A New Method to Infer which Type of Neutralinos make up Galactic Halos

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Abstract. Applying the microcanonical definition of entropy to a weakly interacting and self–gravitating neutralino gas, we evaluate the change in the local entropy per particle of this gas between the freeze out era and present day virialized halo structures. An “entropy consistency” criterion emerges by comparing the obtained theoretical entropy per particle of the virialized halos with an empirical entropy per particle given in terms of dynamical halo variables of actual galactic structures. We apply this criterion to the cases when neutralinos are mostly B-inos and mostly Higgsinos, in conjunction with the usual “abundance” criterion requiring that present neutralino relic density complies with $0.2 < \Omega_{\tilde{\chi}_1^0} < 0.4$ for $h \simeq 0.65$. The joint application of both criteria reveals that a much better fitting occurs for the B-ino than for the Higgsino channels, so that the former seems to be a favored channel along the mass range of $150 \text{GeV} < m_{\tilde{\chi}_1^0} < 250 \text{GeV}$.

These results are consistent with neutralino annihilation patterns that emerge from recent theoretical analysis on cosmic ray positron excess data reported by the HEAT collaboration. The suggested methodology can be applied to test other annihilation channels of the neutralino, as well as other particle candidates of thermal WIMP gas relics\textsuperscript{1}.

INTRODUCTION.

There are strong theoretical arguments favoring lightest supersymmetric particles (LSP) as making up the relic gas that forms the halos of actual galactic structures. Assuming that $R$ parity is conserved and that the LSP is stable, it might be an ideal candidate for cold dark matter (CDM), provided it is neutral and has no strong interactions. The most favored scenario\textsuperscript{2,3,4,5,6,7} considers the LSP to be the lightest neutralino ($\tilde{\chi}_1^0$), a mixture of supersymmetric partners of the photon, $Z$ boson and neutral Higgs boson\textsuperscript{3}. Since neutralinos must have decoupled once they were non-relativistic, it is reasonable to assume that they constituted originally a Maxwell-Boltzmann (MB) gas in thermal equilibrium with other components of the primordial cosmic plasma. In the present cosmic era, such a gas is practically collision–less and is either virialized in

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galactic and galactic cluster halos, in the process of virialization or still in the linear regime for superclusters and structures near the scale of homogeneity \([8, 9, 10]\).

Besides the constraint due to their present abundance as main constituents of cosmic dark matter \((\Omega_{x_1} \sim 0.3)\), it is still uncertain which type of annihilation cross section characterizes these neutralinos. In this paper we present a method that discriminates between different cross sections, based on demanding (together with the correct abundance) that a theoretically estimated entropy per particle matches an empiric estimate of the same entropy, but constructed with dynamic variables of actual halo structures. The application of this “entropy consistency” criterion is straightforward because entropy is a state variable that can be evaluated at equilibrium states, irrespectively of how enormously complicated could be the evolution between each state. In this context, the two fiducial equilibrium states of the neutralino gas are (to a good approximation) the decoupling (or “freeze out”) and their present state as a virialized relic gas. Considering simplified forms of annihilation cross sections, the joint application of the abundance and entropy–consistency criteria favors the neutralinos as mainly “B–inos” over neutralinos as mainly “higgsinos”. These results are consistent with the theoretical analysis of the HEAT experiment \([11, 12, 13]\) which aims at relating the observed positron excess in cosmic rays with a possible weak interaction between neutralinos and nucleons in galactic halos.

The paper is organized as follows. In section 2 we describe the thermodynamics of the neutralino gas as it decouples. Section 3 applies to the post–decoupling neutralino gas the entropy definition of the microcanonical ensemble entropy, leading to a suitable theoretical estimate of the entropy per particle. In section 4 we obtain an empiric estimate of this entropy based on actual halo variables, while in section 5 we examine the consequences of demanding that these two entropies coincide. Section 6 provides a summary of these results.

