Indirect Detection of WIMPs: Principles and Techniques

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The various main methods for indirectly inferring the presence of Weakly Interacting Massive Particles (WIMPs) as the unknown dark matter in the universe are examined. Indirect detection techniques include detecting cosmic-ray contributions from WIMP annihilation in the galactic halo, particularly in the positron, anti-proton, and gamma-ray spectra. WIMPs can also be captured in massive bodies such as stars, producing neutrinos or, in more extreme cases, modifying the luminosity or evolution of the star, both of which provide additional means of indirectly detecting the presence of WIMPs.

1 Introduction

The unknown dark matter in the universe could be composed of a new, massive stable particle; just such a particle with weak-scale coupling would freeze out during the early universe with a relic density of the right scale to account for the dark matter. There are theoretically motivated candidates for these Weakly Interacting Massive Particles (WIMPs), such as a Dirac neutrino and, perhaps one of the most favored dark matter candidates, the neutralino found in many supersymmetric theories [1].

There are three general areas in which WIMPs as dark matter can be probed. They can be produced in accelerators such as the Large Hadron Collider; interactions of relic WIMPs with ordinary matter can be directly observed in a detector (direct detection); or WIMPs can be more indirectly inferred, primarily through detecting the products or impact of relic WIMPs that annihilate elsewhere, such as in the galactic halo or in stars. Here, we examine the principles and techniques behind the most common methods for indirectly detecting WIMPs. Experimental results for indirect detection can be found elsewhere in these proceedings.

We break down the indirect detection methods into two areas: observation of cosmic-rays created by WIMP annihilations in galactic halos (Sec. 2) and signatures from WIMP capture in massive bodies such as stars (Sec. 3).

2 Cosmic rays

Annihilation of WIMPs in the dark matter halo produces high energy particles that contribute to various cosmic-ray spectra; observation of these high energy particles would be an indication of WIMP dark matter [2]. However, many other sources of cosmic rays exist, not all of which are well understood or modelled. These backgrounds present difficulties in identifying any high energy particles as arising from WIMP annihilations. Some of the clearest expected signatures of WIMP annihilations in light of these backgrounds are unique features that might arise in the positron, anti-proton, and gamma-ray spectra. In the case of gamma-rays, which do not diffuse under the galactic magnetic field as do the positrons and anti-protons, the direction the gamma-rays arrive from indicates where they were produced; the mapping of gamma-ray sources provides another possible means to detect WIMP annihilations as WIMP annihilations can occur with a different spatial distribution than background sources.

2.1 Positrons

Positron backgrounds are mainly secondaries from cosmic-ray collisions with interstellar matter that is expected to produce a smooth continuum for the positron flux spectra. Annihilation of WIMPs directly to electrons and positrons would provide a sharp peak (broadened by propagation effects) in the spectrum that is at odds with the expected background and would provide a clear signature for WIMPs. However, direct annihilation to positrons is typically loop suppressed and is not expected to be a significant decay channel. Annihilation of WIMPs to W's, however, will lead to a broader peak from the leptonic W decays. This peak should provide an observable WIMP signature above the background continuum. Other annihilation channels can also produce positrons, but these channels generally give a continuum spectrum not distinguishable from the background. The positron spectrum is examined by experiments such as HEAT [3] and PAMELA [4].

2.2 Anti-protons

Anti-proton backgrounds are also mainly secondaries from cosmic-ray collisions with interstellar matter, producing a smooth continuum. However, collisions energetic enough to produce anti-protons are unlikely to produce low speed anti-protons (kinetic energies of ∼1 GeV or less) due to a kinematic suppression, so the background spectrum is expected to fall rapidly at low energies. Anti-protons produced during hadronization processes of WIMP annihilations are expected to also yield a continuum spectrum; however, low energy anti-protons are not suppressed in this production mechanism. Thus, an anti-proton spectrum that does not fall at low energies would provide a signature for WIMPs. The anti-proton spectrum is examined by experiments such as BESS [5], CAPRICE [6], and AMS [7].

