Big bang nucleosynthesis constrains the total annihilation cross section of neutralino dark matter

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Abstract

Assuming the lightest neutralino forms dark matter, we study its residual annihilation after freeze-out at the early universe. If taking place after the big bang nucleosynthesis (BBN) the annihilation products, especially at the hadronic modes, may cause nonthermal nuclear reaction and change the prediction of the primordial abundance of light elements in the standard BBN scenario. We therefore put constraints on the neutralino annihilation cross section. These constraints are free of the uncertainties of the dark matter profile today suffered by direct or indirect detection of dark matter. We find the constraints by BBN is important, especially when taking large tan $\beta$. If the light element abundances can be determined with higher precision in the future the constraint will become very strong, so that a majority of the parameter space allowed by the relic density requirement may be excluded.
The existence of cosmological dark matter (DM) has been firmly established by a multitude of astronomical observations. However, the nature of the non-baryonic dark matter is still unknown and remains one of the most outstanding puzzles in particle physics and cosmology. Among a large amount of theoretical candidates, the most attractive scenario involves the weakly interacting massive particles (WIMPs). An appealing idea is that the WIMPs freeze out at the very early time and form the thermal relics, which naturally account for the relic abundance observed today \cite{1}. The WIMPs are well motivated theoretically in particle physics beyond the standard model to solve the hierarchical problem. In particular, the minimal supersymmetric extension of the standard model (MSSM) provides an excellent WIMP candidate as the lightest supersymmetric particle, usually the lightest neutralino, which are stable due to R-parity conservation \cite{2}.

The WIMPS can be detected on the present running or future experiments, either directly by measuring the recoil energy when WIMP scatters off the detector nuclei \cite{3} or indirectly by observing the annihilation products of the WIMPs, such as the antiprotons, positrons, $\gamma$-rays or neutrinos \cite{2, 4}. After decades of efforts, the sensitivity of these experiments have been improved by many orders of magnitude. However, no positive signals have been found up to now.

Conversely, the null results put constraints on the parameter space of the dark matter model, such as the MSSM. However, all the WIMP detection experiments depend on the distribution profile of dark matter. Especially for the indirect detection the predicted annihilation products from the Galactic Center (GC) \cite{5} can vary for several orders of magnitude by assuming different dark matter profiles. In theoretical studies, in order to give optimistic predictions a cuspy dark matter profile is usually adopted, such as the NFW \cite{6} or Moore \cite{7} profile which is favored by N-body simulation. However, observations of rotation curve strongly disfavor cuspy profiles. Instead, they generally favor a cored profile \cite{8}. The discrepancy between simulation and observation has been thought a severe challenge to the cold dark matter scenario for cosmological structure formation. If a cored profile is adopted the theoretical prediction of dark matter annihilation (DMA) products from the GC may be below the sensitivities of all present or near future experiments. Therefore, no firm constraints can be set on the MSSM parameter space from the present dark matter detection experiments.

More firm constraints on the dark matter model may come from the early universe pro-
cesses when the density fluctuation is very small. Indeed, the most stringent constraint on the MSSM parameter space today actually comes from the process of the lightest supersymmetric particle (LSP) decoupling at the early universe, by requiring the relic density of the LSP being consistent with the measurement of WMAP [9]. Besides that there are also model independent constraints on the dark matter annihilation cross section from unitarity bound [10,11] or from measurement of the cosmological neutrino flux [12], which, however, set much loser constraints than that given by the decoupling process.

In the present work we will set a new constraint on the MSSM parameter space from another process at the early universe, i.e. the big-bang nucleosynthesis (BBN). Knowing the nuclear reaction processes and the evolution history of the universe in the standard cosmology we can precisely calculate the abundances of the light elements, mainly on D, $^3$He, $^4$He, $^6$Li, $^7$Li. The standard BBN scenario gives consistent predictions of light element abundances compared with observations. The agreement between the BBN predictions and observations can be used to constrain various processes beyond the standard cosmology or standard particle physics. For example, the BBN has been extensively studied in the literature to constrain the long-lived heavy particles, such as gravitino [13], which may decay after BBN.

We will investigate how the standard BBN constrains the neutralino self-annihilation. After neutralino freeze-out there continues to be some residual annihilation of neutralinos. Although rare on the expansion time scale the residual self-annihilation continues to produce high energy particles well after BBN ends, changes the abundances of light elements, thereby ruin the agreement between BBN theory and observations. Therefore observational data of light element abundances constrains the rate of neutralino self-annihilation. It should be noted that since the rate of the WIMP annihilation is proportional to the number density square of the dark matter particles, at the early universe the annihilation rate of neutralino is much higher than the average rate today.

The abundances of light elements are especially sensitive to the injecting of strongly interacting particles during nucleosynthesis. The main effect of the hadronic cascades is that the ambient $^4$He is destroyed and D, T, $^3$He and $^6$Li, $^7$Li are created. BBN with hadronic-dissociation processes induced by hadronic decays of long lived X-particles (any theoretical assumed long lifetime particles) was studied in [13]. In this work we study the effect of injecting hadronic particles from neutralino annihilation on BBN.
To derive the constraint we will follow the calculation given by M. Kawasaki et al.\textsuperscript{[13]} closely. In\textsuperscript{[13]} the authors adopted the most recent data of nuclear reaction cross sections and observational light element abundances, new Monte Carlo event generator for quark/gluon hadronization. The evolution of the hadronic shower in the thermal bath is also carefully treated. Taking the uncertainties of the measurements into account quite conservative constraints on the abundances of X-particles as a function of its life time are derived.