THE NEUTRALINO GAS

The equation of state of a non-relativistic MB neutralino gas is \([8, 9, 10]\)

\[
\rho = m_{x_1} n_{x_0} \left(1 + \frac{3}{2}x\right), \quad p = \frac{m_{x_1} n_{x_0}}{x},
\]

\[
x \equiv \frac{m_{x_1}}{T},
\]

where \(m_{x_1}\) and \(n_{x_0}\) are the neutralino mass and number density. Since we will deal exclusively with the lightest neutralino, we will omit henceforth the subscript \(x_0\), understanding that all usage of the term “neutralino” and all symbols of physical and observational variables (i.e. \(\Omega_0\), \(m\), \(\rho\), \(n\), etc.) will correspond to this specific particle. As long as the neutralino gas is in thermal equilibrium, we have

\[
n \approx n_{\text{eq}} = g \left[\frac{m}{\sqrt{2 \pi}}\right]^3 x^{-3/2} \exp \left(-x\right),
\]
where $g = 1$ is the degeneracy factor of the neutralino species. The number density $n$ satisfies the Boltzmann equation \[\dot{n} + 3H n = -\langle \sigma | v | \rangle \left[n^2 - (n^{eq})^2\right],\] (4)

where $H$ is the Hubble expansion factor and $\langle \sigma | v | \rangle$ is the annihilation cross section. Since the neutralino is non-relativistic as annihilation reactions “freeze out” and it decouples from the radiation dominated cosmic plasma, we can assume for $H$ and $\langle \sigma | v | \rangle$ the following forms

\[H = 1.66 g_*^{1/2} \frac{T^2}{m_p},\] (5)
\[\langle \sigma | v | \rangle = a + b\langle v^2 \rangle,\] (6)

where $m_p = 1.22 \times 10^{19}$ GeV is Planck’s mass, $g_* = g_*(T)$ is the sum of relativistic degrees of freedom, $\langle v^2 \rangle$ is the thermal averaging of the center of mass velocity (roughly $v^2 \propto 1/x$ in non-relativistic conditions) and the constants $a$ and $b$ are determined by the parameters characterizing specific annihilation processes of the neutralino (s-wave or p-wave) \[3\]. The decoupling of the neutralino gas follows from the condition

\[\Gamma = n \langle \sigma | v | \rangle = H,\] (7)

leading to the freeze out temperature $T_f$. Reasonable approximated solutions of (7) follow by solving for $x_f$ the implicit relation \[3\]

\[x_f = \ln \left[\frac{0.0764 m_p c_0 (2 + c_0) (a + 6 b/x_f) m}{(g_* x_f)^{1/2}}\right],\] (8)

where $g_* = g_*(T_f)$ and $c_0 \approx 1/2$ yields the best fit to the numerical solution of (4) and (7). From the asymptotic solution of (4) we obtain the present abundance of the relic neutralino gas \[3\]

\[\Omega_0 h^2 = Y_\infty \frac{S_0 m}{\rho_{crit}/h^2} \approx 2.82 \times 10^8 Y_\infty \frac{m}{\text{GeV}},\] (9)

\[Y_\infty \equiv \frac{n_0}{S_0} = \left[0.264 g_*^{1/2} m_p m \left\{a/x_f + 3(b - 1/4 a)/x_f^2\right\}\right]^{-1},\] (10)

where $S_0 \approx 4000 \text{ cm}^{-3}$ is the present radiation entropy density (CMB plus neutrinos), $\rho_{crit} = 1.05 \times 10^{-5} \text{ GeV cm}^{-3}$.

Since neutralino masses are expected to be in the range of tens to hundreds of GeV’s and typically we have $x_f \sim 20$ so that $T_f > \text{GeV}$, we can use $g_* \approx 106.75$ \[4\] in equations (8) – (10). Equation (8) shows how $x_f$ has a logarithmic dependence on $m$,
while theoretical considerations \[2, 3, 4, 5, 6, 7\] related to the minimal supersymmetric extensions of the Standard Model (MSSM) yield specific forms for \(a\) and \(b\) that also depend on \(m\). Inserting into (9)–(10) the specific forms of \(a\) and \(b\) for each annihilation channel leads to a specific range of \(m\) that satisfies the “abundance” criterion based on current observational constraints that require \(0.1 < \Omega_0 < 0.3\) and \(h \approx 0.65\) [10].

