Lecture Note #6: Indirect Detection of Dark Matter

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Dark matter can produce observable signals when it annihilates at late times. Recall that for thermal DM, cosmological annihilation ended at freeze out. However, long after freeze out the very uniform early DM density underwent gravitational collapse to form regions with much larger densities (*i.e.* structure) than the average cosmological values. One of these regions is our own galaxy, which we think is surrounded by a halo of DM. Since the rate per unit volume of DM annihilation is proportional to n_χ^2, there can be significant annihilation within the galactic halo today. The products of these annihilations are energetic visible particles that can be observed with cosmic ray and other telescopes. Searching for DM in this way is called *indirect detection* (ID), and in this note we describe a broad variety of possible ID signals and explain how to compute them for a given theory of DM.

1 Gamma Rays

One of the products that can arise from DM annihilation are high-energy photons, also called gamma rays. These can be produced directly from annihilation, semi-directly from the decays of the DM annihilation products, or indirectly from the collisions of the annihilation products with CMB or starlight photons. The really nice feature of photons is that they mostly travel in straight lines once they have been produced. This lets us pinpoint precisely where the signal is coming from.

1.1 Photon Flux from DM

The quantity of interest for gamma ray signals of DM is the photon flux per unit energy per unit solid angle in any given direction, $\Phi_\gamma(E,\hat{n})$, where E is the energy and $\hat{n}$ is a unit vector pointing in the direction being observed.[1] In terms of the annihilation rate and the local DM density, this quantity is given by the formula [1]

$$\Phi_\gamma(E,\hat{n}) \;=\; \frac{\langle\sigma v\rangle f_\gamma(E)}{8\pi\, m_\chi^2}\int_{\rm los} d\ell\, \rho_\chi^2(\vec{x}) \ , \tag{1}$$

where $f_\gamma(E) = dN_\gamma/dE$ is the average number of photons of energy E per unit energy emitted in each annihilation (*i.e.* the photon energy distribution), $\langle\sigma v\rangle$ is the DM annihilation cross section thermally averaged over the conditions present today, and the integral runs along the path of the line of sight defined by $\hat{n}$ and illustrated in Fig. 1. The physical content of this expression is simple; it is the sum of all the DM annihilation contributions along the direction being observed.

[1] I would prefer to call this $d\Phi_\gamma/dE\,d\Omega$, but this notation seems to be fairly standard.

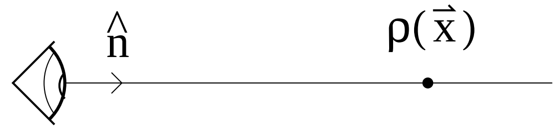

Figure 1: Illustration of the path for the line-of-sight integral.

The result of Eq. (1) depends on particle physics and astrophysics. For comparing theories of DM to experiment, it is convenient to split it into two terms:

$$\Phi_\gamma(E, \hat{n}) = \frac{r_\odot}{4\pi} Q_\gamma(\odot)\ J\ , \tag{2}$$

where $Q_\gamma(\odot)$ contains all the particle physics,

$$Q_\gamma(\odot) = \frac{1}{2}\frac{\rho_\odot^2}{m_\chi^2}\langle\sigma v\rangle f(E)\ , \tag{3}$$

while J contains the astrophysics,

$$J = \int_{\rm los}\left(\frac{d\ell}{r_\odot}\right)\left[\frac{\rho_\chi(\vec{x})}{\rho_\odot}\right]^2\ . \tag{4}$$

In these expressions we have normalized quantities to the distance from the center of our galaxy (the Milky Way) to the Sun $r_\odot \simeq 8.5\,\text{kpc}$, as well as the DM energy density in the local region $\rho_\odot \simeq 0.4\ \text{GeV/cm}^3$. These normalizations are useful because we are usually most interested in photon signals produced by DM annihilation in the Milky Way. Note that in practice, since telescopes have a finite resolution, the quantity J is usually averaged over a small but finite solid angle.

