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Constraining Dark Matter annihilation cross-sections with the Cosmic Microwave Background

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Abstract

The injection of secondary particles produced by dark annihilation around redshift ~ 1000 would inevitably affect the process of recombination, leaving an imprint on cosmic microwave background (CMB) temperature and polarization anisotropies. We show that the most recent CMB measurements provided by the WMAP satellite mission and the ACT telescope place interesting constraints on DM self-annihilation rates. Our analysis includes an accurate treatment of the time-dependent coupling of the DM annihilation energy with the thermal gas. We present constraints for specific models of dark matter annihilation channels, as well as a model-independent approach to calculate constraints with future experiments, based on a principal components analysis. We show that current data place already stringent constraints on light DM particles, ruling out thermal WIMPs with mass $m \lesssim 10$GeV annihilating into electrons and WIMPs with mass $m \lesssim 4$GeV annihilating into muons. Finally, we argue that upcoming CMB experiments such as Planck, will improve the

constraints by at least 1 order of magnitude, thus providing a sensitive probe of the properties of DM particles.

1 Introduction

The measurements of the Cosmic Microwave Background (CMB) flux provided by a number of different experiments, such as WMAP [1] and ACT [2], have confirmed several aspects of the cosmological standard model and improved the constraints on several cosmological parameters. A key ingredient in the CMB precision cosmology is the accurate computation of the recombination process, occurring at redshift $z_r \sim 1000$. Recombination modeling, while not simple, involves only well-understood conventional physics, and the latest models are thought to be accurate at the sub-percent level required for the future Planck [3] satellite mission [4] [5]. While the attained accuracy on the recombination process is impressive, it should be noticed that non-standard mechanisms could produce percent level modifications that are potentially observable in CMB data.

Dark Matter (DM) annihilation is one of these possible mechanisms, as it produces extra-Lyman-α and ionizing photons that can change the evolution of recombination. This kind of process has received particular attention in the last years as it could be one of the possible origins of the excess of positrons and electrons measured in cosmic rays by different experiments, such as PAMELA [7], ATIC [8] and FERMI [9].

Annihilation of dark matter particles during the epoch of recombination produces high-energy photons and electrons, which heat and ionize the hydrogen and helium gas as they cool. The result is an increased residual ionization fraction after recombination, giving rise to a low-redshift tail in the last scattering surface. The broader last scattering surface damps correlations between temperature fluctuations, while enhancing low multipole correlations between polarization fluctuations. With the WMAP results and the future Planck [3] data, it becomes conceivable these deviations may be detected.

$p_{ann}[cm^3/s/GeV]$ at 95% c.l.	
WMAP5	$< 3.6 \times 10^{-27}$
WMAP7	$< 2.5 \times 10^{-27}$
WMAP7+ACT	$< 2.2 \times 10^{-27}$
Planck	$< 3.1 \times 10^{-28}$
CVl	$< 1.1 \times 10^{-28}$

Table 1: Upper limit on p_{ann} at 95% c.l. from current WMAP observations and future upper limits achievable from the Planck satellite mission and from a cosmic variance limited experiment.

2 Annihilating Dark Matter and CMB

The interaction of the shower produced by dark matter annihilation with the thermal gas has three main effects: i) it ionizes the gas, ii) it induces Ly-α excitation of the Hydrogen and iii) it heats the plasma. The first two modify the evolution of the free electron fraction x_e, the third affects the temperature of baryons. The imprint of self-annihilating dark matter in CMB angular power spectra can be quantified with the annihilation parameter $p_{ann} = f(z) < \sigma v > /m_\chi$ where $< \sigma v >$ is the effective self-annihilation rate, m_χ the mass of our dark matter particle and $f(z)$ indicates the fraction of energy which is absorbed *overall* by the gas, under the approximation that the energy absorption takes place locally. The fraction $f(z)$ depends on redshift, on the dark matter model and on the annihilation channel, and has been calculated by e.g. Slatyer et al. [10] for different cases.

2.1 Constraints with a constant f

In Galli et al. [11] and Galli et al. [12] we reported constraints on the p_{ann} parameter obtained using WMAP data, WMAP plus ACT data and using simulated data for the Planck experiment and for a hypotetical cosmic variance limited experiment, under the simplifying assumption that the fraction $f(z)$ is constant with redshift. This approach has the advantage of being model independent, but is clearly less accurate than implementing the whole redshift dependence of the $f(z)$ parameter, as we will show in the next section. Results for the constant $f(z) = f$ case are reported in Tab. 1. As one can notice, WMAP7

m_χ[GeV]	channel	$<\sigma v>$ in [cm^3/s] with Variable f WMAP7	WMAP7+ACT	
1 GeV	e^+e^-	$< 2.90 \times 10^{-27}$	$< 2.41 \times 10^{-27}$	
100 GeV	e^+e^-	$< 3.95 \times 10^{-25}$	$< 3.55 \times 10^{-25}$	
1TeV	e^+e^-	$< 4.68 \times 10^{-24}$	$< 3.80 \times 10^{-24}$	
		$<\sigma v>$ in [cm^3/s] with Constant $f = f(z = 600)$		
m_χ[GeV]	channel	WMAP7	WMAP7+ACT	$f(z = 600)$
1 GeV	e^+e^-	$< 2.78 \times 10^{-27}$	$< 2.41 \times 10^{-27}$	0.87
100 GeV	e^+e^-	$< 3.87 \times 10^{-25}$	$< 3.35 \times 10^{-25}$	0.63
1TeV	e^+e^-	$< 4.02 \times 10^{-24}$	$< 3.48 \times 10^{-24}$	0.60