Suitable forms for \(\langle |v| \rangle\) can be obtained for all types of annihilation reactions [3]. If the neutralino is mainly pure B-ino, it will mostly annihilate into lepton pairs through t-channel exchange of right-handed sleptons. In this case the cross section is p-wave dominated and can be approximated by (6) with [4, 14, 15]

\[
a \approx 0, \quad b \approx \frac{8 \pi \alpha_2^2}{m^2 [1 + m_l^2/m^2]^2},
\]

(11)

where \(m_l\) is the mass of the right-handed slepton \((m_l \sim m [4])\) and \(\alpha_2^2 = g_2^2/4\pi \approx 0.01\) is the fine structure coupling constant for the \(U(1)_Y\) gauge interaction. If the neutralino is Higgsino-like, annihilating into W-boson pairs, then the cross section is s-wave dominated and can be approximated by (6) with [4, 14, 15]

\[
b \approx 0, \quad a \approx \frac{\pi \alpha_2^2 (1 - m_W^2/m^2)^{3/2}}{2 m^2 (2 - m_W^2/m^2)^2},
\]

(12)

where \(m_W = 80.44\) GeV is the mass of the W-boson and \(\alpha_2^2 = g_2^2/4\pi \approx 0.03\) is the fine structure coupling constant for the \(SU(2)_L\) gauge interaction.

In the freeze out era the entropy per particle (in units of the Boltzmann constant \(k_B\)) for the neutralino gas is given by [8, 10, 9]

\[
s_f = \left[\frac{\rho + p}{n T}\right]_f = \frac{5}{2} + x_f,
\]

(13)

where we have assumed that chemical potential is negligible and have used the equation of state (1). From (8) and (13), it is evident that the dependence of \(s_f\) on \(m\) will be determined by the specific details of the annihilation processes through the forms of \(a\) and \(b\). In particular, we will use (11) and (12) to compute \(s_f\) from (8)-(13).

**THE MICROCANONICAL ENTROPY**

After the freeze out era, particle numbers are conserved and the neutralinos constitute a weakly interacting and practically collision–less self–gravitating gas. This gas is only gravitationally coupled to other components of the cosmic fluid. As it expands, it experiences free streaming and eventually undergoes gravitational clustering forming stable bound virialized structures [10, 9, 16, 17]. The evolution between a spectrum of density perturbations at the freeze out and the final virialized structures is extremely complex, involving a variety of dissipative effects characterized by collisional and collision–less relaxation processes [14, 17, 18]. However, the freeze out and present day virialized structures roughly correspond to “initial” and “final” equilibrium states of this gas.
Therefore, instead of dealing with the enormous complexity of the details of the intermediary processes, we will deal only with quantities defined in these states with the help of simplifying but general physical assumptions.

The microcanonical ensemble in the “mean field” approximation yields an entropy definition that is well defined for a self–gravitating gas in an intermediate scale, between the short range and long range regimes of the gravitational potential. This intermediate scale can be associated with a region that is “sufficiently large as to contain a large number of particles but small enough for the gravitational potential to be treated as a constant” [16]. Considering the neutralino gas in present day virialized halo structures as a diluted, non-relativistic (nearly) ideal gas of weakly interacting particles, its microcanonical entropy per particle under these conditions can be given in terms of the volume of phase space [17]

\[
 s = \ln \left( \frac{(2mE)^{3/2}V}{(2\pi\hbar)^3} \right),
\]

where \( V \) and \( E \) are local average values of volume and energy associated with the intermediate scale. For non-relativistic velocities \( v/c \ll 1 \), we have \( V \propto 1/n \propto m/\rho \) and \( E \propto mv^2/2 \propto m/x \). In fact, under these assumptions the definition (14), evaluated at the freeze out, is consistent with (13) and so it is also valid immediately after the freeze out era (once particle numbers are conserved). Since (14) is valid at both the initial and final states, respectively corresponding to the decoupling \((s_f, x_f, n_f)\) and the values \((s^{(0)}, x^{(0)}, n^{(0)})\) associated with a suitable halo structure, the change in entropy per particle that follows from (14) between these two states is given by