The X-particle is assumed to have a two-body decay into monoenergetic quarks with energy $E = m_X/2$, which evolve into two jets. The injection rate of the jets is determined as $n_X/\tau_X$, with $n_X$ and $\tau_X$ the number density and life time of X-particle respectively. Finally the constraint on the relative number density of $X$, $Y_X = n_X/s$ with $s$ the entropy of the Universe, as function of its lifetime $\tau_X$ is given. Considering that neutralino annihilation also produces monoenergetic quarks we can roughly relate the constraints on the injection rate $n_X/\tau_X$ in\textsuperscript{[13]} into the neutralino annihilation rate, which is determined by

\begin{equation}
R = \frac{<\sigma v>}{2} n_X^2 ,
\end{equation}

with $<\sigma v>$ the thermal averaged annihilation cross section and $n_X$ the number density of neutralino. The factor 2 is due to identical particles of initial state.

The density of dark matter is given as $\rho_{DM} = \rho_{DM}^0 a^{-3}$ with $\rho_{DM}^0$ the dark matter density today and $a$ the cosmological scale factor. The entropy $s$ of the Universe is given in the same way. The time is related with the scale factor by

\begin{equation}
t = \int_0^a \frac{da}{\dot{a}} = \int_0^a \frac{da}{aH} = \frac{1}{H_0} \int_0^a \frac{da}{a \sqrt{\frac{\rho}{\rho_0}}},
\end{equation}

where the Hubble constant is related with that today by $\frac{H^2}{H_0^2} = \frac{\rho}{\rho_0}$. The energy density is given by $\rho = \rho_\gamma^0 a^{-4} + \rho_\nu^0 a^{-4} + \rho_m^0 a^{-3} + \rho_\Lambda^0$, with $\rho_\gamma^0$, $\rho_\nu^0$, $\rho_m^0$ and $\rho_\Lambda^0$ the radiation, neutrino, matter and dark energy density today.

Taking the initial conditions of $\rho_i^0$ and integrating Eq. (2) we get the number density and therefore the annihilation rate $R$ of neutralino at any time $t$. From the constraints on the hadronic jets injection rate derived in\textsuperscript{[13]} and Eq. (1) we get constraints on the annihilation cross section $<\sigma v>$ at $t$. An accurate result should be given by solving the Boltzmann equation numerically. Here we give constraint by a simply correspondance between X-particle
decay and neutralino annihilation. This may lead to a conservative constraint on the annihilation cross section. In Fig. 1 we show the constraints on \( < \sigma v > \) as function of time \( t \) for \( 2m_\chi = 100 \text{GeV}, 1 \text{TeV}, \) and \( 10 \text{TeV} \) respectively. The constraints are corresponding to these constraints for \( X \) decay with \( m_\chi = 100 \text{GeV}, 1 \text{TeV}, \) and \( 10 \text{TeV} \) respectively \[13\]. In deriving the constraints, we have assumed that the neutralino annihilates totally into gauge bosons \( W^+W^-/ZZ \) for \( m_\chi > m_W \) or quarks for \( m_\chi < m_W \).

From Fig. 1 the strongest constraints on \( < \sigma v > \) is at \( t \approx 2000 \) sec, which come from the \( ^6\text{Li}/\text{H} \) data. The abundance of \( ^6\text{Li} \) is very sensitive to the nonthermal hadronic jet injection. However, the \( ^6\text{Li} \) abundance is difficult to determine. The standard BBN prediction of \( ^6\text{Li} \) abundance is \( (^6\text{Li}/\text{H})_{\text{SBBN}} = 1.30 \times 10^{-14} \). Taking the large uncertainties in determining \( ^6\text{Li} \) abundance the constraints on hadronic jet injection is given by assuming \( (^6\text{Li}/\text{H}) < 10^{-11} \sim 10^{-10} \), which is several orders of magnitude higher than the standard prediction. Therefore the constraints on the nonstandard process from BBN can be much
FIG. 2: The constraints on $<\sigma v>$ in the MSSM parameter space set from BBN and GLAST by observation of DM annihilation at the GC. For the constraints by GLAST two DM profiles, NFW and isothermal, are adopted.

stronger if $^6$Li can be determined with higher precision.

Adopting the constraints on $<\sigma v>$ at $t \approx 2000$ sec we show how the MSSM parameter space is constrained by BBN in Fig. 2. The dots in the figure are produced randomly in the MSSM parameter space and the corresponding $<\sigma v>$ is calculated using the package DarkSUSY [14]. The constraints on $<\sigma v>$ for different neutralino mass is given by interpolation of the constraints for $2m_\chi = 100 GeV, 1 TeV, 10 TeV$. The ‘BBN bound’ in the figure shows the constraints on $<\sigma v>$ by BBN. The scatter of the bound comes from the different branching ratios of neutralino annihilation to quarks. Near the threshold neutralino may annihilate into leptons dominantly. In such cases we take the constraints from $^3$He/D which is sensitive to the photodissociation process. The most stringent constraint from the photodissociation process is given at $t \approx 8.5 \times 10^7$ sec.