Table 2: Upper limits on self-annihilation cross section at 95% c.l. using WMAP7 data and a combination of WMAP7 and ACT data . On the top part of the table we show the results obtained using the proper variable $f(z)$ for each model. On the bottom part, for sake of comparison, we show the results obtained by taking the constraints for a constant generic f reported in Table 1, and then calculating $<\sigma v>$ for each case imposing that f is equal to the corresponding $f(z = 600)$ for each model. We show results for particles annihilating in an electron/positron pair only.

data improve the constraint of a factor ~ 1.4 compared to WMAP5 data, due to a better measurement of the third peak of the temperature power spectrum at $l \sim 1000 - 1200$ and of the second dip in the temperature-polarization power spectrum at $l \sim 450$. Furthermore, Planck is expected to improve constraints of about an order of magnitude. This is due to the high precision measurement of the CMB polarization that Planck is expected to deliver, and that will be able to break several degeneracies between the annihilation parameter and other cosmological parameters such as the scalar spectral index n_s.

2.2 Constraints with a model dependent f(z)

In Galli et al. [12)] we also considered the more accurate case where the fraction f is not just a constant, but it varies with redshift according to the calculations of Slatyer et al. [10)]. We chose specific values of the mass, model and annihilation channel of the dark matter particle we wanted to test, selected the corresponding $f(z)$ and then calculated the constraints on the annihilation cross-section $< \sigma v >$ with WMAP7 and ACT data. Results for different masses of dark matter particles annihilating in an electron/positron pair are reported in Table 2. Although the implementation of the z-dependence of f clearly leads to more accurate results, we found that taking a simplified analysis with constant f, such that $f(z = 600) = f_{const}$, leads to a difference with respect to the full $f(z)$ approach of less than $\sim 15\%$, depending on the annihilation channel considered.

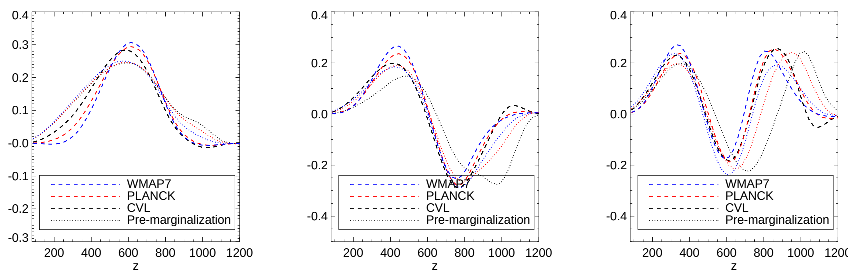

Figure 1: The first three principal components for WMAP7, Planck and a CVL experiment, both before and after marginalization over the cosmological parameters.

2.3 A principal component approach

The constraints obtained in the previous section are precise only for specific models of dark matter. In Finkbeiner et al. [13] we proposed an approach to obtain precise model independent constraints, that could however take into account the redshift dependence of the fraction f. The method exploits the fact that the effects of energy deposition by dark matter annihilation at different redshifts on the CMB spectra are not uncorrelated. Any arbitrary energy deposition history can be decomposed into a linear combination of orthogonal basis vectors, with orthogonal effects on the observed CMB power spectra (C_ℓ's). For a broad range of smooth energy deposition histories, the vast majority of the effect on the C_ℓ's can be described by a small number of independent parameters, corresponding to the coefficients of the first few vectors in a well-chosen

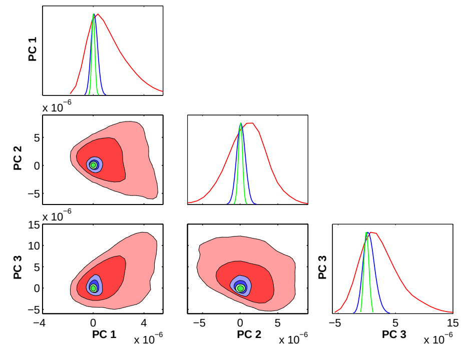

Figure 2: Constraints from the seven-year WMAP7 data (red), and from simulated data for Planck (blue) and a cosmic variance limited experiment (green). The plot shows marginalized one-dimensional distributions and two-dimensional 68% and 95% limits. The mock data for Planck and the CVL experiment assumed no dark matter annihilation. Three Principal Components were used in each run to model the energy deposition from dark matter annihilation. The units of the PC coefficients here are in m^3/s/kg, with 1×10^{-6}m^3/s/kg $= 1.8 \times 10^{-27}$ cm^3/s/GeV.

basis. These parameters in turn can be expressed as (orthogonal) weighted averages of the energy deposition history over redshift. We employ principal component analysis (PCA) to derive the relevant weight functions, and the corresponding perturbations to the C_ℓ spectra. In Fig.1 we show the first three principal components for WMAP7, Planck and a CVL experiment, both before and after marginalization over the cosmological parameters.

For generic energy deposition histories that are currently allowed by WMAP7 data, we find up to 3 principal component coefficients are measurable by Planck and up to 5 coefficients are measurable by an ideal cosmic variance limited experiment. Fig. 2 shows the contraints on the coefficients of the first 3 principal components obtainable from the WMAP7 data, and from simulated data for Planck and a cosmic variance limited experiment, assuming no dark matter annihilation.

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