1.2 DM as a Gamma Ray Source

High-energy gamma-ray photons can be created by DM annihilation in three main ways. The first and most distinctive is direct annihilation, $\chi\chi \to \gamma\gamma$ or $\gamma\, Z^0$. In many theories of DM (such as minimal supersymmetry with R-parity), this is a relatively unlikely annihilation channel. Even so, the great advantage of direct annihilation is that the energy of the photon(s) emitted is monochromatic,

$$E_\gamma = \begin{cases} m_\chi & ;\ \ \gamma\gamma \\ m_\chi\left(1 - m_Z^2/4m_\chi^2\right) & ;\ \ \gamma Z^0 \end{cases}\ . \tag{5}$$

Equivalently, $f_\gamma(E) \propto \delta(E - E_\gamma)$. This monochromatic signal is relatively easy to distinguish from astrophysical backgrounds.

The second source of energetic photons from DM annihilation are non-photonic annihilation modes such as $\chi\chi \to W^+W^-$ or $f\bar{f}$. Photons can be generated in these channels from

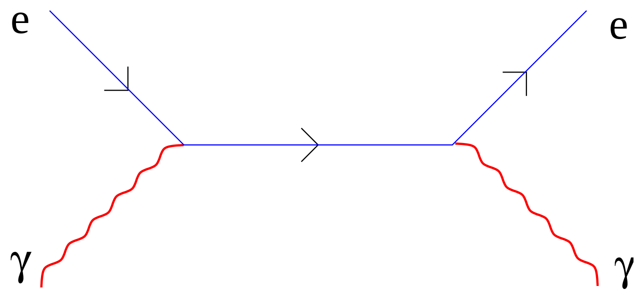

Figure 2: Inverse Compton scattering with an electron.

higher-order Feynman diagrams with an additional photon leg, or from subsequent photonic decays of the annihilation products (such as $\pi^0 \to \gamma\gamma$). The energy distribution of these photons $f_\gamma(E)$ is a smooth function that typically falls with energy.

The third way to get high-energy photons from DM annihilation is inverse Compton (IC) scattering. Recall that IC corresponds to a charged particle colliding elastically with a photon, which we illustrate in Fig. 2. When an energetic charged particle is created in DM annihilation, it can collide with a photon in the interstellar medium (such as starlight or CMB) and give it enough of an energy kick to make it visible in a gamma ray telescope. The spectrum of IC photons due to DM annihilation is a smooth function of energy, but these photons tend to be less energetic than those generated directly by annihilation processes.

1.3 Where to Look

The result of Eq. (1) shows that the net gamma ray signal is proportional to the square of the DM number density, $n_\chi^2 = \rho_\chi^2/m_\chi$. The signal will also be greater from sources that are closer to us. Together, this suggests that our own galaxy is the most promising place to look for gamma rays from DM annihilation. In particular, since we expect the density of DM to be greatest in the centre of our galaxy, many searches focus on this region.

Our galaxy, the Milky Way, is a rotating spiral galaxy. The visible material within it is distributed mostly in two features. First, there is a galactic disk with radius close to 15 kpc and thickness of about 0.3 kpc, and second, there is a roughly spherical central bulge of radius of about 2 kpc. The galactic disk is rotating around the centre of the galaxy. Our own star, the Sun, lies in this disk at a distance of about 8.5 kpc from the galactic centre. We also think there is a large, approximately spherical, non-rotating halo of DM surrounding the galaxy. See the left panel of Fig. 3 for an illustration.

Since our galaxy is also the brightest object in the visible spectrum, astronomers often use coordinates on the sky that are aligned with the galactic plane. Two angles are used: the galactic latitude $b \in [-90°, 90°]$, and the galactic longitude $\ell \in [-180°, 180°]$. They are chosen such that $(b, \ell) = (0°, 0°)$ is the galactic centre and $b = 0°$ defines the galactic plane, as illustrated in the right panel of Fig. 3.

