( \chi\chi \rightarrow \mu^+\mu^- \) and the \( \chi\chi \rightarrow W^+W^- \) channels the time-scale needed for each experiment to observe 100 \( \nu_p + \bar{\nu}_p \) upward events from the direction of \( 5^\circ < |b| < 15^\circ, |l| < 5^\circ \) and in the energy range of 1.0-1.3 TeV (see also Figs. 5 and 6).

**IV. HADRONIC SCENARIO: NEUTRINOS FROM THE FERMI BUBBLES**

As discussed in [11] a possible explanation of the Fermi Bubbles signal [2] is that of copious and long time-scale star formation in the galactic center giving CR protons with energies up to the PeV scale. These CR protons are transferred up to a distance of 10 kpc away from the galactic disk due to strong winds [11]. In that scenario the \( \gamma \)-rays composing the Fermi Bubbles will come from the decay chains of boosted mesons produced in p-p collisions. The same process will produce neutrinos with energies up to the cut-off energy of these hard CR protons. Similarly these processes take place in the atmosphere producing the equivalent background.

The CR protons entering the atmosphere have a significantly softer spectrum (\( \simeq 2.67 \) above 300 GeV) measured most recently from [102, 103, 129], compared to those responsible for the Bubbles that have a spectrum described by [11]:

\[
\frac{dN_p}{dE_p} = N_0 E_p^{-2.1} \exp \left[ -E_p/E_{p0} \right] ,
\]

with \( E_{p0} \) the cut-off energy \( \sim \) PeV. Thus we can expect to see the neutrino component from the Bubbles at high energies [13, 15, 104].

Another difference between the atmospheric neutrino background and the possible neutrino signal from the Fermi Bubbles, is that the CR protons entering the atmosphere due to column densities of matter \( \simeq \) kg cm\(^{-2}\), produce extensive showers that can reach for the most energetic protons up to \( 10^{10} \) particles at peak number [102, 104], while for the CR protons at the Bubbles region one expects much lower column densities [130]. Thus the possible Fermi Bubbles neutrinos can not come from extensive showers, where products (protons mainly) from the hadronization of the initial p-p collision would then
FIG. 7: $\nu_\mu + \overline{\nu}_\mu$ events with energy between 500 GeV and 1.5 TeV from DM annihilation of $M_\chi = 1.5$ TeV $\chi \chi \rightarrow \mu^+ \mu^-$ Einasto prolate profile. 

**Top Left:** With IceCube DeepCore in 3 yr, with “Online Filter” atmospheric background (22477 $\nu_\mu + \overline{\nu}_\mu$ events) and contribution from DM (368 $\nu_\mu + \overline{\nu}_\mu$ events). 

**Top Right:** With KM3NeT in 3yr using HOURS reconstruction technique, atmospheric background (138560 $\nu_\mu + \overline{\nu}_\mu$ events) and contribution from DM (6482 $\nu_\mu + \overline{\nu}_\mu$ events). As in Fig. 2 events numbers refer to the entire sky and we use the same mask of $|b| < 5^\circ$.

**Bottom left and bottom right:** Zooming in the $60^\circ \times 60^\circ$ window for the IceCube (left) and KM3NeT (right) maps of the top row. Even in IceCube some excess of events is expected to be seen towards the GC. With KM3NeT sensitivity and angular resolution a clear signal from that model will be observed or strong constraints will be placed.

hit on new target protons. Rather, the neutrinos will come from the decay chains of the hadronization products related to a single hard p-p inelastic collision. This is an additional reason why the neutrinos from the Bubbles have a harder spectrum than the atmospheric ones.

For the p-p inelastic processes the neutrinos are mainly produced from charged pion decays. For the neutrino spectra we follow the parametrization of [108], that was based on SIBYLL [109] simulations of p-p collisions and is optimal at energies above 100 GeV that we care for.