\[
 s^{(0)} - s_f = \ln \left( \frac{n_f}{n^{(0)}} \left( \frac{x_f}{x^{(0)}} \right)^{3/2} \right),
\]

where (13) can be used to eliminate \( s_f \) in terms of \( x_f \). Considering present day halo structures as roughly spherical, inhomogeneous and self-gravitating gaseous systems, the intermediate scale of the microcanonical description is an excellent approximation for gas particles in a typical region of \( \sim 1 \text{pc}^3 \) within the halo core, near the symmetry center of the halo where the gas density enhancement is maximum but spacial gradients of all macroscopic quantities are negligible [19, 20]. Therefore, we will consider current halo macroscopic variables as evaluated at the center of the halo: \( x_c^{(0)}, n_c^{(0)} \).

In order to obtain a convenient theoretical estimate of \( s_c^{(0)} \) from (15), we need to relate \( n_f \) with present day cosmological parameters like \( \Omega_0 \) and \( h \). Bearing in mind that density perturbations at the freeze out era were very small \( (\delta n_f/n_f < 10^{-4}, [8, 9, 10]) \), the density \( n_f \) is practically homogeneous and so we can estimate it from the conservation of particle numbers: \( n_f = n_0 (1 + z_f)^3 \), and of photon entropy: \( g_{sf}S_f = g_{s0}S_0 (1 + z_f)^3 \), valid from the freeze out era to the present for the unperturbed homogeneous background. Eliminating \( (1 + z_f)^3 \) from these conservation laws yields

\[
 n_f = n_0 \frac{g_{sf}}{g_{s0}} \left[ \frac{T_f}{T^{\text{cmb}}_0} \right]^3 \approx 27.3 n_0 \left( \frac{x_c^{\text{cmb}}}{x_f} \right)^3,
\]

where \( x_c^{\text{cmb}} \equiv \frac{m}{T_0^{\text{cmb}}} = 4.29 \times 10^{12} \frac{m}{\text{GeV}} \).
where $g_{i0} = g_*(T_{0}^{\text{CMB}}) \simeq 3.91$ and $T_{0}^{\text{CMB}} = 2.7$ K. Since for present day conditions $n_0/n_c^0 = \rho_0/\rho_c$ and $\rho_0 = \rho_{\text{crit}} \Omega_0 h^2$, we collect the results from (16) and write (15) as

$$s_{c}^{\text{th}}|_{\text{th}} = x_f + 93.06 + \ln \left( \frac{m}{\text{GeV}} \right)^3 \frac{h^2 \Omega_0}{(x_f x_c^0)^{3/2}} \frac{\rho_{\text{crit}}}{\rho_c^0}$$

$$= x_f + 81.60 + \ln \left( \frac{m}{\text{GeV}} \right)^3 \frac{h^2 \Omega_0}{(x_f x_c^0)^{3/2}} \frac{\text{GeV/cm}^3}{\rho_c^0},$$  

(17)

Therefore, given $m$ and a specific form of $\langle |v| \rangle$ associated with $a$ and $b$, equation (17) provides a theoretical estimate of the entropy per particle of the neutralino halo gas that depends on the initial state given by $x_f$ in (8) and (13), on observable cosmological parameters $\Omega_0$, $h$ and on generic state variables associated to the halo structure.

**THEORETICAL AND EMPIRIC ENTROPIES**

If the neutralino gas in present halo structures strictly satisfies MB statistics, the entropy per particle, $s_{c}^{\text{th}}$, in terms of $\rho_c^0 = m n_c^0$ and $x_c^0 = m c^2/(k_B T_c^0)$, follows from the well known Sackur–Tetrode entropy formula [21]

$$s_{c}^{\text{th}}|_{\text{MB}} = \frac{5}{2} + \ln \left( \frac{m^4 c^3}{h^3 (2\pi x_c^0)^{3/2}} \rho_c^0 \right)$$

$$= 94.42 + \ln \left( \frac{m}{\text{GeV}} \right)^4 \left( \frac{1}{x_c^0} \right)^{3/2} \frac{\text{GeV/cm}^3}{\rho_c^0},$$  

(18)

Such a MB gas in equilibrium is equivalent to an isothermal halo if we identify [22]

$$\frac{c^2}{x_c^0} = k_B T_c^0 = \sigma_c^2,$$  

(19)

where $\sigma_c^2$ is the velocity dispersion (a constant for isothermal halos).

