Prospects for detecting dark matter with neutrino telescopes in intermediate mass black hole scenarios

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Current strategies of indirect dark matter detection with neutrino telescopes are based on the search for high-energy neutrinos from the solar core or from the center of the Earth. Here, we propose a new strategy based on the detection of neutrinos from dark matter annihilations in *mini-spikes* around intermediate mass black holes. Neutrino fluxes, in this case, depend on the annihilation cross-section of dark matter particles, whereas solar and terrestrial fluxes are sensitive to the scattering cross-section off nucleons, a circumstance that makes the proposed search complementary to the existing ones. We discuss the prospects for detection with upcoming underwater and under-ice experiments such as ANTARES and IceCube, and show that several, up to many, sources could be detected with both experiments. A kilometer-scale telescope in the Mediterranean appears to be ideally suited for the proposed search.

Current strategies of indirect dark matter (DM) detection with neutrino telescopes are based on the search for high-energy neutrinos from the solar core or from the center of the Earth (for recent reviews see Refs. [1–3]). The idea, proposed more than 20 years ago [4], is quite simple: if we live immersed in a halo of DM, then there is a wind of DM particles passing through the Sun and the Earth. A fraction of all these particles is expected to lose enough energy, by scattering off the nuclei of the star or planet, to become gravitationally bound. Captured particles will then slowly sink at its center, due to subsequent scattering events, and will annihilate producing a steady flux of high-energy neutrinos (see Refs. [1,3], and references therein).

At equilibrium, the flux of neutrinos is determined by the number of DM particles captured per unit time by the Sun or Earth, a quantity that depends on the local density (and velocity distribution) of DM and on the scattering cross-section of DM particles off nucleons, i.e. the same quantities that are probed by direct detection experiments (e.g. Ref. [5] and references therein). Unfortunately, a large portion of the DM parameter space will not be accessible to neutrino telescopes in these scenarios. In particular, only the most optimistic neutralino models in the minimal supersymmetric standard model will be accessible to kilometer sized experiments (e.g. Ref. [6]), while for Kaluza-Klein DM candidates, and more specifically for the $B^{(1)}$, first excitation of the hypercharge gauge boson in theories with universal extra dimensions [7], between 0.5 and 10 events per year are anticipated in kilometer-scale neutrino telescopes [8].

We propose here a new strategy for the search of DM with neutrino telescopes, based on the detection of secondary neutrinos produced by DM annihilations in "mini-spikes," i.e. recently proposed enhancements of DM around intermediate mass black holes (IMBHs). We argue that mini-spikes can be bright sources of neutrinos, and we study the prospects for detecting them with upcoming neutrino telescopes ANTARES [9] and IceCube [10].

Mini-spikes result from the reaction of DM mini-halos to the formation or growth of IMBHs. In fact, the *adiabatic* growth of a massive object at the center of a power-law distribution of DM with index γ, induces a redistribution of matter into a new power-law with index $\gamma_{\rm sp} = (9 - 2\gamma)/(4 - \gamma)$ [11]. This formula is valid over a region of size $R_s \approx 0.2 r_{\rm BH}$, where $r_{\rm BH}$ is the radius of gravitational influence of the black hole, defined implicitly as $M(<r_{\rm BH}) = M_{\rm BH}$, with $M(<r)$ mass of the DM distribution within a sphere of radius r, and $M_{\rm BH}$ mass of the black hole [12].

To make quantitative predictions, we focus on a specific IMBH's formation scenario [13], representative of a class of models where these objects form directly out of cold gas in early-forming DM halos, and are characterized by a large mass scale, of order $10^5 M_\odot$ (see also Ref. [14] and references therein). In this case, mini-spikes can be bright sources of DM annihilation radiation; indirect searches with gamma-ray telescopes, and in particular with GLAST [15], expected to be launched in 2007, are particularly promising [16]. However, GLAST will be sensitive to energies up to 300 GeV, which means that the most interesting feature of the annihilation spectrum, i.e. the presence of an identical cutoff at an energy equal to the DM particle mass, would be missed if the DM particle is heavy. Air Cherenkov Telescopes (ACTs) such as CANGAROO [17], HESS [18], MAGIC [19] and VERITAS [20] could extend the observations to higher energies, but due to their narrow field-of-view, they are not optimized for full-sky surveys.