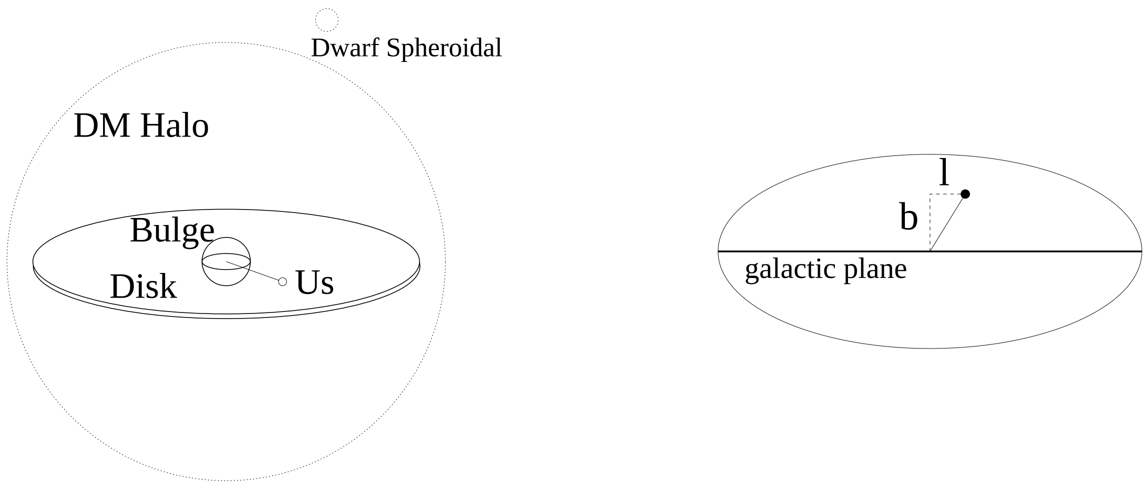

Figure 3: Home sweet home. In the left panel we show a cartoon of our galaxy and its surrounding DM halo. In the right panel we illustrate the standard galactic coordinates b and ℓ.

Recall from `notes-1` (Eqs. (6,8)) that the density of DM in our galaxy is expected to be largest at the galactic centre (GC). This makes the GC and its close surroundings, corresponding to small $|b|$ and $|\ell|$, a promising target to search for gamma rays from DM. In terms of the formula of Eq. (2), the quantity J is very large in this region. However, the GC also contains a lot of visible matter which can produce gamma rays as well. There is a significant additional uncertainty in the distribution of DM near the GC, so even the expected signal can't be predicted with high precision. For these reasons, it is also useful to search for DM-induced gamma rays away from the GC and the galactic plane.

An alternative target for gamma ray searches are dwarf spheroidals (dSph), which are small mini-galaxies orbiting our own. These seem to have high ratios of mass to visible light, suggesting that they consist mostly of DM. They also produce less astrophysical gamma rays than the GC, and the distribution of DM within them has a smaller uncertainty. For these reasons, observations of dwarf spheroidals currently give the best limit on the annihilation of DM to gamma rays.

1.4 Experimental Results

Gamma ray signals due to DM annihilation have been searched for extensively. The most powerful current tool is the Fermi Large Area Telescope (LAT) [2]. This device is mounted on a satellite orbiting the Earth, and is sensitive to gamma rays with energies between about 20 MeV and 300 GeV. Other tools include HESS [4] and VERITAS [5], which are sensitive to higher-energy gamma rays.

At the moment there is no definitive evidence of DM from gamma rays. Even so, the data has been used to derive very stringent limits on the properties of a DM candidate that can