However, an exactly isothermal halo is not a realistic model, since its total mass diverges and it allows for infinite particle velocities (theoretically accessible in the velocity range of the MB distribution). More realistic halo models follow from “energy truncated” (ET) distribution functions [17, 22, 23, 24, 28] that assume a maximal “cut off” velocity (an escape velocity). Therefore, we can provide a convenient empirical estimate of the halo entropy, $s_{c}^{\text{th}}$, from the microcanonical entropy definition (14) in terms of phase space volume, but restricting this volume to the actual range of velocities (i.e. momenta) accessible to the central particles, that is up to a maximal escape velocity $v_c(0)$. From theoretical studies of dynamical and thermodynamical stability associated with ET distribution functions [23, 24, 25, 28, 27, 29, 26] and from observational data for elliptic and LSB galaxies and clusters [30, 31, 19, 32, 33], it is reasonable to assume

$$v_c^2(0) = 2|\Phi(0)| \simeq \alpha \sigma_c^2(0), \quad 12 < \alpha < 18,$$  

(20)
where $\Phi(r)$ is the newtonian gravitational potential. We have then

$$s_{c}^{(h)}|_{\text{em}} \simeq \ln \left[ \frac{m^4 v_e^3}{(2\pi\hbar)^3 \rho_{c}^{(h)}} \right] = 89.17 + \ln \left[ \left( \frac{m}{\text{GeV}} \right)^4 \left( \frac{\alpha}{x_f} \right)^{3/2} \frac{\text{GeV/cm}^3}{\rho_{c}^{(h)}} \right],$$

(21)

where we used $x_{c}^{(h)} = e^2 / \sigma_{c}^2(0)$ as in (19). As expected, the scalings of (21) are identical to those of (18). Similar entropy expressions for elliptic galaxies have been examined in [34].

Comparison between $s_{c}^{(h)}$ obtained from (21) and from (17) leads to the constraint

$$s_{c}^{(h)}|_{\text{th}} = s_{c}^{(h)}|_{\text{em}} \Rightarrow x_f = 7.57 + \ln \left[ \frac{(\alpha x_f)^{3/2}}{h^2 \Omega_0 \text{GeV}} \right].$$

(22)

which does not depend on the halo variables $x_{c}^{(h)}, \rho_{c}^{(h)}$, hence it can be interpreted as the constraint on $s_f = 5/2 + x_f$ that follows from the condition $s_{c}^{(h)}|_{\alpha} = s_{c}^{(h)}|_{\text{em}}$. Since we can use (9) and (10) to eliminate $h^2 \Omega_0$, the constraint (22) becomes a relation involving only $x_f, m, a, b, \alpha$. This constraint is independent of (8), which is another (independent) expression for $s_f = 5/2 + x_f$, but an expression that follows only from the neutralino annihilation processes. Therefore, the comparison between $s_{c}^{(h)}|_{\alpha}$ and $s_{c}^{(h)}|_{\text{em}}$, leading to a comparison of two independent expressions for $s_f$, is not trivial but leads to an “entropy consistency” criterion that can be tested on suitable desired values of $m, a, b, \alpha$. This implies that a given dark matter particle candidate, characterized by $m$ and by specific annihilation channels given by $x_f$ through (8), will pass or fail to pass this consistency test independently of the details one assumes regarding the present day dark halo structure. This is so, whether we conduct the consistency test by comparing (8) and (22) or (17) and (21). However, the actual values of $s_{c}^{(h)}$ for a given halo structure, whether obtained from (21) or from (17), do depend on the precise values of $\rho_{c}^{(h)}$ and $x_{c}^{(h)}$. Since the matching of either (8) and (22) or (17) and (21) shows a weak logarithmic dependence on $m$, the fulfillment of the “entropy consistency” criterion identifies a specific mass range for each dark matter particle. This allows us to discriminate, in favor or against, suggested dark matter particle candidates and/or annihilation channels by verifying if the standard abundance criterion (9) is simultaneously satisfied for this range of masses.