The neutrinos coming from the Bubbles will have the same morphology as the $\gamma$-rays, which is relatively flat in longitude and latitude with clear edges [2]. However, it may not be trivial for the CR protons and the ISM target material transferred with them by the galactic winds, to cause such a flat morphology in $l$ and $b$, at $\gamma$-rays; following the assumptions of [11] for the $\gamma$-rays we will take the morphology of the neutrinos shown in Fig. 8 to be flat within the Bubbles region, with clear edges as in the Fermi Bubbles signal of [2].

As can be seen by comparing the morphology of Fig. 8 to those of Fig. 1 that are for neutrinos from DM scenarios which fit the Fermi and WMAP haze, the two types of morphologies are distinctively different. Moreover the neutrino spectra and fluxes as we will show differ dramatically. In both Figs. 1 and 8 we show the same number of neutrino events without specifying the energy range or period of observation and we are not taking into account that any actual neutrino telescope has (or will have) a strong angular dependence of its sensitivity. This is done to “spotlight” the different morphologies of the possible neutrino signals. Even after taking into account the specific properties of neutrino telescopes that we show results for, the different morphologies lead to searching for these signals in different parts of the sky.

The total energy stored in the CR protons in the Bubbles is estimated to be $\sim 10^{56}$ erg due to an estimated averaged $10^{39}$ erg/s of injected power to hard CR protons transferred from the GC via galactic winds in the
Fermi Bubbles regions. This process is estimated to have been ongoing for a timescale of multi Gyrs \cite{11}. These assumptions can result in a quasi-steady state injected energy from protons to $\gamma$, $e^\pm$ and $\nu$ of $Q_p \simeq 3.6 \times 10^{38}$ erg/s from 10 GeV to 1 PeV \cite{11}. Of that power from approximate equal partitions of energy to $\pi^0$, $\pi^+$ and $\pi^-$, 1/3 goes to $\gamma$s giving the better estimated power in the Fermi Bubbles of $\simeq 2 \times 10^{37}$ erg/s for $\gamma$-ray with energy 1-100 GeV \cite{2}, or after extrapolation of the $\gamma$-ray spectrum, $\simeq 1.2 \times 10^{38}$ erg/s for energies between 10 GeV and 1 TeV. Also from the energy equipartition to the product pions we can estimate that the power to neutrinos is $\sim 2 \times 10^{38}$ erg/s inside the Bubbles. We take the power to neutrinos to be $1 \times 10^{38}$ erg/s, to account for an overestimation by a factor of 2 on the $\gamma$-ray luminosity of the bubbles by \cite{11}. Assuming isotropic emission of $\nu$s inside the bubbles and a mean distance squared $D^2 \simeq R^2_{\text{sun}} \simeq 8.5^2$ kpc$^2$ from us, we can estimate their flux. Their observed morphology as shown in Fig. 5 is isotropic within the Bubbles.

In Fig. 5 (left) we show the expected $\nu_\mu + \bar{\nu}_\mu$ events mock map, with energy between 100 TeV to 1 PeV from IceCube DeepCore after 10 yrs of data collection. We show 74 events from the Bubbles and 63 from the atmospheric background. In Fig. 6 (right) we also show what KM3NeT experiment with 3 yrs of reconstructed events would observe.

For the Bubbles explanation of \cite{11}, masking out or not the disk, can not affect the arguments on detecting the signal since most of the signal neutrino events are significantly above or below the disk.

