Gravitino Thermal Density assuming Gravitino Dark Matter models

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Outline

- Why still SUSY, Supersymmetric DM scenarios
- Direct, indirect searches of DM
- Gravitino Dark Matter
- Gravitino thermal production and reheating temperature
- Recap
SUSY and Higgs mass

\[ m_h = \sqrt{\frac{1}{2} [M_A^2 + M_Z^2 - \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2M_Z^2\cos^2\beta}] < M_Z} \]

\[ \tan\beta = \frac{v_2}{v_1} \]

\[ \Delta m_h^2 \approx \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \log \left( \frac{m_t^2}{m_t^2} \right) + \frac{X_t^2}{m_t^2} - \frac{X_t^4}{12m_t^4} \right] \]

\[- \frac{3}{48\pi^2} \frac{m_b^4}{v^2} \frac{t_\beta^4}{(1 + \epsilon_b t_\beta)^4} \frac{\mu^4}{m_b^4} \]

\[- \frac{1}{48\pi^2} \frac{m_\tau^4}{v^2} \frac{t_\beta^4}{(1 + \epsilon_\ell t_\beta)^4} \frac{\mu^4}{m_\tau^4} \]

\[ X_t = A_t + \frac{\mu}{\tan\beta} \approx A_t \]
27. Cosmic microwave background

Figure 27.2: CMB temperature anisotropy band-power estimates from the Planck, WMAP, ACT, and SPT experiments. Note that the width of the \(\ell\)-bands vary between experiments and have not been plotted. This figure represents only a selection of the most recent available experimental results, and some points with large error bars have been omitted. At the higher multipoles these band-powers involve subtraction of particular foreground models, while proper analysis requires simultaneous fitting of CMB and foregrounds over multiple frequencies. The \(\ell\)-axis here is logarithmic for the lowest multipoles, to show the Sachs-Wolfe plateau, and linear for the other multipoles. The acoustic peaks and damping region are very clearly observed, with no need for a theoretical curve to guide the eye; however, the curve plotted is the best-fit Planck model.

27.7. CMB Polarization

Since Thomson scattering of an anisotropic radiation field also generates linear polarization, the CMB is predicted to be polarized at the level of roughly 5% of the temperature anisotropies [54]. Polarization is a spin-2 field on the sky, and the algebra of the modes in \(\ell\)-space is strongly analogous to spin-orbit coupling in quantum mechanics [55]. The linear polarization pattern can be decomposed in a number of ways, with two quantities required for each pixel in a map, often given as the \(Q\) and \(U\) Stokes parameters. However, the most intuitive and physical decomposition is a geometrical one, splitting the polarization pattern into a part that comes from a divergence (often referred to as the 'E-mode') and a part with a curl (called the 'B-mode') [56]. More explicitly, the modes are defined in terms of second derivatives of the polarization amplitude, with the Hessian for the E-modes having principle axes in the same sense as the polarization.
DM/ Evidence

- Baryon density $\Omega_B h^2$
- $Y_p$ vs. Baryon-to-photon ratio $\eta_{10}$
- $^4\text{He}$
- $^3\text{He}/H|_p$
- $^7\text{Li}/H|_p$
- D/H|_p

Comparisons with BBN and CMB constraints.
DM/ Evidence

\[ \Omega_{\text{tot}} \sim 1.0 \]

\[ \Omega_M = 0.315 \pm 0.016 \]

\[ \Omega_\Lambda = 0.685 \pm 0.017 \]

\[ \Omega_B = 0.0499 \pm 0.0022 \]

\[ \Omega_{\text{DM}} = \Omega_M - \Omega_B = 0.265 \pm 0.011 \]

\[ \Omega_\chi h^2 = 0.112 \pm 0.12 \]
DM/ Direct searches

Limits on Dark Matter from Direct Detection

DM–nucleon cross-section

Dark Matter Mass [GeV]

- CRESST (2015)
- CDMSlite (2015)
- PandaX (2016)
- LUX (2016)

