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Dark matter indirect searches: Multi-wavelength and anisotropies

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Abstract. If dark matter is made of particles governed by weak-scale physics, they may annihilate or decay to leave observable signatures in high-energy gamma-ray sky. In addition, any charged particles produced by the same process will also give low-frequency photons through successive electromagnetic interactions. Plenty of data from modern astrophysical measurements of various wavelengths, especially gamma rays, enabled new analysis techniques to search for these dark matter signatures with an unprecedented sensitivities. Since it is very likely that signatures of dark matter annihilation or decay is hidden in the gamma-ray data, one should fully utilize all available data including: (1) energy spectrum of all wavelengths ranging from radio to very-high-energy gamma rays; (2) spatial clustering probed with the angular power spectrum of the gamma-ray background; (3) cross correlation between the gamma-ray distribution with nearby galaxy catalogs; and (4) gamma-ray-flux distribution. I will review recent theoretical and observational developments in all these aspects, and discuss prospects for the future towards discovery of dark matter as an elementary particle in physics beyond the standard model.

1. Introduction

One of the most popular and best-studied candidates of dark matter is a weakly interacting massive particle (WIMP). The argument that gives it a strong motivation is that the measured density of dark matter in the present Universe can be well explained by thermal freeze-out mechanism, in which WIMP dark matter particles were in thermal equilibrium, but at later time, left the thermal bath as a relic particle without being annihilated due to the cosmic expansion. The relic density is related to the annihilation cross section, and if weak-scale physics is assumed (i.e., electron charge as a coupling, mass of weak bosons as energy scale), the predicted relic density nicely matches with the observations [1].

One important consequence for this model is that the WIMP dark matter has to self-annihilate in dense environment such as dark matter halos. Unless the WIMPs have even lighter, undiscovered particles to interact with, they have to annihilate into the standard model particles. In many cases, the annihilation ends up producing lots of gamma-ray photons, neutrinos, and charged particles such as electrons and positrons. Therefore, in order to maximize our sensitivity to the WIMP dark matter, one should utilize all the available channels. They are multi-wavelength observations ranging from radio to very-high-energy gamma rays, as well as other probes such as neutrinos.

Since the WIMP signatures would be hidden in astrophysical backgrounds, it is also important to utilize all the available information one could obtain. The anisotropies of the extragalactic gamma-ray background (EGRB) [2] has been established as one of the main analysis strategies

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to look for WIMP signatures in the Fermi data. Such new analyses became possible as the number of gamma-ray photons that Fermi collected from all sky well exceeds a million. Spectral analysis, as has been traditionally done [3], is still the major and important method, but this way, by confining millions of photons in only tens of energy bins, one loses lots of information that should be otherwise available.

In this contribution, I will summarize recent developments on both the multi-wavelength and anisotropy analyses to look for indirect dark matter signatures.

2. Dark matter annihilation

The rate of dark matter annihilation, and hence total number of particles created from the annihilation (such as gamma rays) depends on the annihilation cross section times relative velocity $\langle\sigma v\rangle$ (here $\langle\cdots\rangle$ represents average over velocity distribution), WIMP mass, and mass density squared: $\langle\sigma v\rangle\rho_{\rm dm}^2/m_{\rm dm}^2$. This dependence on density squared makes it particularly important to discuss dense regions of dark matter particles—halos. In addition, recent numerical simulations find that halos contain lots of smaller-scale objects, and they are called substructures or subhalos [4]. If there are many subhalos in a host halo, their presence will further enhance the signature of the annihilation. This effect is often referred to as substructure boost, and its proper modeling is essential in interpreting analysis results in terms of dark matter parameters [5].

Thus far, the most reliable upper limits on the annihilation cross section is obtained with dwarf satellites, which are believed to be highly dark-matter-dominated system and hence with little astrophysical contamination. It is also considered that the substructure boost can be subdominant compared with the contribution from the smooth component [5]. The latest limits on $\langle\sigma v\rangle$ reaches 3×10^{-26} cm^3 s^{-1}, the "canonical" value that is preferred for thermal freeze-out scenarios for the WIMPs [1], for dark matter lighter than 100 GeV.

Another interesting possibility is a possible WIMP explanations of the gamma-ray excess towards the Galactic center, which suggests tens of GeV WIMPs annihilating into $b\bar{b}$ [6, 7], although recent studies seem to imply that the excess is produced by superposition of point-like sources such as millisecond pulsars [8, 9] rather than diffuse component including dark matter annihilation.