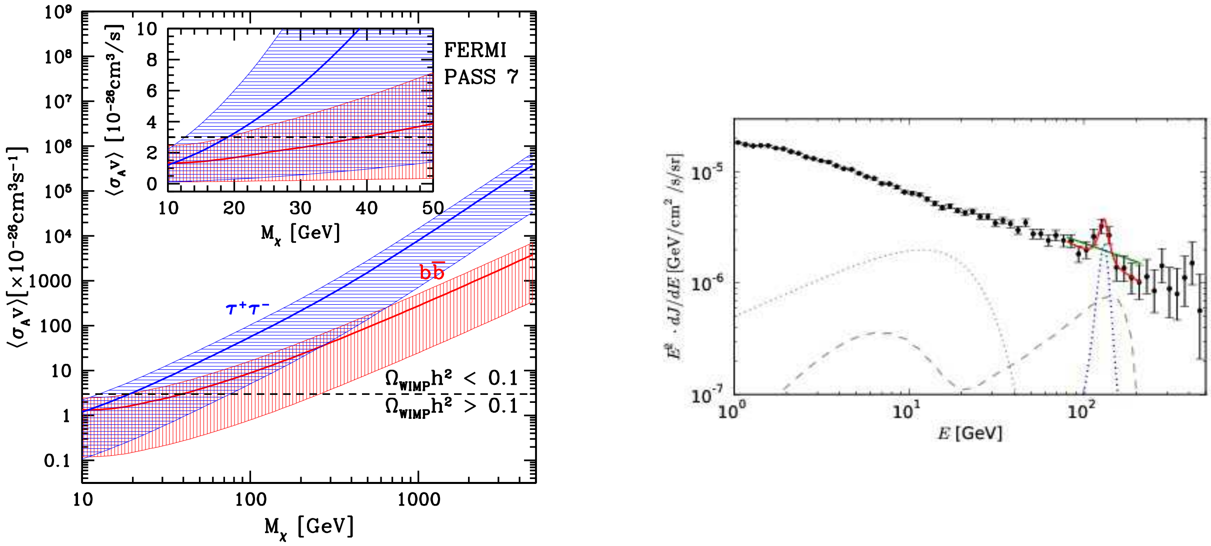

Figure 4: Limits and hints of DM in our galaxy. In the left panel we show the current limits on DM annihilation in nearby dSph systems, from Ref. [6]. In the right panel we show the apparent excess of gamma rays with $E_\gamma \simeq 130$ GeV from near the GC, from Ref. [7].

annihilate today. The strongest limits come from observations of dwarf spheroidal galaxies orbiting our own. The analysis of Ref. [6] rules out the annihilation $\chi\chi \to b\bar{b}$ with a cross section $\langle\sigma v\rangle > 3 \times 10^{-26}\text{cm}^3/s$ for DM masses up to about 100 GeV. We show their main exclusion plot in the left panel of Fig. 4.

This limit is strong, but it should be taken with a grain of salt. Recall from `notes-3` that $\langle\sigma v\rangle_{f.o.} \simeq 3\times 10^{-26}\text{cm}^3/s$ gives about the right thermal DM abundance. Note, however, that this is the value of the annihilation cross section at thermal freeze out when $v \sim 1/6$. The annihilation cross section that appears Eq. (1) and is bounded by the data is the thermally-averaged cross section in our galaxy at present. Since $v \sim 10^{-3}$ in the galaxy, the galactic value today can be much smaller at freeze-out if $\langle\sigma v\rangle \propto v^2$, which occurs if p-wave channels dominate.

Despite these limits, there are also a few anomalies in the data that could turn out to be a signal of DM. One of the most promising recent results is the discovery of a bump in the gamma ray spectrum near the GC at energies close to $E_\gamma = 130$ GeV [7, 8]. Such a bump is precisely what one would expect from the monochromatic photon emitted in the direct annihilation modes $\chi\chi \to \gamma\gamma$ or $\chi\chi \to \gamma Z^0$ with a cross section of about $\langle\sigma v\rangle \simeq 1 \times 10^{-27}\text{cm}^3/s$. This result is still controversial, and there have been suggestions that it could be an instrumental effect. It is also challenging to explain theoretically, since the $\gamma\gamma$ and γZ^0 direct annihilation modes are usually expected to be much less likely than other annihilation channels that are already constrained to have cross sections below about $5 \times 10^{-26}\text{cm}^3/s$ [9].

2 Cosmic Rays

Dark matter annihilation can also create (non-photon) cosmic ray signals. Since the annihilation products generally have to travel a long distance before reaching us, we can focus on stable species such as

$$p,\ \bar{p},\ e^-,\ e^+,\ \nu,\ \bar{\nu},\ D,\ \ldots \tag{6}$$

Of these, the promising are the first four, (anti-)protons and (anti-)electrons, and we will concentrate on them. Predicting the flux of particle cosmic rays from DM annihilation is more difficult than for photons because they interact with the interstellar medium on the way to our detector.

2.1 Cosmic Ray Propagation

The quantity we want to compute is $\Psi_i(\vec{x}, E)$, the number density per unit energy of species i at point $\vec{x}$ with energy E. This density gets contributions from DM annihilation, but it is also modified by astrophysical effects on the propagation of the particle species from where it was created to point $(t, \vec{x})$. These effects are typically modelled with a steady-state diffusion equation of the form

$$Q_i(\vec{x}, E) = \partial_z \left(\hat{z}\cdot\vec{v}_c\Psi_i\right) - K\nabla^2\Psi_i + \partial_E \left(b_{loss}\Psi_i - K_{EE}\partial_E\Psi_i\right)\ . \tag{7}$$

This equation is solved in a cylindrical region aligned with the galactic disk and centred at the GC. Outside the diffusion cylinder, particles are allowed to escape freely.