CaWO4
ν Floor
Xe

Z Portal g=10^{-4}

Higgs Portal λ=1

Higgs Portal λ=10

Higgs Portal λ=10

1 pb
1 fb
1 ab
1 zb
1 yb
DM/ Indirect searches gammas GC

Figure 4. Differential fluxes for the $15\times15$ region about the GC for the four IEMs constrained as described in Section 3.1. Upper row shows the results for the intensity-scaled IEMs based on the Pulsars (left) and OBstars (right) source distributions. Lower row shows the results for the index-scaled IEMs based on the Pulsars (left) and OBstars (right) source distributions. Line styles: solid (total model), long-dash (IC, annulus $\Pi$), dot-dash (HI + CO gas $\Pi$-decay, annulus), dot-dot-dot-dash (point sources), dash (Galactic interstellar emission excluding annulus 1 for IC, HI and CO gas $\Pi$-decay). Solid circles: data.
FIG. 1. Constraints on the DM annihilation cross section at 95% CL for the $\bar{b}b$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J-factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of Pass 7 Reprocessed data and the same sample of 15 dSphs [13]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman et al. [5].

DM Mass (GeV/c$^2$)

$10^{-22}$ $10^{-23}$ $10^{-24}$ $10^{-25}$ $10^{-26}$ $10^{-27}$

$10^1$ $10^2$ $10^3$ $10^4$

In conclusion, we present a combined analysis of 15 Milky Way dSphs using a new and improved LAT data set processed with the Pass 8 event-level analysis. We exclude the thermal relic annihilation cross section ($\sigma < 2 \times 10^{-26}$ cm$^3$/s) for WIMPs with $m_{DM} < 100$ GeV annihilating through the quark and $\tau$-lepton channels. Our results also constrain DM particles with $m_{DM}$ above 100 GeV surpassing the best limits from Imaging Atmospheric Cherenkov Telescopes for masses up to 1 TeV. These constraints include the statistical uncertainty on the DM content of the dSphs. The future sensitivity to DM annihilation in dSphs will benefit from additional LAT data taking and the discovery of new dSphs with upcoming optical surveys such as the Dark Energy Survey [37] and the Large Synoptic Survey Telescope [38].

ACKNOWLEDGMENTS

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DM/ Indirect searches antiprotons

Ellis, Olive, VCS
DM searches status

- Direct searches, up to date, have found nothing

- Indirect searches uncertainties: halo, direct x-section etc

- Neutralino models “currently not favoured” by LHC SUSY searches

- Gravitino
Gravitino Dark Matter

Gravitino thermal production

\[ Y_{3/2}(T) \approx 4.48 \times 10^{-11} \left( \frac{T_{\text{reh}}}{10^{10} \text{GeV}} \right) \times \left[ \left( 1 + 0.558 \frac{m_{1/2}^2}{m_{3/2}^2} \right) - 0.011 \left( 1 + 3.062 \frac{m_{1/2}^2}{m_{3/2}^2} \right) \ln \left( \frac{T_{\text{reh}}}{10^{10} \text{GeV}} \right) \right] \]

Important constraints from BBN data
Gravitino thermal abundance

Figure 11: The bands show the region where the thermal gravitino abundance equals the DM abundance (3σ regions), assuming unified gaugino masses with $m_{1/2} = 150$ GeV (roughly the minimal value allowed by present data) or $m_{1/2} = 1$ TeV at the unification scale, and negligible $A_t$. Model-dependent issues are here ignored, including who is the LSP and the NLSP. Successful thermal leptogenesis with zero initial right-handed neutrino abundance is not possible within the gray band [24], [19].

We recall that we computed thermal production of gravitinos from MSSM particles at temperatures $T_{RH} \gg m_3/2, m_{soft}$. The true physics might be different. For example, the messenger fields with mass $M_{GM}$ employed by gauge mediation models might be so light that the gravitino thermalized (together with the hidden sector) and later decay back to MSSM particles, leaving atthermalized Goldstino. Eq. (6.3) shows that this phenomenon is dominant, $M_{GM} \ll \sim (10 \div 100) T_{RH}$, as the gravitino abundance gets washed-out as $Y \propto T^5$ during reheating at $T > \sim T_{RH}$.

