The CMB as a probe for DM annihilation properties

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Abstract: In these proceedings, we summarize the effects of Dark Matter (DM) annihilation on the Recombination and Reionization history of the Universe, and how such effects can be used to constrain DM properties, thus constituting an independent, additional tool to other indirect detection probes. We present an overview of current state-of-the-art results.

Keywords: CMB, Dark Matter, annihilation, constraints

1 Effects of DM annihilation onto CMB

Within the context of self-annihilating DM models, such as for instance many classes of Weakly Interacting Massive Particles (WIMPs), the products or signatures of DM self-annihilation into standard model particles constitute the leading "indirect" search channel. However, the signatures of DM annihilation taking place in local targets, producing charged particles, photons, or neutrinos, depend on the DM density in the target, which is frequently quite uncertain. The magnitude of this uncertainty is different for different local targets, but always present, and limits the applicability of constraints from indirect DM searches.

It is well understood that the effects of energy injection from DM annihilation can significantly modify the ionization history of the universe after hydrogen recombination, although at late times the DM density becomes too small for this effect to be significant (and the lowered gas density also suppresses absorption of the energy).

The shower of high energy primaries produced by DM annihilation interacts with the slightly ionized Inter-Galactic Medium[1] (IGM) and is partially absorbed, thus causing the gas to be additionally heated, excited, and ionized. Though the modifications with respect to the standard (non-DM) case are small, they are large enough to cause modifications to the CMB anisotropy power spectrum at a level detectable with current CMB observations, for regions of the DM parameter space comparable to those currently explored through other indirect probes.

We address the reader to the original literature on the subject [1, 2, 3] noting here the following key points:

1. For the redshifts of interest, the cooling time of high energy particles is typically smaller than or at worst comparable to the Hubble time, thus making the energy deposition from DM annihilation effective without dramatic redshifting of the produced radiation;

2. the energy injected by DM annihilation can *not* efficiently modify the CMB blackbody spectrum *for values of self-annihilation cross-sections and masses that are not ruled out by the anisotropy spectrum*;

3. at zeroth order, the mechanism described takes place efficiently (i.e. contributing a signal potentially observable with current and future experiments) only during the cosmic dark ages (i.e. redshift $100 \leq z \leq 1500$).

The effect of DM annihilation on the IGM gas properties will eventually affect the CMB power spectrum, as discussed below.

1.1 The physical quantities, parameters and technical details

The technique described draws a direct connection between the physical observables (i.e. the CMB anisotropy power spectrum) and the physical unknown quantities, in our case the DM mass, self-annihilation cross section and branching ratios.

As stated and explained in [1, 3], the energy absorption rate from DM annihilation is given by,

$$\frac{dE}{dt}(z) = f(z)A(z) = f(z)\rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \frac{\langle\sigma v\rangle(z)}{m_\chi}. \quad (1)$$

The power per volume injected by DM annihilation is proportional to the self annihilation cross section $\langle\sigma v\rangle$ and inversely proportional to the DM mass m_χ; the branching ratio dependence is taken into account by the fraction $f(z)$, which describes the amount of energy degraded from the injection scale (GeV/TeV) down to the energy threshold at ~ 3 keV (this value will be justified in Section 3) where atomic processes dominate, normalized to the amount of energy injected at the same redshift. The fraction $f(z)$ can be self-consistently computed for both leptonic and hadronic channels, as in [4] and [5], as a function of redshift.

Without great loss of constraining power, at least for the current CMB data, $f(z)$ can be approximated as a constant $f = f(z = 600)$ [6, 7]. Therefore, the only free parameter is a combination of f, mass and self-annihilation cross-section, which is usually written as,

$$p_{\rm ann} = f \frac{\langle\sigma v\rangle}{m_\chi}. \quad (2)$$

1. A misnomer, since galaxies have not yet formed at the relevant time, but used for compactness throughout this paper and the whole literature.

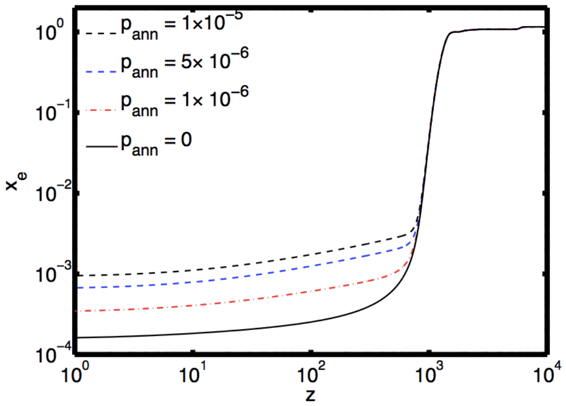

Fig. 1: The recombination history – free electron fraction vs redshift – in the presence of DM annihilation at different values of p_{ann}, from [3].