Extragalactic point sources also can lead to an additional isotropic neutrino component at very high energies where the atmospheric background gets suppressed. Again the same process (p-p collisions) producing high energy ($\sim$ PeV) neutrinos will also produce $\gamma$-rays with a spectrum that extends to lower energies. Due to the high sensitivity of the Fermi LAT instrument at the 0.1-100 GeV range, the more likely extragalactic sources to produce neutrinos have already been detected as point sources in $\gamma$-rays as in \cite{10}. With KM3NeT angular resolution of $> 0.1^\circ$ above PeV energies it will be very easy to associate even single neutrino events to known $\gamma$-ray point sources where p-p collisions is expected to be the dominant mechanism for their production (as for instance in star-forming galaxies). Alternatively on can mask out known $\gamma$-ray point sources. Thus extragalactic point sources contribution to the neutrino background can be accounted for. Finally cosmogenic neutrinos from Ultra high energy CR (UHECR) protons interacting with the CMB are already being constrained from the equivalent $\gamma$-ray spectrum at the Fermi LAT energies \cite{111–114} and are expected to be a significant component only at energies above the $O$(1) PeV range. Thus cosmogenic neutrinos do not contribute in the maps of Fig. 9 that show energies of neutrinos with $100$ TeV $< E_{\nu_\mu} < 1$ PeV \cite{131}.

The optimal region for IceCube DeepCore to search for a signal of Bubbles at neutrinos would be the left part of the north bubble $10^\circ < b < 50^\circ$, $0^\circ < l < 20^\circ$, for which in Fig. 10 (left) we show the reconstructed fluxes from atmospheric and from Bubbles after 3 yrs. Just based on that, one should expect soon a detection of the Bubbles with IceCube DeepCore if the scenario of \cite{11} is correct, or alternatively setting constraints on the hard CR proton component inside the Bubbles.

With KM3NeT after 3 yrs as we show in Fig. 9 (right) the optimal region is the part of the south bubble with $-50^\circ < b < -10^\circ$, $-20^\circ < l < 0^\circ$. A clear observation of the morphology (i.e. the south and right edge) would be expected. In Fig. 10 (right) we also show the reconstructed fluxes, which when/if observed at that level, would provide a very good measurement also of the injected energy to neutrinos (providing an alternative estimate of the CR protons energy). Alternatively, lack of detection at KM3NeT should exclude the model of \cite{11} as a possibility for the Fermi Bubbles (see also Table I).

V. AGN AND ALTERNATE EXPLANATIONS FOR THE FERMI BUBBLES

An alternative explanation for the Fermi Bubbles/haze to those of sections \textbf{IV} and \textbf{V} is strong AGN jet activity in the Galaxy as \cite{K11, K12}. The AGN case is supported by very recent evidence of $\gamma$-ray jets extending out from the galactic center, together with a $15^\circ$ width and $40^\circ - 45^\circ$ length cocoon at the south galactic hemisphere \cite{115, 116}. For the AGN scenario, the $\gamma$-ray signal is mainly from CR electrons with energies up to at least $\sim$ TeV that up-scatter the local radiation field (mainly CMB at high latitudes). CR protons can not contribute much of the observed $\gamma$-ray signal since the ISM gas targets have a very low density at high distances (up to 10 kpc) above the disk. Given the CR energy density profiles from the MHD simulations of \cite{K10}, it will be very difficult for CR protons to explain the morphology of the Bubbles that is relatively flat in latitude, suggesting a limb brightening
FIG. 9: $\nu_\mu + \overline{\nu}_\mu$ events, with energy between 100 TeV and 1.0 PeV. Right: With IceCube DeepCore in 10 yr, with "Online Filter" atmospheric background (63 $\nu_\mu + \overline{\nu}_\mu$ events) and contribution from the Fermi Bubbles (74 $\nu_\mu + \overline{\nu}_\mu$ events). Left: With KM3NeT in 3yr using HOURS reconstruction technique, atmospheric background (465 $\nu_\mu + \overline{\nu}_\mu$ events) and contribution from Fermi Bubbles (1795 $\nu_\mu + \overline{\nu}_\mu$ events).

Thus the scenario of $\S$ may give only few neutrino events at high latitudes.

The recent uncovering of the Fermi Bubbles/haze $\S$ and $\S$ in the Fermi $\gamma$-ray data has generated theoretical work in explaining such a signal in combination (or not) with the WMAP haze signal of $\S$ $\S$.