In Fig 2 we also show the parameters that can be detected by GLAST [15]. In theoretical prediction of dark matter annihilation we usually adopt the dark matter profile from N-body simulation, which generally predicts cuspy profiles such as NFW [6] or Moore [7] profiles. The NFW or Moore profiles have singularities at the halo center as $\rho_{\text{NFW}} \to r^{-1}$ and $\rho_{\text{Moore}} \to r^{-1.5}$ respectively. The singularity leads to large (or divergent) annihilation flux and can be detected by the satellite detectors, such as GLAST. However, observation of rotation curves usually strongly favor a cored dark matter profile, instead of cuspy ones [8].
FIG. 3: The parameter space that satisfies $\Omega_c h^2 < 0.125$ and these excluded by BBN constraints. ‘BBN*10’ and ‘BBN*100’ means how the parameter space is constrained if the precision of $^6\text{Li}$ data is improved by one and two orders of magnitude.

If adopting a cored dark matter profile the present detectors will have much weaker potential to detect the signals from dark matter annihilation. In Fig. 2 we show the constraints on $<\sigma v>$ from observation of DM annihilation at the GC by GLAST, assuming both NFW and cored profiles. In deriving the constraints by GLAST we take the gamma ray source detected by HESS at the GC [16] as background and extend it to lower energy. The present bound by BBN has been stronger than that set by GLAST taking a cored profile, while weaker if taking a NFW profile.

Further, we set the exclusion region by BBN in the parameter space of the minimal super-gravity mediated SUSY breaking model (mSUGRA). In calculating the relic density of mSUGRA models, the package MicrOMEGAs 2.0.7 is adopted [17], where the package ISAJET [18] is incorporated to run the renormalization group equations from the GUT scale to the low energy scale. The BBN bounds are especially important when taking large
values of $\tan \beta$. In Fig. 3 we show the exclusion region on the $m_0 - m_{1/2}$ plane set by BBN taking $\tan \beta = 50, 55, \text{and} 60$ respectively. We have taken $A_0 = 0$, and $\mu$ positive. In the $m_0 - m_{1/2}$ plane the whole shaded region represents the models which satisfy the WMAP constraints on the relic density. The WMAP 5-year data gives $\Omega_c h^2 = 0.1143 \pm 0.0034$. The shaded region in Fig. 3 is given by requiring the CDM relic density be smaller than the $3\sigma$ upper bound, i.e., $\Omega_c h^2 < 0.125$. The excluded region marked as ‘BBN*10’ and ‘BBN*100’ represent that the precision of $^6$Li data is improved by 10 and 100 times in the future respectively. For $\tan \beta = 60$ the present BBN bound has excluded a large part of the allowed models. For $\tan \beta = 50, 55$ only these models with small values of $m_0$ and $m_{1/2}$ are excluded by BBN. If the $^6$Li data is improved by 2 orders of magnitude we can see that most of the parameters allowed by WMAP will be excluded.

It should be noted that we only take the upper bound of the relic density from WMAP into account. That means the neutralino may only account for a part of dark matter density, or there are nonthermal contribution to the relic density [19]. Therefore the present BBN bound set constraints only for the large annihilation cross section. However, as have been seen, it is even more severe than that set by GLAST for a cored profile. Although the neutralino decoupling process gives the most stringent constraint now, it can be changed in nonstandard cosmology as shown by Gelmini and Gondolo [20] since the process takes place at very early time when we know very little. However, the bound from BBN is much solid and hard to invalidate it. BBN and cosmic microwave background have long been taken as two classic proof of the success of the standard cosmology. Compared with other model independent bound on the DM annihilation rate [10, 11, 12], the present bound is much more severe. With the improvement of the precision of light element abundances the exclusion bound can also be greatly improved. Anyway, we present a new constraint on the MSSM parameter space independent of the N-body simulation result, besides that from the decoupling process.

In summary, in this work we study how the residual annihilation of neutralino after freeze-out can affect the abundance of light elements predicted in the standard scenario. According to the study we try to set constraints on the SUSY parameter space. The constraints are different from these set by direct or indirect detection of dark matter which heavily depends on the dark matter profile. The dark matter profiles are usually predicted by N-body simulations, which, however, seem to show discrepancy with the observation of rotation curves. This has been taken as a serious problem in structure formation in the cold dark
matter scenario. Our result shows that BBN can give quite strong constraints on the SUSY parameter space. Especially, the most stringent constraint comes from the $^6\text{Li}$ data which, however, has very large uncertainties. The present constraint is given by requiring that the $^6\text{Li}$ abundance is lower than $10^3 \sim 10^4$ times the prediction of the standard scenario. If the bound can be improved by 2 orders of magnitude we find a large part of the important SUSY parameter space will be excluded by BBN.

Acknowledgments

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