3. Multi-wavelength and multi-messenger test of dark matter models

From the annihilation or decay, particles produced are not just gamma rays but also charged particles such as electrons and positrons. They will produce lower-frequency photons by interacting surrounding photon fields and magnetic fields. For example, inverse-Compton scattering off star lights and microwave-background radiation will produce X-ray emission. If the annihilation happens in magnetized environment such as clusters of galaxies, then the charged particles will emit synchrotron radiation in radio. Reference [10] discussed such multi-wavelength prospects for nearby galaxies and clusters of galaxies. They also tested dark matter models that were motivated by GeV excess as well as measurements of the Galactic positrons and anti-protons with AMS-02.

For heavy-mass WIMPs in the multi-TeV range, Cherenkov telescopes such as HESS or the Cherenkov Telescope Array (CTA) in the near future might be more sensitive. Particularly because there is no indication of new physics at the Large Hadron Collider yet, it might simply imply that the energy scale of new physics is well beyond the TeV scale. Studies of constrained minimum supersymmetric standard model with nine parameters show that there are two preferred regions: $\sim$1 TeV higgsinos and $\sim$3 TeV winos [11]. The region for the wino dark matter is already in tension with the upper limits on gamma-ray lines from the Galactic center, and the one for the higgsino dark matter may be probed with the CTA if the density profile is steeper than r^{-1}.

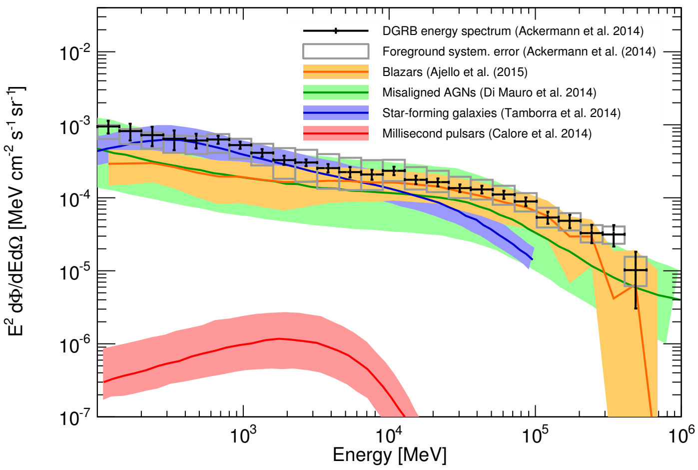

Figure 1. Energy spectrum of the EGRB. The Fermi data are compared with theoretical predictions for several astrophysical sources: blazars, star-forming galaxies, mis-aligned active galactic nuclei, and millisecond pulsars. Figure from Ref. [15].

It has also been suggested that the PeV neutrinos detected with IceCube might have the dark matter origin at least partly [12, 13]. Such a possibility can be tested with multi-messenger approach, if the dark matter signal is accompanied with some other hadronic channels, which will produce gamma rays through hadronic cascades. These models can soon be tested with further data from IceCube or the next generation neutrino detectors [14].

4. Extragalactic gamma-ray background

Because dark matter exists everywhere and has been annihilating ever since the beginning of structure formation, it should give certain contributions to the measured EGRB photons [3]. Potentially EGRB could provide a very strong way of searching for dark matter annihilation. The information one could use in order to maximize the sensitivity will be as follows:

- Energy;
- Spatial clustering of sources;
- Redshift distribution of sources;
- Luminosity distribution of sources.

4.1. Energy spectrum

The energy spectrum is the best studied probe of the origin of EGRB. It is well fitted with a single power-law function with a cutoff due to gamma-ray absorption by the extragalactic background light [3]. By studying luminosity functions of detected sources (i.e., BL Lac objects, flat-spectrum radio quasars, misaligned active galactic nuclei, and star-forming galaxies), however, at least some of them appears to give equally large contributions to the measured intensity [15, 16], and their combinations can address most (if not all) of the measured data (Fig. 1). This means that there is little room for dark matter to give substantial contributions to the EGRB spectrum. Turning this argument around, one will find a tight upper limit on $\langle \sigma v \rangle$. By analyzing the EGRB spectrum including relevant astrophysical contributions, Refs. [17, 18] found that the upper limits on $\langle \sigma v \rangle$ could be very tight, reaching the canonical cross section of 3×10^{-26} cm^3 s^{-1}.

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Depending on the substructure boost, the EGRB constraints can exceed those obtained with the dwarf galaxies, especially for heavy WIMPs.

