Dark matter searches: looking for the cake or its frosting?  
(Detectability of a subdominant component of the CDM)

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The dark matter candidates we are searching for, e.g. neutralinos, may be one of many components of the cold dark matter (CDM). We point out here that very subdominant components, constituting even 1% of the CDM for indirect detection and much less for direct detection, remain observable in current and future searches. So if a CDM signal is confirmed in CDM search experiments (except for a signal from annihilations in the dark halo) we will need to find out the halo fraction accounted for the CDM component we detected.

We live in a Universe with a complex composition, about 0.7 of the total density is in dark energy and 0.3 of it in cold dark matter (CDM), with smaller components of baryons and neutrinos. This is a composition we would not have guessed fifteen years ago. It is thus conceivable that the composition of the CDM could be as complex, the Weakly Interacting Massive Particle (WIMP) candidate we are looking for in direct and indirect searches being only one of the components. The most common WIMP candidate is the neutralino (although there are other possible lightest supersymmetric particle candidates). We find many other possible DM candidates in the literature such as axions, Q-balls, heavy non-thermal relics, warm or cool DM, interacting DM, etc. which cannot be found in WIMP searches.

So the questions that come to mind are: if WIMPs constitute only a fraction, $f$, say 1% or less, of the local dark matter halo, would these particles still be observable in the current and proposed direct and indirect dark matter searches? If we confirm a CDM signal in any of our searches, have we found the bulk of the CDM? The answers to these questions, found in the literature since the inception of the subject (e.g. \cite{1-2} and references therein), are: yes! to the first and no! to the second. However in \cite{1} we explored for the first time how small the halo fraction $f$ can be for detectable neutralinos and additionally, if a combination of direct and indirect detection data could tell the value of $f$.

Although the event rate $R$ in direct detection searches is proportional to the local WIMP density $\rho_\chi$, it does not necessarily decrease linearly with $\rho_\chi$, as naively could be expected. This is because the local WIMP density is proportional to the cosmological WIMP density $\Omega_\chi$, which in turn (for all particles that have been in equilibrium in the early Universe) is inversely proportional to the WIMP annihilation cross section (in the early Universe), $\Omega_\chi \sim \sigma_a^{-1}$. Thus, a reduction in $\rho_\chi$ requires an increase in $\sigma_s$. This increase is often associated with an increase in the scattering cross section $\sigma_s$ of WIMPs off atomic nuclei. In fact there are “crossing symmetries” that relate the amplitudes of both processes and both increase with decreasing mediators mass and increasing coupling constants. The relation between $\sigma_s$ and $\sigma_a$ is complicated in many ways, however in many instances it holds that they increase in the same manner. Then, in direct detection rates the decrease in density is compensated by an increase in $\sigma_s$ and rates may remain high even for very subdominant WIMPs, $R \sim \sigma_s \rho_\chi \sim \sigma_s \sigma_a^{-1} \simeq \text{constant}$.

In \cite{1} models implemented in the “DarkSUSY” code were used in which a neutralino is the CDM candidate, and the halo and cosmological neu-
neutralino fractions were taken to be the same, \( f = \Omega_{\chi}/\Omega_{DM} = \Omega_{\chi}h^2/0.15 \) (\( \Omega_{\chi} = 0.3 \) and \( h = 0.7 \)). The latter is correct if segregation mechanisms for different CDM components are not important, e.g. if all components are non-collisional.

\[
\Omega_{\chi}h^2 = \Omega_{\chi}h^2/0.15 \approx 0.3 \times 0.7^2 = 0.105
\]

Figure 1. Each point corresponds to a neutralino model with \( f \) between 0.1 and 1\% together with present direct detections bounds (thicker lines) and future direct detection discovery limits.

The DAMA region was not explored in [1] (the models used provide practically no candidates in that region), however subdominant candidates, even with halo fraction 1\% or smaller, are among the candidates in this region studied by the Torino group [3], for example. If the DAMA signal is not confirmed, Fig. 1 shows that CRESST-II could probe neutralino halo factions \( f > 10^{-3} \). In [1] is shown that ZEPLIN II, CDMS at the Soudan mine and EDELWEISS II could probe \( f > 10^{-4} \). These are experiments from which data are expected in the next few years. Further in the future, another generation of detectors, such as ZEPLIN IV, CryoArray, GENIUS and XENON, may be able to reach down to neutralino halo fractions of order \( 10^{-5} \), which are the smallest found in [1].