Conclusions

Previous computations of the thermal gravitino production rate [2], [3] were performed leading order in small gauge couplings, finding a rate of the form $\gamma \propto g^2 \ln 1/g$, which behaves unphysically when extrapolated to the true MSSM values of the egauge couplings, $g \sim 1$ (see fig. 1). We improved on these results in the following ways:

1. We included gravitino production via gluon $\rightarrow$ gluino + gravitino and other decays: these effects first arise at higher order in $g$ (the phase space is opened by thermal masses), but are enhanced with respect to scattering processes by a phase-space $\pi^2$ factor, typical of 3-body vs 4-body rates. The gravitino production rate becomes about twice larger, or more if $M_3 > \sim M_{1/2}$.

2. We added production processes induced by the top quark Yukawa coupling. This enhances the gravitino production rate by almost 10% or more if $A_t$ is bigger than gaugino masses.

3. Finally, we computed the gravitino abundance replacing the instant reheating approximation with the standard definition of the reheating process, where $T_{RH}$ is not the maximal temperature but defines the temperature at which inflaton decay ends, ceasing to release entropy. This improvement decreases the gravitino abundance by 25% and allows a precise comparison with leptogenesis [24], where reheating was included in [19].

Our result for the gravitino production rate is

$$\gamma = \gamma_D + \gamma_{subS} + \gamma_{top}. \quad (7.1)$$
Big Bang Nucleosynthesis

Light Elements observed abundances:

- $^4\text{He}$ observed in extragalactic HII regions:
  abundance by mass $\sim 25\%$

- $^7\text{Li}$ observed in the atmosphere of dwarf halo stars:
  abundance by number $\sim 10^{-10}$

- $^3\text{He}$ observed in solar wind, meteorites, and in ISM:
  abundance by number $\sim 10^{-5}$
\[
p + n \rightarrow D; \\
D + p \rightarrow ^3\text{He}; \\
D + D \rightarrow ^4\text{He},
\]
Nucleosynthesis Delayed
(Deuterium Bottleneck)

\[ p + n \rightarrow D + \gamma \quad \Gamma_p \sim n_B \sigma \]

\[ p + n \leftarrow D + \gamma \quad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T} \]

**Nucleosynthesis begins when** \( \Gamma_p \sim \Gamma_d \)

\[ \frac{n_\gamma}{n_B} e^{-E_B/T} \sim 1 \quad @ \quad T \sim 0.1 \text{ MeV} \]

**All neutrons \( \rightarrow \) \(^4\text{He}\)**

\[ Y_p = \frac{2(n/p)}{1 + (n/p)} \sim 25\% \]

**Remainder:**

\( D, \; ^3\text{He} \sim 10^{-5} \) and \( ^7\text{Li} \sim 10^{-10} \) by number
Conditions in the Early Universe:

\[ T \gtrsim 1 \text{ MeV} \]
\[ \rho = \frac{\pi^2}{30} (2 + \frac{7}{2} + \frac{7}{4}N_\nu)T^4 \]
\[ \eta = n_B/n_\gamma \sim 10^{-10} \]

**β-Equilibrium maintained by weak interactions**

Freeze-out at \( \sim 1 \text{ MeV} \) determined by the competition of expansion rate \( H \sim T^2/M_p \) and the weak interaction rate \( \Gamma \sim G_F^2T^5 \)

\[ n + e^+ \leftrightarrow p + \bar{\nu}_e \]
\[ n + \nu_e \leftrightarrow p + e^- \]
\[ n \leftrightarrow p + e^- + \bar{\nu}_e \]

At freezeout \( n/p \) fixed modulo free neutron decay, \( (n/p) \sim 1/6 \rightarrow 1/7 \)
Light elements production

\[ \tau_n = 887 \text{ sec} \]
\[ N_v = 3 \]
\[ \Omega_N = 0.01h^{-2} \]
Gravitino field representation