We show here that neutrino telescopes can extend full-sky searches at higher energies. In case of detection, the better sensitivity and energy resolution of ACTs can then be used to effectively discriminate mini-spikes from ordinary astrophysical sources.

We generate here a mock catalog of IMBHs, and associated mini-spikes, from the (200) realizations of Milky-Way like halos presented in Ref. [16], by randomly assigning to every object of given galactocentric distance r_{GC}, two angular coordinates (θ, ϕ), following a uniform probability distribution on the surface of the unit sphere. The specifics of the Monte Carlo halo evolution procedure are given in Ref. [21] and the method for populating black holes at high redshift are described in detail in Refs. [16,22]. The resulting distribution is shown in

Fig. 1, where we chose to adopt equatorial coordinates, to emphasize the different regions that will be accessible to Antares and Icecube. We multiply all neutrino fluxes by a visibility factor $V_\phi(\delta)$, which keeps into account that the effective area of a neutrino telescope at terrestrial latitude ϕ, drops abruptly for sources above the horizon. The visibility factor is thus proportional to the fraction of time spent by a given source of declination δ *below* the horizon. By means of simple geometrical considerations we find that

$$V_\phi(\delta) = \begin{cases} 0, & \text{if } |\delta| > \pi/2 - |\phi|, \delta \cdot \phi > 0 \\ \arccos[\tan(\phi)\tan(\delta)]/\pi, & \text{if } |\delta| \leq \pi/2 - |\phi| \\ 1, & \text{if } |\delta| > \pi/2 - |\phi|, \delta \cdot \phi < 0. \end{cases} \qquad (1)$$

For Antares $\phi = 42°50'$, while for IceCube $\phi = -90°$. In the case of IceCube the visibility factor reduces to

$$V_{\text{IceCube}} = \begin{cases} 0, & \text{if } \delta < 0 \\ 1, & \text{if } \delta > 0. \end{cases} \qquad (2)$$

Mini-spikes would be copious sources of neutrinos, which can be produced either by the direct annihilation of DM to neutrino pairs, or through fragmentation and decay of secondary particles such as quarks, leptons and gauge bosons. If $N_{\nu_\ell}(E)$ is the spectrum of neutrinos ν_ℓ, of flavor $\ell = e, \mu, \tau$, per annihilation, the flux of neutrinos from an individual mini-spike *in absence of oscillations* can be expressed as [16]

$$\Phi^0_{\nu_\ell}(E) = \phi_0 m_{\chi,100}^{-2} (\sigma v)_{26} D_{\text{kpc}}^{-2} L_{\text{sp}} N_{\nu_\ell}(E) \qquad (3)$$

with $\phi_0 = 9 \times 10^{-10}$ cm^{-2} s^{-1}. The first two factors depend on the particle physics parameters, viz. the mass of

the DM particle in units of 100 GeV $m_{\chi,100}$, and its annihilation cross-section in units of 10^{-26} cm^3/s, $(\sigma v)_{26}$, while the third factor accounts for the flux dilution with the square of the IMBH distance to the Earth in kpc, D_{kpc}. Finally, the normalization of the flux is fixed by an adimensional *luminosity factor* L_{sp}, that depends on the specific properties of individual spikes. In the case where the DM profile *before* the formation of the IMBH follows the commonly adopted Navarro, Frenk and White profile [23], the final DM density $\rho(r)$ around the IMBH will be described by a power law $r^{-7/3}$ in a region of size R_s around the IMBHs. Annihilations themselves will set an upper limit to the DM density $\rho_{\text{max}} \approx m_\chi/[(\sigma v)t]$, where t is the time elapsed since the formation of the mini-spike, and we denote with R_c the "cut" radius where $\rho(R_c) = \rho_{\text{max}}$. With these definitions, the intrinsic luminosity factor in Eq. (3) reads

$$L_{\text{sp}} \equiv \rho_{100}^2(R_s) R_{\text{s,pc}}^{14/3} R_{\text{c,mpc}}^{-5/3}, \qquad (4)$$

where $R_{\text{s,pc}}$ and $R_{\text{c,mpc}}$ denote respectively R_s in parsecs and R_c in units of 10^{-3} pc, $\rho_{100}(r)$ is the density in units of 100 GeV cm^{-3}. Typical values of L_{sp} lie in the range 0.1–10 [16].