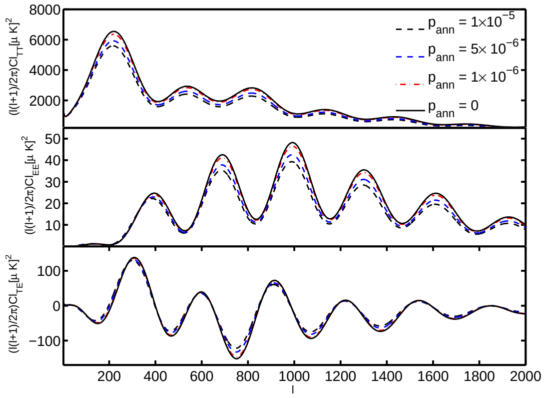

Fig. 2: The modified CMB cross-correlation power-spectrum, in the presence of DM annihilation at different values of p_{ann}, from [3].

In Figs. 1 and 2 – both from [3] – we show the effect of increasing p_{ann} on the free electron fraction as a function of redshift, and consequently on the cross-correlation anisotropy spectrum of the CMB.

1.2 Recombination vs Reionization

One important point is that all the existing literature (see [8], [9], [10]), converges on the following result: annihilation in late-time bound structures is subdominant with respect to annihilation during the recombination phase ($100 \leq z \leq 2000$). That is, the amount of free electrons per baryon created by annihilation in structures is not comparable with that indirectly contributed by DM annihilation during recombination, for the same annihilation cross-section, and *provided that the effective annihilation cross section during recombination and inside the halos is the same*.

This is due to the fact that as redshift decreases the IGM gas density decreases, thus decreasing the IGM opacity[2] and the absorption of the DM annihilation products; even if the spatially averaged DM annihilation rate grows due to the onset of structure formation, the overall effect is suppressed. Furthermore, much of the power absorbed at a given redshift comes from energy injection at earlier times, when the density enhancement from structure formation was not so pronounced.

This may no longer hold true in the case that the annihilation cross section has a positive proportionality to the DM velocity, namely has a p-wave component in addition to the s-wave usually considered in model-independent analyses. In this case, annihilation of DM in bound halos would be more efficient due to the higher virialization velocities reached by the DM, compared to the adiabatically cooled smooth background. This quantitative point must be considered case by case in model-dependent studies, where the actual velocity dependence of the cross section is properly taken into account, as well as the virial velocity related to the corresponding halo mass.

2 Constraints

The forecast signal due to DM annihilation can be searched for in existing data, for regions of parameter space currently within the range of interest $1\mathrm{GeV} \leq m_\chi \leq 10\mathrm{TeV}$, and $10^{-27}\mathrm{cm}^3/\mathrm{s} \leq \langle\sigma v\rangle \leq 10^{-22}\mathrm{cm}^3/\mathrm{s}$. The presence or absence of a signature, and in the latter case an upper limit on p_{ann}, can be established by adding one degree of freedom – namely the p_{ann} parameter itself – to the usual Markov Chain Monte Carlo codes used for standard cosmological analysis, such as e.g. `COSMOMC`.

Details can be found in [3, 7]. We find it worth recalling that in the TT spectrum, the signature from p_{ann} is degenerate with variation of the spectral index n_s and electron optical depth τ. This degeneracy is broken in the TE and EE spectra, and strong constraints on p_{ann} therefore require the use of polarization data.

The most recent constraints from our group – obtained using the WMAP7 data on both temperature and polarization, and the Atacama Cosmology Telescope (ACT) data on temperature only, limited to multipoles $l \leq l_{max}$=3500 – are shown in Fig. 3.

In more recent analyses, other groups have included updated data from the South Pole Telescope (up to $l \leq l_{max}$=6000), obtaining similar constraints from the CMB *only* [11, 12]. Studies with mock data have shown that PLANCK has the potential to access a larger region of the parameter space, reaching a thermally averaged cross-section $\langle\sigma v\rangle = 3\times10^{-26}\mathrm{cm}^3/\mathrm{s}$ for DM masses $m_\chi \sim 50\mathrm{GeV/c}^2$ (depending on the annihilation channel); see [3] and Fig. 4.

However, at the time of the writing of these proceedings, polarization data from the PLANCK collaboration have not been made public, and the constraints that can be obtained from PLANCK temperature data, together with WMAP7 polarization, are – as expected – not quantitatively superior to the bounds obtained with WMAP7 alone.

2. If the DM annihilates inside the halo, absorption by the halo gas itself is negligible.

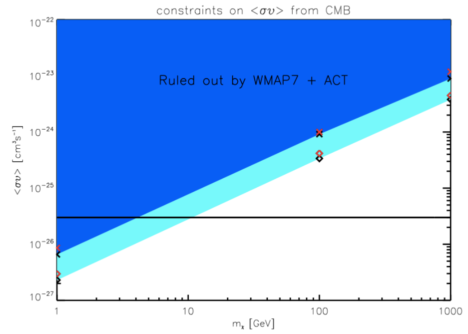

Fig. 3: Constraints on DM mass m_χ and self annihilation cross-section $\langle\sigma v\rangle$ for leptonic annihilation channels, from [7].