The four polarisation states of the gravitino field in the momentum space in terms of spin-1 and spin-1/2 components:

\[ \psi_{\mu}(k, \frac{3}{2}) = u(k, \frac{1}{2}) \epsilon_{\mu}(k, 1), \]

\[ \psi_{\mu}(k, \frac{1}{2}) = \sqrt{\frac{1}{3}} u(k, -\frac{1}{2}) \epsilon_{\mu}(k, 1) + \sqrt{\frac{2}{3}} u(k, \frac{1}{2}) \epsilon_{\mu}(k, 0) \]

\[ \psi_{\mu}(k, -\frac{1}{2}) = \sqrt{\frac{1}{3}} u(k, \frac{1}{2}) \epsilon_{\mu}(k, -1) + \sqrt{\frac{2}{3}} u(k, -\frac{1}{2}) \epsilon_{\mu}(k, 0) \]

\[ \psi_{\mu}(k, -\frac{3}{2}) = u(k, -\frac{1}{2}) \epsilon_{\mu}(k, -1), \]

From the field equation for the spin-3/2 particle, the so called Rarita-Schwinger equation, we get three equations in momentum space, which we have to fulfill by the right choice of the spin-1 and spin-1/2 component representations

\[ \gamma^\mu \psi_{\mu}(k, \lambda) = 0 \]

\[ k^\mu \psi_{\mu}(k, \lambda) = 0 \]

\[ (\slashed{k} - m_{\tilde{G}}) \psi_{\mu}(k, \lambda) = 0 \]
Gravitino Interactions with the MSSM

The relevant supergravity Lagrangian reads

\[
\mathcal{L}^{(\alpha)}_{G, \text{int}} = -\frac{i}{\sqrt{2}M_\text{P}} \left[ \mathcal{D}_\mu^{(\alpha)} \phi^i \bar{G}_\nu \gamma^\mu \gamma^\nu \chi_L^i - \mathcal{D}_\mu^{(\alpha)} \phi^i \bar{\chi}_L \gamma^\nu \gamma^\mu \bar{G}_\nu \right] \\
- \frac{i}{8M_\text{P}} \bar{G}_\mu [\gamma^\rho, \gamma^\sigma] \gamma^\mu \chi^{(\alpha) a} F_{\rho \sigma}^{(\alpha) a},
\]

with the covariant derivative given by

\[
\mathcal{D}_\mu^{(\alpha)} \phi^i = \partial_\mu \phi^i + ig_\alpha A^{(\alpha) a}_\mu T^{(\alpha)}_{a, ij} \phi^j,
\]

and the field strength tensor \( F_{\mu \nu}^{(\alpha) a} \) reads

\[
F_{\mu \nu}^{(\alpha) a} = \partial_\mu A^{(\alpha) a}_\nu - \partial_\nu A^{(\alpha) a}_\mu - g_\alpha f^{(\alpha) ab} c A^{(\alpha) b}_\mu A^{(\alpha) c}_\nu.
\]

The index \( \alpha \) corresponds to the three groups \( U(1)_Y \), \( SU(2)_L \), and \( SU(3)_c \) with \( a = 1, 3, 8 \) and \( i = 1, 2, 3 \), respectively.
Steps

- Calculate the partial and the total decay widths
- Employ PYTHIA event generator to simulate the EM and HD products of Z, Higgs bosons, quarks and taus
- Incorporate in the BBN code the effects of the EM and HD injections
- Estimate for each point of the SUSY parameter space the light element abundances
- Important point: Bound state phenomena of charged metastable particles like stau!
\( \chi \rightarrow \tilde{G} \gamma \)

\( \chi \rightarrow \tilde{G} Z \)

\( \chi \rightarrow \tilde{G} H_i \)
\[ \tilde{G} \rightarrow \tilde{\chi}^0_i W^- W^+ \]
\[ \tilde{\tau} \to \tilde{G} \tau \]
All possible three-body decays of neutralino1 into gravitino

<table>
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<th>number of graphs</th>
<th>first decay $\tilde{\chi}_1^0 \to XY$</th>
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<td>$G(h^0, H^0, \gamma, Z^0),$ $W^+ \tilde{\chi}_j^+$, $\tilde{\chi}_j^+ W^-$</td>
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<tr>
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<td>4 + 4 pt</td>
<td>$G(A^0, Z^0),$ $Z^0 \tilde{\chi}_k^0, \tilde{\chi}_k^0 h^0$</td>
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<tr>
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<tr>
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<tr>
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<td>$H^0$</td>
</tr>
</tbody>
</table>

19 individuel decay channels
Bound-state catalysis

standard BBN reaction is suppressed

\[ ^4\text{He} + d \rightarrow ^6\text{Li} + \gamma \]

the bound state reaction is not suppressed by photon emission

\[ (^4\text{He}X^-) + d \rightarrow ^6\text{Li} + X^- \]

possible solution of Li puzzle
Figure 3: As in Fig. 2, but with an assumed lifetime $\tau_X = 10^6$ sec.