The shape and normalization of the ν_ℓ spectrum per annihilation $N_{\nu_\ell}(E)$, depends on the nature of the DM particle. Here we work out the prospects for detection in two different annihilation scenarios, one corresponding to annihilation to $b\bar{b}$ pairs, representative of a large class of supersymmetric models (see e.g. the discussion in [24]), and one where DM annihilates directly to neutrino pairs, representative of models without helicity suppression, such as the aforementioned B$^{(1)}$ in theories with Universal extra-dimensions [7]. In the case of direct annihilation, we assume that all flavors are produced with equal branching ratios, $N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1:1:1$, as is appropriate for Kaluza-Klein DM [7]. The neutrino spectrum per annihilation is in this case monoenergetic $N_{\nu_\ell}(E) = 2\delta(E - m_\chi)/m_\chi$. The
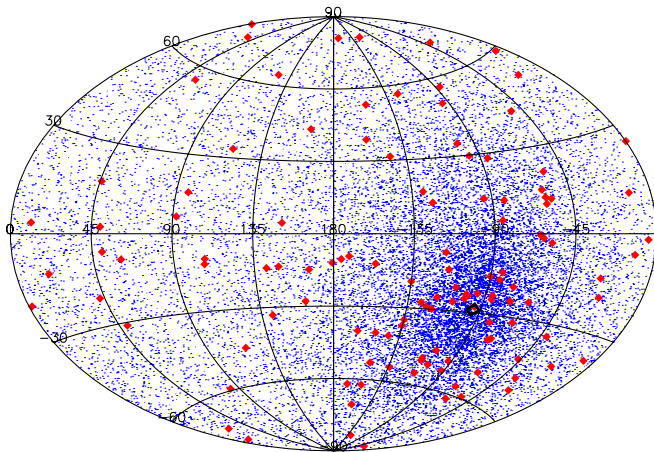

FIG. 1 (color online).   Sky map in equatorial coordinates showing the position of intermediate mass black holes in one random realization (red diamonds), and in all 200 realizations (blue dots). The concentration at negative declinations corresponds to the position of the Galactic center (black open diamond).

case of annihilation to $b\bar{b}$ is more complicated, since in this case neutrinos originate from the decay of hadrons produced in quark fragmentation, as well as from semileptonic decay of b quarks (see e.g. the discussion in Ref. [25]). A typical fragmentation and decay chain is $b \to \pi^{\pm} + \ldots$, $\pi^{\pm} \to \mu + \nu_{\mu}$, $\mu \to e + \nu_{\mu} + \nu_e$. Here we fold pion spectra obtained from fragmentation functions [26], with the spectra of neutrinos from pion decay (see e.g. [27]). For semileptonic decay, subdominant at low values of E/m_{χ}, but inducing a hardening of the spectrum at high energies, we follow the treatment of Ref. [28].

We focus here on the ν_{μ} flux at the ground, since neutrino telescopes are most sensitive to muons produced by charged-current interactions of ν_{μ} with nuclei around the detector. However, we cannot use directly Eq. (3), because flavor ratios are modified by neutrino oscillations in vacuum. For the energies ($E > 1$ GeV) and distances ($D_{\text{kpc}} > 1$) considered here, neutrino oscillations will be completely averaged out [29,30]. The flux at the detector can in this case be expressed as

$$\Phi_{\nu_{\mu}}(E) = \sum_{\ell=e,\mu,\tau} P(\nu_{\ell} \to \nu_{\mu})\Phi^0_{\nu_{\ell}}(E), \qquad (5)$$

where $P(\nu_{\ell} \to \nu_{\mu})$ is the probability for a ν_{ℓ} to oscillate into ν_{μ}, which depends on the neutrino oscillation matrix elements [31]

$$P(\nu_{\ell} \to \nu_{\mu}) = \sum_j |U^2_{\ell j}||U^2_{\mu j}|. \qquad (6)$$

The analysis of solar and atmospheric neutrino oscillation, as well as a number of reactor and accelerator experiments, severely constrain the oscillation matrix elements [31], and we adopt here $P(\nu_{\ell} \to \nu_{\mu}) = (0.2, 0.4, 0.4)$ [32]. The rate of muons induced by a neutrino flux $\Phi_{\nu_{\mu}}(E)$ is given by