The EGRB spectrum has been shown to give robust and stringent constraints on dark matter decay lifetimes. The limits obtained the same manner were shown to be better than those obtained from the analyses of the dwarf galaxies and clusters of galaxies [19]. These constraints give interesting implications for decaying dark matter models that were proposed to address excess of positrons and anti-protons with AMS-02.

4.2. Angular power spectrum

Dark matter annihilation should imprint a characteristic angular pattern on the gamma-ray sky, reflecting its intrinsic clustering. In addition, its density-squared dependence of the annihilation rate should leave quite different features compared with ordinary astrophysical sources that simply trace dark matter density [2].

This EGRB anisotropies were recently detected in the form of angular power spectrum at degree-level angular scales for energy bins between 1 GeV to 50 GeV [20]. The measured power spectrum was consistent with a point-source origin for $100 < \ell < 500$, and its amplitude was found consistent with predictions of gamma-ray blazars [21]. The results were then interpreted as upper limits on $\langle \sigma v \rangle$ for the WIMP dark matter by comparing the measurement with theoretical predictions, and although weaker than the best limits yet, the first important constraints were obtained [22, 23].

4.3. Cross correlation with galaxy catalogs

Galaxies trace dark matter. Therefore, there should be positive spatial cross correlation between the gamma-ray map (due to dark matter annihilation) and galaxy catalogs [24, 25]. Since clustering features at different redshift ranges are in general uncorrelated, taking cross correlation with pre-selected galaxy catalog corresponds to filtering gamma-ray sources in the particular redshift range in which these galaxy are located. An important difference between dark matter annihilation (or decay) and the relevant astrophysical sources are that the contribution to the EGRB comes from much lower redshift ranges for the former [26]. Therefore, by adopting low-redshift galaxy catalogs such as 2MASS, one can efficiently reduce astrophysical contamination to the EGRB to look for the dark matter component. Figure 2 demonstrates that even if the dark matter annihilation gives subdominant contribution to the EGRB energy spectrum, it can excel the other astrophysical components in the cross-correlation power spectrum and detectable with several years of Fermi data.

Such *tomographic* method is proven to indeed enhance sensitivities to the dark matter annihilation. By adopting the 2MASS Redshift Survey catalog [27], Ref. [24] predicted that one can reach the canonical cross section for WIMPs lighter than about a few hundreds of GeV, although it depends on the boost modeling (Fig. 3). This can get further improved by dividing the catalogs into a few smaller redshift bins [26].

Recently, Ref. [28] analyzed 60 months of Fermi data, by taking cross correlation with several galaxy catalogs including 2MASS. Positive cross correlations were found from all the galaxy catalogs analyzed. They interpreted the signal in terms of astrophysical contributions, but Ref. [29] obtained the upper limits on the annihilation cross section by modeling the astrophysical components. They found that the upper limits were quite competitive.

The same idea was proposed for the cross correlation between gamma rays and weak lensing data [30], for which several measurements were already made and interpreted in terms of astrophysical contributions as well as dark matter constraints [31, 32]. The tomographic method can also be applied to obtain stringent constraints on properties of sources for high-energy neutrinos detected with IceCube [33].