Figure 4: As in Fig. 2, but with an assumed lifetime $\tau_X = 10^3$ s.
\[ A_0 = 2.5 m_0 \]
\[ A_0 = 2m_0. \]
$$A_0 = 2.5 m_0$$
Figure 8: Light-element abundances in the $(m_1/2, m_0)$ plane for $A_0 = 2.5 m_0$.

Whilst it is difficult to use $^3$He to constrain BBN, it is possible to use the ratio $^3$He/D [104]. Although $^3$He may be created or destroyed in stars, D is always destroyed in the pre-main sequence of stellar evolution and, as a result, the ratio is a monotonically increasing function of time. Thus one can use the solar ratio of about 1 [105] to constrain the BBN ratio. Because $^3$He can be produced and/or D can be destroyed, we do not assume a lower bound to the ratio.

Although the determination of the $^4$He abundance in extragalactic HII regions is dominated by systematic uncertainties [106], using the Markov Chain-Monte Carlo methods described in [107] and data compiled in [108], one finds $Y_p = 0.2534 \pm 0.0083 (15)$.
GDM/ results

Gravitino DM parameter space

Figure 10: Summary of the light-element-abundance constraints in the $(m_{1/2}, m_0)$ plane for $A_0 = 2.5 m_0$, tan $\beta = 10$ and $m_{3/2} = 100$ GeV (left) and $m_{3/2} = 0.1 m_0$ (right).

For a given gaugino mass, the NLSP lifetime is longer. As a result, the acceptable arc of D/H moves to larger $m_{1/2}$. More importantly, the $^6$Li constraint would now exclude all values of $m_{1/2}$ between 1 and 5 TeV. The $^9$Be constraint similarly would exclude the entire stau NLSP region displayed. Had we chosen instead $m_{3/2} = m_0$, a gravitino LSP would be present only in the lower right half of the plane. Once again lifetimes would typically be longer, affecting the light element abundances. In this case, only a small corner of the parameters at very large $m_{1/2}$ and very small $m_0$ would survive all constraints.

We now describe an analogous analysis for the CMSSM $(m_{1/2}, m_0)$ planes for $A_0 = 2.5 m_0$, tan $\beta = 40$. Fig. 11 displays our results for the option $m_{3/2} = 100$ GeV. In this case, the D/H constraint would allow most of the lower half of the parameter plane. This region would be allowed by both the $^3$He/D (except for a small area with low $m_{1/2}$ and $m_0$) and $^4$He constraints, but much of it is excluded by the $^6$Li/$^7$Li ratio, and more strongly excluded by the $^9$Be/H ratio. Improvement in the $^7$Li/H ratio only occurs around an arc starting at $(m_{1/2}, m_0) = (3.2, 2)$ TeV. This arc is for the most part allowed by the other constraints.

Fig. 12 displays the results of a similar analysis for $m_{3/2} = 0.1 m_0$, but with the same values of the CMSSM parameters. Once again, the neutralino NLSP region is excluded by the D/H ratio, which is also problematic for a large area with $m_0 > 1$ TeV. The $^3$He/D and $^4$He constraints are qualitatively similar to the previous case. However, the effect of the $^6$Li/$^7$Li constraint is somewhat different: it excludes a bulbous region of the stau NLSP segment extending almost to $m_{1/2} \sim 5$ TeV and the $^9$Be constraint. In this case, the arc allowed by the $^7$Li/H ratio is wider and has shifted to larger masses. As a result, the only region that has a chance of being compatible with all the light-element constraints has
GDM/ results

Figure 13: Summary of the light-element-abundance constraints in the $(m_{1/2}, m_0)$ plane for $A_0 = 2 m_0$, $\tan \beta = 40$ and $m_{3/2} = 100 \text{ GeV}$ (left) and $m_{3/2} = 0.1 m_0$ (right).