**TESTING THE ENTROPY CONSISTENT CRITERION**

Since we can write (22) as:

$$\ln(h^2 \Omega_0) = 7.57 - x_f + \ln \left[ (\alpha x_f)^{3/2} m \right].$$

(23)

this constraint becomes a new estimate of the cosmological parameters $h^2 \Omega_0$, given as in terms of a structural parameter of galactic dark matter halos, $\alpha$, the mass of the
neutralino, $m$, and the temperature of the neutralino gas at freeze out, $x_f$. This last quantity depends explicitly not only on $m$, but also on its interaction cross section, and hence on the details of its phenomenological physics viz. (8).

At this point we consider values for the constants $a$ and $b$ that define the interaction cross section of the neutralino, and use (23) to plot $\Omega_0$ as a function of $m$ in GeV’s. Using $h = 0.65$ and given the uncertainty range of $\alpha$, we will obtain not a curve, but a region in the $\Omega_0 - m$ plane. Considering first condition (12), corresponding to Higgsino–like neutralinos, leads to the shaded region in figure 1a. On this figure we have also plotted the relation which the abundance criterion (9) yields on this same plane. Firstly, we notice that the mass range that results from our entropy criterion intersects the one resulting from the abundance criterion. However, it is evident that within the observationally determined range of $\Omega_0$ (the horizontal dashed lines 0.2-0.4), there is no intersection between the shaded region and the abundance criterion curve. This implies that both criteria are mutually inconsistent, thus the possibility that Higgsino-like neutralinos make up both the cosmological dark matter and galactic dark matter appears unlikely.

Repeating the same procedure for mainly B–ino neutralinos, (11) yields figure 1b. In this case, we can see that the abundance criterion curve falls well within the shaded region defined by the entropy criterion. Although we can not improve on the mass estimate provided by the abundance criterion alone, the consistency of both criteria reveals the B-ino neutralino as a viable option for both the cosmological and the galactic dark matter.

It is also interesting to evaluate (21) and (17) for the two cases of neutralino channels: the B-ino and Higgsino, but now considering numerical estimates for $x_f$ and $\rho$ that correspond to central regions of actual halo structures. Considering terminal velocities in rotation curves we have $v_{\text{term}}^2 \sim 2\sigma^2_{(0)}$, so that $x_f^{(b)} \sim 2(c/v_{\text{term}})^2$, while recent data from LSB galaxies and clusters [32, 33, 35, 20, 36] suggest the range of values
FIGURE 2. Figures (a) and (b) respectively correspond to the Higgsino and B-ino channels. The figures display $s_{c}^{\text{th}}$ from (20)–(21) (gray strip), $s_{c}^{\text{em}}$ from (17) for $h = 0.65$ and the uncertainty strip $\Omega_0 = 0.3 \pm 0.1$ (thick curves) and $s_{c}^{\text{th}}_{\text{mb}}$ from (18) (crosses), all of them as functions of $\log_{10} m$. The vertical strip marks the range of values of $m$ that follow from (9)–(10) for the same values of $\Omega_0$ and $h$.

It is evident that only the B-ino channels allow for a simultaneous fitting of both the abundance and the entropy criteria.

0.01 M$_{\odot}$/pc$^3 < \rho_{c}^{w} < 1$ M$_{\odot}$/pc$^3$. Hence, we will use in the comparison of (17) and (21) the following numerical values: $\rho_{c}^{w} = 0.01$ M$_{\odot}$/pc$^3 = 0.416$ GeV/cm$^3$ and $x_{c}^{w} = 2 \times 10^{6}$, typical values for a large elliptical or spiral galaxy with $v_{\text{term}} \approx 300$ km/sec [35, 20, 36]. Figure 2a displays $s_{c}^{\text{em}}$ and $s_{c}^{\text{th}}$ as functions of $\log_{10} m$, for the halo structure described above, for the case of a neutralino that is mostly Higgsino. The shaded region marks $s_{c}^{\text{em}}$ given by (21) for the range of values of $\alpha$, while the vertical lines correspond to the range of masses selected by the abundance criterion (9) for $\Omega_0 = 0.2, 0.3, 0.4$. The solid curves are $s_{c}^{\text{em}}$ given by (17) for the same values of $\Omega_0$, intersecting the shaded region associated with (21) at some range of masses. However, the ranges of coincidence of a fixed (17) curve with the shaded region (21) occurs at masses which correspond to values of $\Omega_0$ that are different from those used in (17), that is, the vertical lines and solid curves with same $\Omega_0$ intersect out of the shaded region. Hence, this annihilation channel does not seem to be favored.