$$R = V_{\phi}(\delta) \int_{E^{\text{thr}}_{\mu}}^{m_{\chi}} dE_{\nu} \int_0^{y_{\nu}} dy A(E_{\mu})P_{\mu}(E_{\nu}, y)\Phi_{\nu_{\mu}}(E_{\nu}), \qquad (7)$$

where $y_{\nu} = 1 - E^{\text{thr}}_{\mu}/E_{\nu}$ and E^{thr}_{μ} is the muon threshold energy of the experiment (we adopt here $E^{\text{thr}}_{\mu} = 100$ GeV). $A(E_{\mu})$ is the effective area of the detector. In our case we have used an energy-dependent $A(E_{\mu})$ for Antares [33], while for IceCube we assumed the indicative value $A(E_{\mu}) = 1$ km^2. $P_{\mu}(E_{\nu}, y)$ is the probability that a neutrino of energy E_{ν} interacts with a nucleon producing a muon of energy $E_{\mu} \equiv (1 - y)E_{\nu}$ above the detector threshold energy, and can be estimated as

$$P_{\mu}(E_{\nu}, y) = N_A R(E_{\mu}, E^{\text{thr}}_{\mu})\sigma(E_{\nu}, y), \qquad (8)$$

where $R(E_{\mu}, E^{\text{thr}}_{\mu})$ is the muon range, i.e. the distance traveled by muons before their energy drops below E^{thr}_{μ}, $N_A = 6.022 \times 10^{23}$ g^{-1} is Avogadro's number and $\sigma(E_{\nu}, y) \equiv d\sigma^{\nu N}_{\text{CC}}(E_{\nu}, y)/dy$ is the differential cross-

section for neutrino-nucleon charged-current scattering (for further details see e.g. Ref. [3] and references therein). In our treatment of high-energy neutrino-nucleon interactions we follow Ref. [34], but we make use of an updated set of parton distribution functions [35].

The results are shown in Fig. 2, where we plot the number of black holes producing a rate of events R, or larger, in ANTARES and IceCube, assuming $m_{\chi} = 1$ TeV, and $\sigma v = 10^{26}$ cm^3 s^{-1}. For comparison, we show the rate of atmospheric neutrino events in a search cone of size 1° around the source, for Antares and for a kilometer-scale telescope. For the atmospheric background in Antares we have adopted the value derived in a dedicated study [33], relative to a point source coincident with the Galactic center, while for kilometer-scale telescopes, we have used the so-called Bartol flux [36], and a source at the same declination.

The choice of a heavy DM particle in Fig. 2 was motivated by the fact that the sensitivity of neutrino telescopes increases with energy, due, in particular, to the increase of the neutrino-nucleon cross-section, while the atmospheric background rapidly decreases with energy, a circumstance that leads to a better signal to noise ratio for high-energy fluxes. Unlike other indirect searches, annihilation fluxes from mini-spikes around IMBHs are not very sensitive to the particle physics parameters of the DM candidate. In fact, the luminosity factor L_{sp} implicitly depends on the
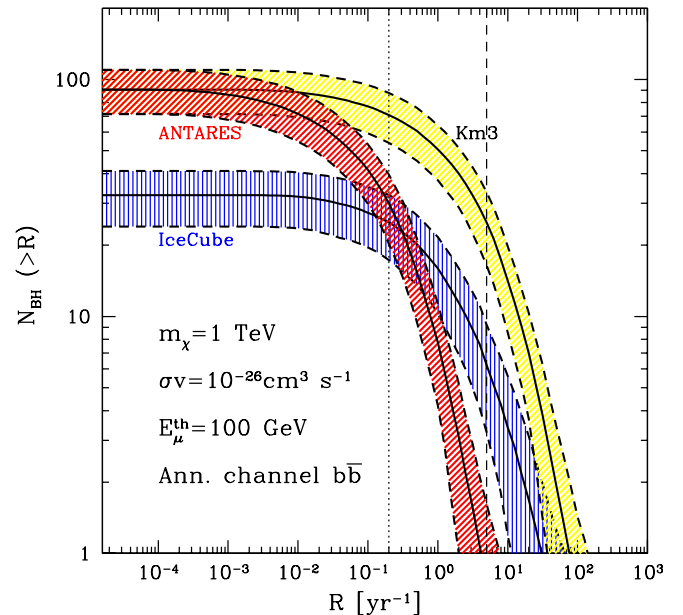