Concerning indirect detection, the flux of rare cosmic rays and of gamma-rays produced in halo annihilations depend on the product of the square of the density and the annihilation cross section into a particular channel, \( \sigma_a\rho_{\chi}^2 \). Thus, even if an increase in the cross section compensates for the decrease in one of the powers of the density, the fluxes still decrease linearly with the halo WIMP density. Hence WIMPs which are a subdominant component of the total CDM would be extremely difficult to detect through this method, as already concluded in [12] (e.g. see Fig. 2).

\[
\sigma_a\rho_{\chi}^2 \sim \frac{\Gamma_{\text{ann}}}{\Omega_{DM}} \sim \frac{\Omega_{\chi}h^2}{0.15} \sim 10^{-3}
\]

Figure 2. Solar modulated anti-proton flux at 1 GeV kinetic energy at solar minimum (using the force-field approximation in DarkSUSY) as a function of the neutralino relic density. A regular grid of points shows the region with models.

The intensity of the high-energy neutrino emission from neutralino annihilations in the Sun and the Earth, instead, would in many cases remain high with decreasing density. As the Sun and Earth sweep through the dark matter halo interactions with nuclei within these bodies slow WIMPs enough so they can become gravitationally captured. It is the capture rate \( C \) which becomes constant when the “compensation argument” holds, \( C \sim \sigma_a\rho_{\chi} \sim \text{constant} \). At small times \( t \) the number of capture neutralinos \( N_{\chi} \sim Ct \), increases with time \( t \) and also the annihilation rate increases \( \Gamma_{\text{ann}} \sim \sigma_aN_{\chi}^2 \sim \sigma_aC^2 \sim \sigma_a \sim \Omega_{\chi}^{-1} \) thus we could expect “overcompensation”, namely an increase in the rate for subdominant WIMP’s. The annihilation rate increases until at some time, called the equilibration time,
the annihilation and capture rates become equal (except for a factor of 2). For the Earth, the equilibration time is longer than the present life time, and we could expect “overcompensation”. In the Sun, instead, equilibrium has been reached and \( \Gamma_a \simeq C/2 \simeq \text{constant} \) in the presence of compensation. In [1] it was shown that up-going muon rates in underwater or under-ice \( \text{km}^3 \) detectors (such as IceCube, ANTARES, NESTOR) from annihilations in the Sun (see Fig. 3) and the Earth remain observable even for neutralinos constituting only 1% of the halo dark matter.

![Figure 3. Muon fluxes in \( \text{km}^3 \) detectors from annihilations in the Sun.](image)

Figure 3. Muon fluxes in \( \text{km}^3 \) detectors from annihilations in the Sun. The energy threshold for detection and the minimum observable flux were taken to be 25 GeV and 10 muons/km\(^2\)/yr.

“Overcompensation” was found in neutrino signals from the Earth for light neutralinos (\( m_\chi < 150 \text{ GeV} \)) for which signals are largest around a halo fraction of 1%. Except in this case, in [1] it was not found that the detectability of subdominant relic neutralinos is usually favored, as was previously stated [2]. Moreover, notice that while in [1] the value of \( \Omega_{CDM} h^2 \) is fixed, in [2] a range of possible \( \Omega_{CDM} h^2 \) values is considered, such that as long as \( \Omega_\chi h^2 \) is within that range neutralinos are taken to account for the whole halo. In this case as \( \Omega_\chi h^2 \) decreases within this allowed range, detectability increases when \( \sigma_s \sigma_a^{-1} \simeq \text{constant} \), as cross sections become larger at constant halo density.

Many neutralino models constituting from 1% to 100% of the dark matter halo are detectable in three ways (direct, indirect from the Sun, indirect from the Earth), some in two, and some in only one. All models in [1] detectable through annihilations in the Earth are also visible through annihilations in the Sun (but the converse is not true) and will be either detected or rejected already by CRESST-II. Models detectable through a neutrino signal from the Sun may or not be seen through direct detection (see Fig. 4).

![Figure 4. Each point represents a model detectable through annihilations in the Sun.](image)

Figure 4. Each point represents a model detectable through annihilations in the Sun.

REFERENCES

1. G. Duda, G. Gelmini and P. Gondolo, Phys. Lett. B 529 (2002) 187; G. Duda, G. Gelmini, P. Gondolo, J. Edsjo and J. Silk, Phys. Rev. D 67 (2003) 023505.
2. A. Bottino, N. Fornengo, S. Scopel, F. Donato, in La Thuile, 2001 and in Nucl. Phys. Proc. Suppl. 113, 50 (2002); A. Bottino, N. Fornengo, S. Scopel, in COSMO-01, 2001; S. Scopel, Nucl. Phys. B (Proc. Suppl.) 110, 76 (2002).
3. A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D 62, 056006 (2000); Phys. Rev. D 63, 125003 (2001).