The terms in Eq. (7) have simple physical interpretations. The left-hand side is the source term, corresponding to particle creation by DM annihilation and astrophysics. The DM contribution is

$$Q_i^{DM}(\vec{x}, E) = \frac{1}{2}\frac{\rho_\chi^2(\vec{x})}{m_\chi^2}\langle\sigma v\rangle\, f_i(E)\ , \tag{8}$$

where $f_i(E) = dN_i/dE$ is the average number of i-type particles of energy E emitted per unit energy in the annihilation. This expression is just like what we had for photons.

On the right-hand side of Eq. (7), the first term corresponds to convection of the cosmic rays. This arises from supernova (*i.e.* exploding star) shock waves emanating from the galactic disk that push matter away from it (in the z direction), and $\vec{v}_c = v_c\, sgn(z)\, \hat{z}$ is the corresponding convection velocity. The second term on the right side corresponds to spatial diffusion induced by the turbulent magnetic fields in the galaxy. The third term describes changes in the particle energy; the b_{loss} piece energy loss by the species from scattering with dust and photons (IC scattering) in the interstellar medium, while the K_{EE} piece describes diffusion in energy space due to scattering with turbulent magnetic fields.

The parameters in the diffusion equation have significant uncertainties, but they can be constrained by studying the cosmic fluxes of heavy nuclei. A particularly important quantity is the ratio of fluxes of Boron to Carbon, the B/C ratio. Carbon is created mostly in stars, and propagates outward due to supernova shocks. Instead, Boron is produced mostly as a *secondary* product of collisions of other particles (called *spallation*). Fits to the data give a range of allowed values for the parameters of the diffusion equation. The central value obtained is called the MED model, while the models that predict the largest and smallest fluxes of $\bar{p}$ are called MAX and MIN.

Solutions to the diffusion equation (which must usually be done numerically) can be written in a nice form using a Green's function.[2] The result is

$$\Psi_i(\vec{x}, E) = \int dE_s \int d^3x_s \; G_i(\vec{x}, \vec{x}_s; E_s \to E) \; Q(\vec{x}_s, E_s) \; , \tag{9}$$

where the Green's function G_i describes the propagation in position and energy of the i-th species from where it was created at $\vec{x}_s$ with energy E_s to where it is observed at $\vec{x}$ with energy E. The quantity that is measured is the differential cosmic ray flux per unit energy per unit solid angle at our local position $x_\odot$,

$$\Phi(\vec{x}_\odot, E) = \frac{v}{4\pi} \Psi_i(\vec{x}_\odot, E) \tag{10}$$

$$= \frac{v}{8\pi} \langle \sigma v \rangle \left(\frac{\rho_\odot}{m_\odot} \right)^2 \int dE_s \; f_i(E_s) \, I_i(E, E_s) \tag{11}$$

with

$$I_i(E, E_s) = \int d^3x_s \; G_i(\vec{x}, \vec{x}_s; E_s \to E) \left[\frac{\rho_\chi(\vec{x}_s)}{\rho_\odot} \right]^2 \; . \tag{12}$$

All we have done here is rewrite the previous expression, but this form is useful because it factorizes the particles physics part from the astrophysics part.

Protons and antiprotons can be created when DM annihilates to quarks and antiquarks. Equal numbers of both are expected to be generated in this way. The propagation of protons and antiprotons through the interstellar medium is found to be relatively efficient, with both types of particles able to travel significant distances. Even so, the propagation is affected by diffusion, and the local flux of protons and antiprotons is expected to be isotropic. Some of the antiproton flux can also be lost through annihilation with hydrogen or helium. On the other hand, antiprotons can be created by inelastic scattering processes such as $p + p \to p + p + p + \bar{p}$. This is expected to be the main source of astrophysical antiprotons. A good way to look for a signal from DM is therefore to compare the observed ratio of antiprotons to protons; we expect $\bar{p}/p \simeq 1$ from DM but a much smaller value from astrophysics.

Electrons and antielectrons can arise both from hadronic and leptonic annihilation channels of DM, and equal numbers of both are expected. They do not propagate as well as protons and antiprotons, and they tend to lose energy to synchrotron emission and IC scattering. Calculations suggest that they do not travel much further than a kpc. While DM produces equal number of electrons and antielectrons, astrophysics is expected to produce

[2] A popular code to do this is called GALPROP [10].

many more electrons. Antielectrons can be created by $p + H \to X + \pi^+$ with $\pi^+ \to e^+ + \nu$s, but they are less abundant than electrons at high energies. As before, a fairly robust signal of DM annihilation is a large ratio of e^+/e^-.