VI. CONCLUSIONS

We have shown that for the DM explanation of the combined Fermi haze and WMAP haze as in $\S$ under the annihilation channel to muons that is optimal for neutrinos (XDM $\S$ annihilation to $\mu^\pm$) and for a prolate DM halo we can observe a counterpart signal with a km$^3$ telescope located in the north hemisphere at $\sim$3 yrs of data collection (see discussion in section $\S$ and Figs. $\S$ $\S$). IceCube DeepCore and ANTARES will not observe any signal for such a model; while for the case of XDM annihilation to $e^\pm$ through a very light scalar boson $\phi < 2m_\mu$ no neutrinos are produced.

For other channels/models of DM annihilation that produce more neutrinos either from larger suggested boost factors as is $\chi\chi \rightarrow \mu^+\mu^-$ for the explanation of the Fermi $e^+ + e^-$ signal (see for example $\S$ $\S$), or due...
to large hadronic branching ratios as is $\chi \rightarrow W^+W^-$, the neutrino events are enhanced significantly. Some signal from DM is expected even after excluding the disk region where non atmospheric backgrounds are concentrated (see Fig. 1). Yet neutrinos cannot provide the strongest limits for the hadronic channels of annihilating DM. For leptonic to muons case the limits can be useful though, since they can be more robust than the pretty weak limits from $\gamma$s and $p$. 

For the Fermi Bubbles explanation of [11], a significant number of $>10$ TeV neutrinos is estimated and even with IceCube DeepCore we should expect detection or limits (see Figs. 9 and 10). Furthermore, a km$^3$ telescope in the north hemisphere will either exclude the model of [11] or confirm the morphology of the Bubbles at neutrinos and measure the injected power to neutrinos from inelastic pp collisions inside the Bubbles as we show in Figs. 9 and 10.

Leptonic scenarios for the Fermi Bubbles such as those of [6, 9, 10] would also predict some CR protons, but are not expected to give any significant neutrino signal, since the main source for the $\gamma$-rays is IC scattering from CR electrons.

With the current IceCube DeepCore telescope a first probe to some of the models of the Fermi Bubbles/haze can be achieved, while with a km$^3$ telescope located in the north hemisphere, discrimination between the hadronic [11], the leptonic [6, 9, 10] and the DM [3] cases will be attained.

As this paper was being written, a new analysis of Fermi $\gamma$-rays has suggested the evidence of $\gamma$-rays jets in the Milky Way extending out to $\sim 10$ kpc from the galactic center [13]. Additionally, a cocoon structure has been revealed in the southern galactic hemisphere. While according to [35] the total luminosity of the north and the south jet-like features is $(1.8 \pm 0.35) \times 10^{35}$ erg/s at 1-100 GeV i.e. 2 orders of magnitude less in luminosity than the Bubbles $(2 \times 10^{37}$ erg/s in the same energy range), such an additional signal favors the AGN case, with the Bubbles coming from the decelerated jet material [11].

Yet the two signals, i.e the combined $\gamma$-ray cocoon and jets and the Fermi Bubbles may be created at a different time. Such a case would allow for a combination of sources, DM & AGN, Hadronic model & AGN to account for the total $\gamma$-ray Bubbles/haze $\&$ jets and cocoon signals. For the hybrid scenario of DM $\&$ AGN, the edge at $l > 0$ (left) of the south bubble could just be the result of the presence (overlap on the sky) of the AGN cocoon and thus morphologically would not need to be explained by DM annihilation. Similarly a cocoon in the northern galactic hemisphere (not claimed to be clearly revealed yet) could account for the north to the right edge (at $l < 0$) in the data. Additionally the AGN responsible for the jets and the cocoon of [11] could evacuate the cavity of the Bubbles which then the high energy $e^\pm$ from annihilating DM fill 2.

Since the luminosity of the jets alone is only 1% of that of the Bubbles/haze, assuming that the current state of the jets is representative of the time-averaged state[13], the predictions for the neutrino fluxes from the DM/Hadronic cases remain the same[13].

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major part of the south Bubble $\gamma$-ray luminosity.