2.3 Gamma-rays

Unlike the positrons and anti-protons, gamma-rays are uncharged and travel mainly unimpeded from their source to a gamma-ray detector. Thus, in addition to the gamma-ray flux spectrum, the spatial distribution of gamma-ray sources can be used to identify WIMP cosmic-ray contributions. The background spectrum for gamma-rays is expected to be a continuum only. Annihilation of WIMPs directly to gammas or a gamma + Z will produce a mono-energetic peak or a peak + continuum, respectively, though both annihilation channels are usually loop suppressed and not significant. Internal bremsstrahlung processes will provide a hard spectrum that can also offer a signature for WIMPs. Other channels that produce gammas produce a continuum similar to the background. The spatial resolution for gamma-rays allows spectra to be observed from different sources. The backgrounds depend on the observational target. The galactic center, with its high WIMP density, should produce a high signal, but the backgrounds are also expected to be high there. Dwarf galaxies and subhalos, on the other hand, would have a much smaller signal, but the backgrounds would also be low (possibly giving a better signal-to-noise ratio). In addition, spatial variations in the spectra can provide further mechanisms for extracting WIMP contributions to cosmic rays. Gamma-rays are examined by experiments such as EGRET [8], HESS [9], and Fermi [10].

3 Capture in massive bodies

WIMPs can become captured within massive bodies such as stars and planets, primarily through scattering off of nuclei, providing several possible signatures of WIMP dark matter. The process proceeds as follows: WIMPs within the dark matter halo of a galaxy will pass through a star (or planet), occasionally scattering off of a nucleus. Some WIMPs that undergo such scatters will lose enough energy that they become gravitationally bound to the star. Subsequent orbits through the star will lead to additional scatters and loss of energy, resulting in the WIMP that falls towards to the center of the star. As a population of such WIMPs grows at the center of the star, they will annihilate with each other, producing (most significantly) neutrinos and heat. The former (neutrinos) can pass through the star and possibly be observed by a neutrino detector if the source is close enough. The latter (heat) can lead to several observable effects, depending on the circumstances, from changes in the chemical abundances in a star, moderate increases in the stellar luminosity, to a wholesale change in a star's formation and evolution.

3.1 Neutrinos from the Sun/Earth

The Sun and Earth are the only two massive bodies near enough that the neutrino flux from WIMP annihilations at their centers could potentially be detected [11]. Of these two bodies, the Sun is expected to provide a more easily detected flux of neutrinos as the small size of the Earth leads to a small capture rate with the further issue that the small capture rate typically requires a period much longer than the age of the Earth for a large enough population of WIMPs to accumulate at the center to efficiently annihilate. The Sun, however, is likely to have accumulated enough WIMPs at its center that the annihilation rate has come to equilibrium with the capture rate and the population size has become stable. Searches for WIMP annihilation neutrinos from the Sun and Earth are (or will be) undertaken by neutrino detection experiments such as Super-Kamiokande [12], IceCube/DeepCore [13], and ANTARES [14].

3.2 WIMP burners and dark stars

At the galactic center, where the WIMP density (and therefore capture rate) increases, the heat from the annihilations in the center of a star might be significant enough to increase the luminosity or modify the evolution of a star; such objects are referred to as “WIMP burners” [15]. The effects are expected to be most notable in smaller, dimmer objects such as white dwarfs or low mass stars that are in close orbits around the galaxy's central black hole. In the case of white dwarfs, the relative boost in luminosity could be large; in addition, white dwarfs in eccentric orbits about the black hole could have a luminosity that varies as they pass through regions of higher and lower WIMP densities. Low mass main sequence stars near the black hole might achieve longer lifetimes and undergo a modified track in the HR diagram.

In the early universe, the first protostellar halos collapsed to produce the population III stars. Adiabatic contraction of these halos would lead to high dark matter densities. In the case of WIMPs, the increased density would lead to WIMP annihilations. For high enough densities, the heat from the annihilations would halt the collapse of the baryons before the baryon densities were sufficient to begin the nuclear fusion process. The result would be a massive, stable body ("dark star") powered by WIMP annihilation instead of fusion [16]. Even after the dark matter density is depleted enough to allow the star to further collapse and initiate fusion, WIMP annihilation can contribute a large amount of energy for a long period of time, significantly altering the evolution of these population III stars. These stars may be more massive, have a different luminosity versus temperature relationship, and be far longer lived than standard population III stars. These early universe objects may be observable by the Hubble and James Web Space Telescopes.

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