2.2 Observational Results

Cosmic ray data has also been used to search for DM annihilation, and some interesting results have been obtained. The PAMELA cosmic ray telescope has found a significant excess of positrons relative to astrophysical expectations, which was recently confirmed by AMS-02, and the Fermi-LAT sees a somewhat large net flux of electrons and positrons. On the other hand, no significant excess of antiprotons is seen. The interpretation of these results in terms of DM is challenging, and has been a very active topic of research in the last few years. Some astrophysical explanations of the PAMELA positron excess have also been proposed. Hopefully the situation will become clearer with more data.

The PAMELA cosmic ray telescope observes a rise in the ratio $\Phi_{e+}/(\Phi_{e+} + \Phi_{e-})$ at energies above $E \gtrsim 10$ GeV [11], and the result has been confirmed by Fermi-LAT [11], and AMS-02 [13]. Simple astrophysical predictions suggest that this ratio should be a falling function of energy. Both the data and the expected astrophysics signal are shown in the left panel of Fig. 5. (Don't worry about the funny data below 10 GeV – this is a solar effect not accounted for in the background estimate.) The Fermi-LAT telescope also sees a mild excess in the net electron and positron flux above 100 GeV, but this appears to be much less significant relative to the uncertainty on the astrophysical background. Antiprotons were studied by PAMELA as well, but no significant excess relative to the expected background is observed, as shown in the right panel of Fig. 5.

Interpreting the PAMELA positron excess together with the other data in terms of DM annihilation is challenging. The first issue is the annihilation rate needed to account for the rise:

$$\langle \sigma v \rangle \simeq (10^{-25}\text{cm}^3/s) \left(\frac{m_\chi}{100\text{ GeV}}\right)^2 \frac{1}{BR_\ell}\ , \tag{13}$$

where BR_ℓ is the fraction of annihilations that produce leptons. Since the DM mass must be larger than 100 GeV to generate the rise (which extends to about 100 GeV), the annihilation rate today must be significantly larger than the value that gives the right thermal abundance during freeze out ($\langle \sigma v \rangle_{fo} \simeq 3 \times 10^{-26}\ \text{cm}^3/s$). The second difficulty is that the DM should not annihilate very often to hadrons, since otherwise it would predict too large of an antiproton flux; most WIMP models predict relatively similar hadronic and leptonic rates (*e.g.* $\chi\chi \to W^+W^-$). The third obstacle is that DM annihilation to leptons will also produce a flux of photons, which is strongly constrained by gamma ray searches.

Despite these challenges, some potentially viable models have been proposed. A very popular one was given in Ref. [15], in which DM annihilates to a new light mediator particle ϕ with $m_\phi \sim$ GeV that subsequently decays to $\mu^+\mu^-$ or e^+e^-. With $m_\chi/m_\phi \gg 1$, the annihilation of χ can be enhanced at low velocities by a mechanism called *Sommerfeld enhancement* [16]. This can allow for a thermal abundance of χ particles while giving a