FIG. 2 (color online). Number of IMBHs producing a rate R, or larger, in Antares, IceCube and Km3. Solid lines corresponds to the average over all realizations, while dashed line denote the 1-σ scatter from one simulation to another. For reference we show the rate induced by atmospheric neutrinos in Antares (vertical dotted) and Km3 (vertical dashed) in a 1° cone around a source located at the Galactic center.

DM mass and cross-section, partially compensating the $(\sigma v)/m_\chi^2$ factor in Eq. (3), so that the neutrino flux is actually proportional to $(m_\chi)^{-9/7}(\sigma v)^{2/7}$, as for gamma-rays [16]. An additional reason to focus on a heavy DM candidate is that the prospects for detection with gamma-ray telescopes are more promising for DM particles lighter than 300 GeV.

As one can see from Fig. 2, IceCube is expected to detect a larger number of sources with a high event rate, with respect to Antares, and several of those are expected to exceed the atmospheric background. However, the sources are more concentrated toward the Galactic center, i.e. a region that cannot be seen by IceCube. The Antares location is more favorable, although the event rate is inevitably smaller due to reduced size of the experiment. A kilometer sized detector in the Mediterranean [37], combining the large, km^2, area of IceCube, with the visibility function of Antares, appears ideally suited for this type of searches. We show in Fig. 2 what can be achieved with a detector with $A(E_\mu) = 1$ km^2 at the same latitude as Antares. Note also that the specific example in Fig. 2 is consistent with null searches with the Amanda-II telescope [38], although the collected data can already be used to constrain the parameter space of the proposed scenario.

The results for direct annihilation to $\nu_\ell \bar{\nu}_\ell$ are less promising, unless the mass of the DM particle is just above $E_\mu^{\rm thr}$. This is due the fact that in the $b\bar{b}$ channel, fragmentation and decay of secondary particles produce a *large* number of neutrinos, with energy much *smaller* than m_χ. The direct annihilation thus dominates only when most of these neutrinos are produced at energies below $E_\mu^{\rm thr}$. For the parameters in Fig. 2, the $\nu_\ell \bar{\nu}_\ell$ flux is smaller by a factor ~3.5 for Antares, and ~5 for IceCube and Km3. Note that although neutrinos from the Galactic center may in principle represent an interesting alternative, the prospects for detecting gamma-rays from the same source are more interesting both for supersymmetric [39] and Kaluza-Klein DM [25,40].

We recall that we derived our results in the framework of a specific IMBH's scenario, characterized by a heavy mass scale $\sim10^5 M_\odot$. Alternatively, we could have chosen to work in a different scenario, where IMBHs form in over-dense regions at high redshift, $z \sim 20$, as remnants of Population III stars, and have a characteristic mass-scale of a few $10^2 M_\odot$ [41]. However, in this scenario the formation of IMBHs is not adiabatic [16], and mini-spikes can only form by the subsequent growth of IMBHs by accretion of baryons [42,43], a circumstance that makes the mini-spikes more shallow, and the whole scenario more problematic.

We have shown that upcoming neutrino telescopes may detect the neutrino flux from DM annihilations around IMBHs. The prospects for detection appear promising, especially for a kilometer-scale neutrino telescope in the Mediterranean. Both Antares and IceCube should be able to detect several, up to many, IMBHs.

Unlike searches of high-energy neutrinos from the Sun or the Earth, which in most cases are only sensitive to *scattering* cross-section of DM particles off-nuclei, the proposed search is only sensitive to the *annihilation* cross-section, a circumstance that makes the proposed search complementary to the existing ones.

We stress the importance of a dedicated analysis that keeps into account the peculiar experimental details of the various neutrino telescopes, and a careful study of the detectability of sources in different regions of the DM parameter space.

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