The results shown above have been for slices through the CMSSM parameter space corresponding to $(m_{1/2}, m_0)$ planes for fixed $\tan \beta$ and $A_0$. We have also explored how the results for $\tan \beta = 40$ vary as functions of $A_0$ for a couple of values of $m_0 = 1000$, 3000 GeV, with the results summarized in Fig. 17. The left panel is for $m_0 = 1000$ GeV, which is typical of the range of $m_0$ in the unshaded regions in the cases studied above. We see that a large region with $m_{1/2} > 4 \text{ TeV}$ and $A_0 < 2 \text{ TeV}$ is unshaded and hence $^7\text{Li}$-compatible.

On the other hand, we see no unshaded region in the right panel for $m_0 = 3000$ GeV, which is less typical of the values of $m_0$ found in the unshaded regions of previous summary plots. Therefore, we expect that the features found earlier are quite generic.

Also shown in Figs. 10, 13, 16 and 17 are some representative contours of the lightest MSSM Higgs boson $M_h$, as calculated using the FeynHiggs code [94]. This code is generally thought to have an uncertainty $\sim 1.5 \text{ GeV}$ for generic sets of CMSSM parameters, but warns of larger uncertainties at the large values of $m_{1/2}$ of interest here. Accordingly, we consider calculated values of $M_h \in [124, 127] \text{ GeV}$ to be compatible with the observed range of 125 to 126 GeV [93], and an even larger range of calculated values of $M_h$ may be acceptable at large $m_{1/2}$. In the cases displayed in Fig. 10, we see that the ends of the BBN-compatible $^7\text{Li}$ may be linked with the irregular behaviours of some calculated contours of $M_h$ in Figs. 13, 16 and 17.
GDM/ results

Figure 16:
Summary of the light-element-abundance constraints in the $(m_{1/2}, m_0)$ plane for $A_0 = 2.5 m_0$, $\tan\beta = 40$, $m_{3/2} = 100$ GeV (left) and $m_{3/2} = 0.1$ GeV (right).

Figure 17:
Summary of the light-element-abundance constraints in the $(m_{1/2}, A_0)$ plane for $\tan\beta = 40$, $m_{3/2} = 100$ GeV with $m_0 = 1000$ GeV (left) and $m_0 = 3000$ GeV (right).

\[ (4\text{He})^+ + (4\text{He}) \rightarrow (8\text{Be})^+ + \gamma \]

must be high enough to allow for $(4\text{He})^+ + (4\text{He}) \rightarrow (8\text{Be})^+ + \gamma$ to be exothermic, i.e., $Q > 0$ (cf. eq. 1). Our analysis has assumed as default the $B_{8\text{Be}} = 1.1679$ value of ref. [75], which implies the formation reaction is strongly exothermic, and thus the reverse photodissociation.

Cyburt, Ellis, Fields, Luo, Olive, VCS
Figure 16: Summary of the light-element-abundance constraints in the $(m_{1/2}, m_0)$ plane for $A_0 = 2.5$ GeV, $\tan \beta = 40$, and $m_{3/2} = 100$ GeV (left) and $m_{3/2} = 0.1$ m (right).

Figure 17: Summary of the light-element-abundance constraints in the $(m_{1/2}, A_0)$ plane for $\tan \beta = 40$ and $m_{3/2} = 100$ GeV with $m_0 = 1000$ GeV (left) and $m_0 = 3000$ GeV (right).

must be high enough to allow for $(^{4}\text{He} X − ^{4}\text{He})^{+}$ to be exothermic, i.e., $Q > 0$ (cf. eq. 1). Our analysis has assumed as default the $B_{8} = 1.1679$ value of ref. [75], which implies the formation reaction is strongly exothermic, and thus the reverse photodissociation $^{3}\text{He} → ^{4}\text{He} X − ^{4}\text{He}$ is not possible.
Summary & Prospects

✶ Gravitino is natural candidate in SUGRA models for DM

✶ GDM scenario can be quite involved (bound state effects)

✶ Inclusion of Gravitino thermal production is important to set bound to reheating temperature

✶ DM scenario and phenomenology can open an window to Planck scale