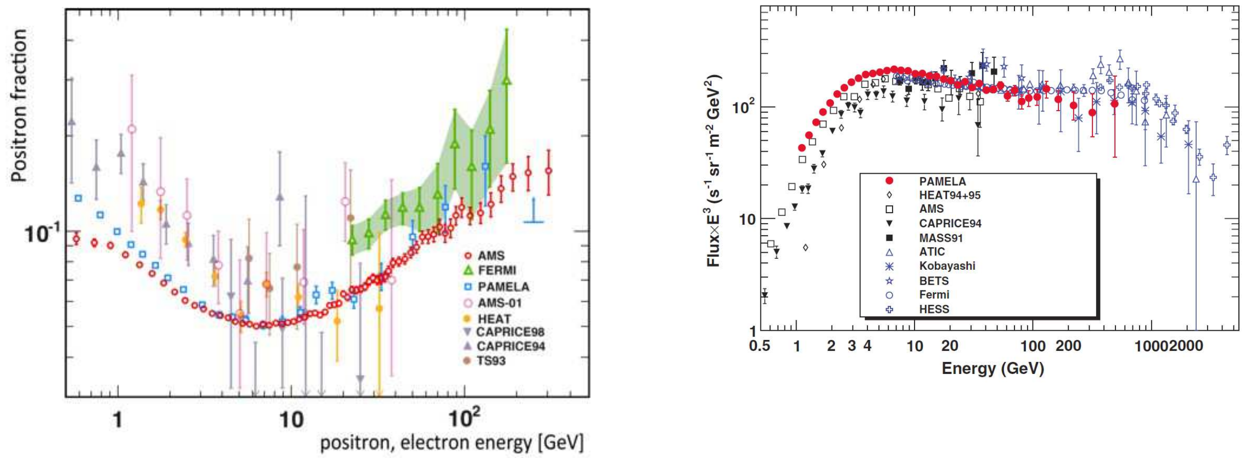

Figure 5: Positron and antiproton cosmic ray fluxes. In the left panel we show the excess in the positron flux $(\Phi_{e+}/(\Phi_{e+} + \Phi_{e-})$ relative to the expected background seen by PAMELA [11], AMS-02 [13], and other experiments. In the right panel we show the antiproton flux observed by PAMELA and other experiments [14].

significantly larger annihilation rate in our galaxy today. Since the annihilation product ϕ decays only to leptons, there is no problem with the lack of an excess in the flux of antiprotons. A multi-stage annihilation of this type is also found to give a relatively mild photon flux that can be consistent with the data within astrophysical uncertainties [17].

Several reasonable astrophysical explanations for the PAMELA positron excess have also been put forward. A promising example is *pulsars*, rotating neutron stars that generate enormous magnetic fields. These fields can generate cosmic rays by accelerating particles to very high energies. Pulsars could also contribute to the positron excess if there is significant e^+e^- pair production within them, giving rise to high energy electrons and positrons [18, 19]. In this case, the lack of new signals in antiprotons and gamma rays is consistent with the PAMELA excess. Unfortunately, it is difficult to distinguish this explanation from annihilating DM, other than measuring the properties of the DM in some other way.

3 Indirect Indirect Detection

The annihilation of DM in our galaxy (and beyond) can lead to observable signals in other ways. We describe two of them here: modifications to the CMB power spectrum, and radio-frequency synchrotron emission.

3.1 CMB Spectrum Modifications

DM annihilation injects energy into the cosmological plasma, and this can have an observable effect on the Cosmic Microwave Background (CMB). Recall that the CMB consists of photons left over from recombination at $z \simeq 1089$, when the free electrons and protons came together to form neutral hydrogen. When this occurred, the photons in the plasma decoupled from the baryons and were suddently above to propagate freely. Those leftover photons that have not interacted between then and now are what we see today as the CMB.

The correlation spectrum of temperature fluctuations in the CMB carries a great deal of information about the contents of the Universe between recombination and now. Energy injection into the cosmological medium by DM annihilation (or any other source) will ionize some of the neutral hydrogen after recombination and modify the fluctuation spectrum for a given set of cosmological parameters [20]. By comparing the measured CMB temperature spectrum to the modified spectra induced by DM annihilation, an upper limit on the DM annihilation cross section at recombination can be obtained [21],

$$\langle\sigma v\rangle < \frac{3.6\times 10^{-25}\,\mathrm{cm}^3/s}{f}\left(\frac{m_\chi}{100~\mathrm{GeV}}\right)\ , \tag{14}$$

where f corresponds to the fraction of energy released per annihilation that goes to ionizing neutral hydrogen.

3.2 Synchrotron Emission

Our galaxy is thought to support a large magnetic field near the centre. The annihilation of DM near the GC can inject high-energy electrons into this region. In the presence of the magnetic field, these electrons will be accelerated and lose energy to synchrotron radiation [22]. For electron energies of a few tens of GeV, the radiation will have a frequency in the GHz (radio to microwave) range, which is currently probed by CMB and other instruments [23].

The limits on DM annihilation from synchrotron emission are quite severe, but they are also significantly uncertain [23]. The two main challenges are that we do not know the precise density of DM very close to GC, and we are also unsure of the strength of the magnetic field in this region. On the flip side, an apparent excess of radio-frequency radiation near the GC is observed in CMB telescopes, termed the *WMAP haze* [24]. This excess has been interpreted as a signal of synchrotron radiation induced by DM annihilation.

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