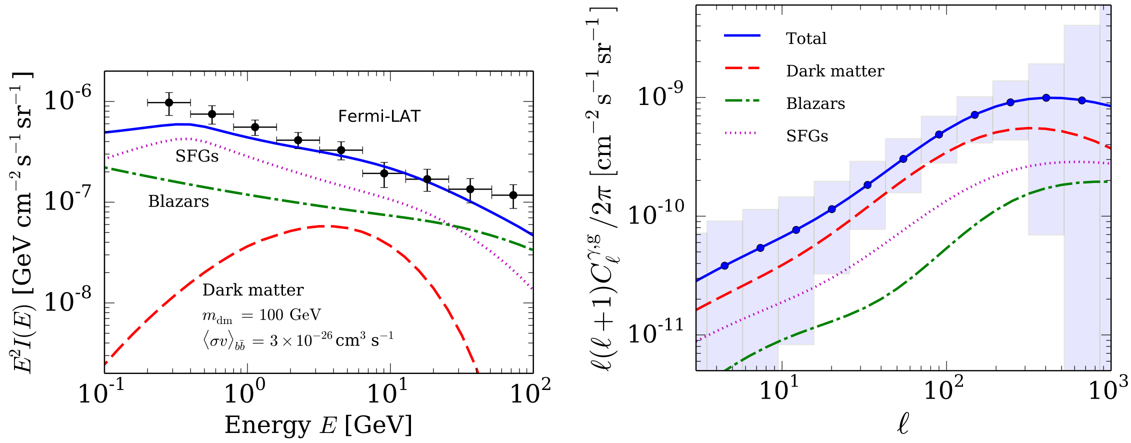

Figure 2. *Left*: The spectrum of EGRB from dark matter annihilation (dashed), blazars (dot-dashed), and star-forming galaxies (dotted). The total contribution is shown as solid. The parameters for dark matter annihilation are indicated in the figure. *Right*: The angular cross-power spectrum between the EGRB (5–10 GeV) and galaxies from the 2MASS Redshift Survey. Line types as well as dark matter parameters are the same as the left panel, while the boxes represent expected 1σ errors assuming 5-year exposure of Fermi. Figure from Ref. [24].

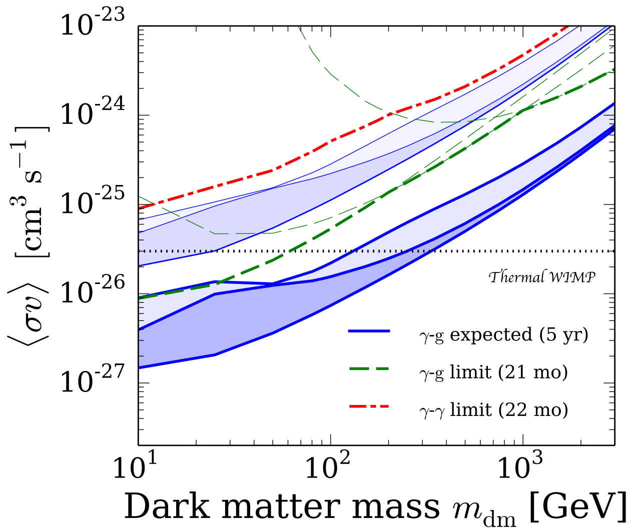

Figure 3. Sensitivity to the dark matter annihilation cross section from the cross-correlation between five years of Fermi data and the 2MASS Redshift Survey galaxy catalog. Lower and upper bands correspond to more and less optimistic boost models, respectively. Three curves in each band show the case where astrophysical backgrounds are understood perfectly (bottom), moderately (middle), and little (top). For comparison, the upper limits due to auto-correlation and the cross-correlation measurements with 22-month of Fermi data are shown as dot-dashed and dashed curves, respectively. Figure from Ref. [24].

4.4. Probability distribution function of gamma-ray flux

Distribution of gamma-ray photons will be non-Gaussian. If they come from sources including astrophysical emitter as well as dark matter annihilation, there will be particularly bright spots in the sky that is associated to locations of nearby, luminous sources. Since the intrinsic gamma-ray luminosity distribution depends on source classes, such information can be used as another diagnosis for testing the origin of the EGRB. Reference [34] calculated the probability distribution function of the gamma-ray flux from dark matter annihilation in Galactic subhalos. Reference [35] extended the study by including the contribution from extragalactic halos. The authors also adopted a new way of calculating the probability density by combining the central limit theorem at low-flux regime and Monte Carlo simulations at high-flux regime. The flux distribution is proven to provide stringent constraints on dark matter parameters by disentangling the astrophysical components efficiently.

Reference [36] performed the first analysis along this line, and found that the flux distribution is well explained with the Galactic diffuse emission, isotropic background emission, and point sources. The analysis was revisited recently with more data and refined method [37]. The authors showed that the flux distribution can be reconstructed by about one order of magnitude lower than the traditional analysis method.

5. Conclusions

Plenty of data from modern astrophysical measurements of various wavelengths, especially gamma rays, enabled new analysis techniques to search for dark matter signatures with an unprecedented sensitivities. Of particular importance from recent studies are multi-wavelength approach as well as anisotropies of the diffuse gamma-ray background.

Since it is very likely that signature of dark matter annihilation or decay is hidden in the gamma-ray data (buried by lots of astrophysical source contributions), one should fully utilize all available data. They include: (1) energy spectrum of all wavelengths ranging from radio to very-high-energy gamma rays; (2) spatial clustering probed with studies of angular power spectrum; (3) cross correlation with nearby galaxy catalogs that will be a probe of redshift distribution; and (4) probability distribution function of gamma-ray flux. In all of the above, dark matter will give characteristic signatures that will be distinguished from ordinary astrophysical sources such as active galactic nuclei and star-forming galaxies. Although challenging, combining all of them will be an essential asset towards potential discovery of dark matter as a new elementary particle.

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