Figure 2b depicts the same variables as figure 2a, for the same halo structure, but for the case of a neutralino that is mostly B-ino. In this case, the joint application of the abundance and entropy criteria yield a consistent mass range of 150 GeV < $m_{\tilde{\chi}_1^0}$ < 250 GeV), which allows us to favor this annihilation channel as a plausible dark matter candidate, with $m$ lying in the narrow ranges given by this figure for any chosen value of...
Ω_0. As noted above, the results of figures 1a and 1b are totally insensitive to the values of halo variables, \( x^c_h \) and \( \rho^c_h \), used in evaluating (21) and (17). Different values of these variables (say, for a different halo structure) would only result in a relabeling of the values of \( s^c_h \) along the vertical axis of the figures.

CONCLUSIONS

We have presented a robust consistency criterion that can be verified for any annihilation channel of a given dark matter candidate proposed as the constituent particle of the present galactic dark matter halos. Since we require that the empirical estimate \( s^c_{\text{em}} \|_{\text{em}} \) of present dark matter haloes must match the theoretical value \( s^c_{\text{th}} \|_{\text{th}} \), derived from the microcanonical definition and from freeze out conditions for the candidate particle, the criterion is of a very general applicability, as it is largely insensitive to the details of the structure formation scenario assumed. Further, the details of the present day halo structure enter only through an integral feature of the dark halos, the central escape velocity, thus our results are also insensitive to the fine details concerning the central density and the various models describing the structure of dark matter halos. A crucial feature of this criterion is its direct dependence on the physical details (i.e. annihilation channels and mass) of any particle candidate.

Recent theoretical work by E. A. Baltz et al. \[11\] confirmed that neutralino annihilation in the galactic halo can produce enough positrons to make up for the excess of cosmic ray positrons experimentally detected by the HEAT collaboration \[12, 13\]. Baltz et al. concluded that for a boost factor \( B_s \sim 30 \) the neutralinos must be primarily B-inos with mass around 160 GeV. For a boost factor \( 30 < B_s < 100 \), the gaugino–dominated SUSY models complying with all constraints yield neutralino masses in the range of \( 150 \text{GeV} < m_{\tilde{\chi}_1^0} < 400 \text{GeV} \). On the other hand, Higgsino dominated neutralinos are possible but only for \( B_s \sim 1000 \) with masses larger than 2 TeV. The results that we have presented in this paper are in agreement with the predictions that follow from \[11\], as we obtain roughly the same mass range for the B-ino dominated case (see figure 1b) and the Higgsino channel is shown to be less favored in the mass range lower than TeV’s.

We have examined the specific case of the lightest neutralino for the mostly B-ino and mostly Higgsino channels. The joint application of the “entropy consistency” and the usual abundance criteria clearly shows that the B-ino channel is favored over the Higgsino. This result can be helpful in enhancing the study of the parameter space of annihilation channels of LSP’s in MSSM models, as the latter only use equations (8) and (9)–(10) in order to find out which parameters yield relic gas abundances that are compatible with observational constraints \[2, 3, 4, 5, 6, 7\]. However, equations (8) and (9)–(10) by themselves are insufficient to discriminate between annihilation channels. A more efficient study of the parameter space of MSSM can be achieved by the joint usage of the two criteria, for example, by considering more general cross section terms (see for example \[3\]) than the simplified approximated forms \(11\) and \(12\). This work is currently in progress.
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