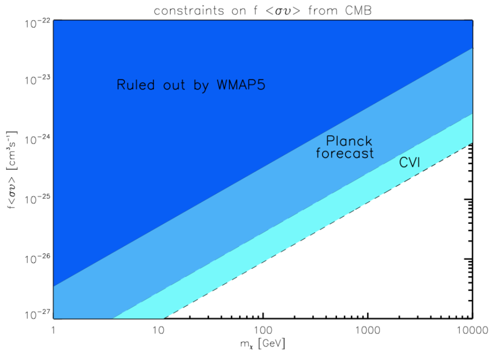

Fig. 4: Forecast constraints for PLANCK and a Cosmic Variance Limited (CVl) experiment, from [7].

3 Associated uncertainties

The most remarkable property of the constraints shown so far is that they are entirely free from the usual systematic uncertainties associated with local astrophysical sources – e.g. the uncertainties on the density profile and/or halo mass function – because the annihilation relevant to this signature takes place before structure formation. The uncertainties on the CMB data and cosmological parameters, as well as effects related to parameter reconstruction, are all taken into account in the calculated results.

In the following we highlight a few possible sources of systematic uncertainty, all arising from the treatment of the secondary shower and its absorption by the gas. An exhaustive study of all the discussed effects (and more) is presented in [13].

As mentioned, the thermalization of the electromagnetic shower produced by DM annihilation is a process that takes place over several orders of magnitude in energy, from the WIMP mass scale (of order GeV-TeV) down to atomic physics energy scales of the order of a few eV.

Given the different physical processes taking place at different energies, usually the computation of the shower thermalization is split between two regimes: above and below the $\sim$ keV scale.

Above this scale, inverse Compton scattering (ICS) on the CMB dominates the energy losses of electrons, and photons can possibly free-stream to the present day, since they cool by a number of processes with timescales comparable to a Hubble time (see [4] and [5] for a detailed list). Below this scale, photoionization becomes very rapid relative to a Hubble time, while for electrons, atomic processes – such as e.g. collisional ionization and free-free interactions – become dominant [14].

One approach, adopted in e.g. [4], is to compute the fraction of the original energy produced in the annihilation – $E_{\rm ann} = 2m_\chi c^2$ – that eventually degrades down to this keV scale (as opposed to free-streaming as high-energy photons, neutrinos or protons), by propagating the shower of Standard Model primaries and secondaries through the IGM. This can be done while tracking the expansion of the universe; the cascade need not occur entirely at a single redshift. The low-energy component is then regarded as being completely deposited to the IGM; it is the “absorbed energy” of Eq. 1, characterized by the function $f(z)$, and its interactions with the thermal gas (to produce ionization, excitation and heating) are separately computed. The effects of the resulting additional ionization and heating are calculated via a customization of existing codes such as RECFAST or COSMOREC.

An alternative approach, the “unique cascade” treatment, of e.g. [15], attempts to follow the full cascade from the injection energy to the eV scale. This approach has the advantage of conceptual simplicity and a careful treatment of the atomic processes at all energy scales, but relies on an “on-the-spot” approximation; the expansion of the universe during the cascade is not included, instead the entire shower is assumed to occur at the redshift of injection. The failure of the on-the-spot approximation can lead to “leakage” of energy to lower redshifts, and from higher redshifts; since the annihilation rate is larger at higher redshifts, this generally increases the energy deposition at a given redshift. Consequently, assuming the on-the-spot approximation when it is not accurate should yield *conservative* constraints (the actual signal should generally be larger than predicted).

The “split” approach avoids the on-the-spot approximation via the construction of $f(z)$, which is effectively integrated over past energy injections; see the explanations in [4, 5, 13]. However, one might instead worry that the assumption of a “universal” electron spectrum below keV energies might be an oversimplification – and in particular, might miscount as “absorbed” energy in photons below the threshold for excitation (10.2 eV), which will *not* actually interact with the gas. This error goes in the opposite direction; the calculated constraints would be too *strong*, as the actual (physical) effect on the ionization history would be lessened.

In [13], the authors have carefully accounted for this effect, studied several (all known) possible systematics arising by the use of the “split” technique, and examined other sources of systematic uncertainty as well. We address the reader to that paper for a thorough account of the possible uncertainties affecting this indirect detection technique, and the current bounds arising by its use. A compilation of actual f values has been also presented by [16] for several primary channels and annihilating DM masses.

4 Conclusions

In these proceedings we have described a technique for indirect Dark Matter detection which is complementary to searches for charged particles (cosmic rays) and gamma rays produced by DM annihilation. In contrast to techniques based on the latter messengers, any constraints (or future detection) from the Cosmic Microwave Background are unaffected by uncertainties in the DM distribution in the target. Physically, this is because all the signal is produced at times when bound structures have not yet formed.

Once freed of this uncertainty, we have highlighted the possible systematics caused by the treatment of the secondary shower and its effect on the ionization history, pointing to recent studies addressing these issues. We conclude that the systematic uncertainties associated with this method are under control, making this technique both qualitatively and quantitatively competitive with those based on charged particles, gamma rays, and other local-Universe signals.

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