Massive Gravitino Decays, Residual Dark Matter Annihilations, Nuclear Reaction Uncertainties and the Cosmological Lithium Problems

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Motivation

Constrain particle decay or/and annihilation scenarios by BBN

$$\text{e.g., } m_{3/2} + \text{CMSSM } \{m_{1/2}, m_0, A_0, \tan\beta, \text{sgn}(\mu)\}$$

Try to solve $^7\mathrm{Li}$ or/and $^6\mathrm{Li}$ problem

- $^7\mathrm{Li}$

$$\begin{aligned} \textit{observations}, \quad \left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{halo}*} &= (1.23^{+0.34}_{-0.16}) \times 10^{-10} \\ \left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{GC}} &= (2.35 \pm 0.05) \times 10^{-10} \\ \textit{standard BBN}, \quad \left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{SBBN}} &= (5.12^{+0.71}_{-0.62}) \times 10^{-10} \end{aligned}$$

- $^6\mathrm{Li}$

$$\textit{observations}, \left(\frac{^6\mathrm{Li}}{^7\mathrm{Li}}\right)_{\mathrm{halo}*} \sim 0.05 \Longrightarrow {}^6\mathrm{Li}/\mathrm{H} \sim (6-25) \times 10^{-12}$$

$$\textit{standard BBN}, \qquad {}^6\mathrm{Li}/\mathrm{H} \sim 10^{-14}$$

Method Outline

$\star$ CMSSM input (4 parameter and a sign)

$\downarrow$ RGEs

sparticle masses and couplings

$\downarrow$ input $m_{3/2}$

decay spectra

$\downarrow$ PYTHIA

hadronic and electromagnetic showers

$\downarrow$ $\zeta_{3/2} \equiv \frac{m_{3/2} n_{3/2}}{n_\gamma}$ and BBN code including non-thermal reactions

light element abundances prediction

$\downarrow$ compare with observations

constraints on $m_{3/2}, \zeta_{3/2}$ and CMSSM parameters,

$^7\mathrm{Li}$ and/or $^6\mathrm{Li}$ solved?

Goto $\star$

$$\Gamma_{hb\to\ell} = \int N_h(\epsilon)\; v\; \sigma_{hb\to\ell}(\epsilon)\; d\epsilon$$

Nuclear reactions of non-thermal particles

	Reaction	Uncertainty ϵ		Reaction	Uncertainty ϵ
1	$p^4\mathrm{He} \to d^3\mathrm{He}$		2	$p^4\mathrm{He} \to np^3\mathrm{He}$	20%
3	$p^4\mathrm{He} \to ddp$	40%	4	$p^4\mathrm{He} \to dnpp$	40%
5	$d^4\mathrm{He} \to {}^6\mathrm{Li}\gamma$		6	$t^4\mathrm{He} \to {}^6\mathrm{Li}n$	20%
7	${}^3\mathrm{He}^4\mathrm{He} \to {}^6\mathrm{Li}p$	20%	8	$t^4\mathrm{He} \to {}^7\mathrm{Li}\gamma$	
9	${}^3\mathrm{He}^4\mathrm{He} \to {}^7\mathrm{Be}\gamma$		10	$p^6\mathrm{Li} \to {}^3\mathrm{He}^4\mathrm{He}$	
11	$n^6\mathrm{Li} \to t^4\mathrm{He}$		12	$pn \to d\gamma$	
13	$pd \to {}^3\mathrm{He}\gamma$		14	$pt \to n^3\mathrm{He}$	
15	$p^6\mathrm{Li} \to {}^7\mathrm{Be}\gamma$		16	$p^7\mathrm{Li} \to {}^8\mathrm{Be}\gamma$	
17	$p^7\mathrm{Be} \to {}^8\mathrm{B}\gamma$		18	$np \to d\gamma$	
19	$nd \to t\gamma$		20	$n^4\mathrm{He} \to dt$	
21	$n^4\mathrm{He} \to npt$	20%	22	$n^4\mathrm{He} \to ddn$	40%
23	$n^4\mathrm{He} \to dnnp$	40%	24	$n^6\mathrm{Li} \to {}^7\mathrm{Li}\gamma$	
25	n (thermal)		26	$n^7\mathrm{Be} \to p^7\mathrm{Li}$	
27	$n^7\mathrm{Be} \to {}^4\mathrm{He}^4\mathrm{He}$		28	$p^7\mathrm{Li} \to {}^4\mathrm{He}^4\mathrm{He}$	
29	$n\pi^+ \to p\pi^0$		30	$p\pi^- \to n\pi^0$	
31	$p^4\mathrm{He} \to ppt$	20%	32	$n^4\mathrm{He} \to nn^3\mathrm{He}$	20%
33	$n^4\mathrm{He} \to nnnpp$		34	$p^4\mathrm{He} \to nnppp$	
35	$p^4\mathrm{He} \to N^4\mathrm{He}\pi$		36	$n^4\mathrm{He} \to N^4\mathrm{He}\pi$	

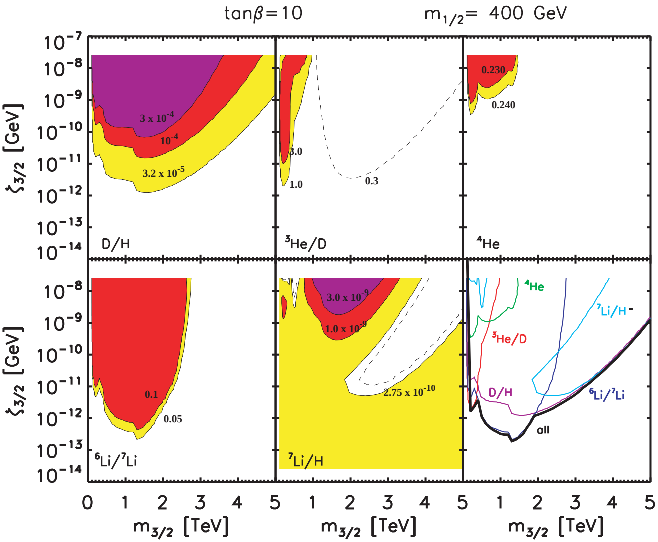


Figure: *For benchmark C, with $m_{1/2} = 400$ GeV on the WMAP coannihilation strip for a CMSSM scenario with $\tan\beta = 10$, $A_0 = 0$. The white regions in each panel are those allowed at face value by the light-element abundances.*

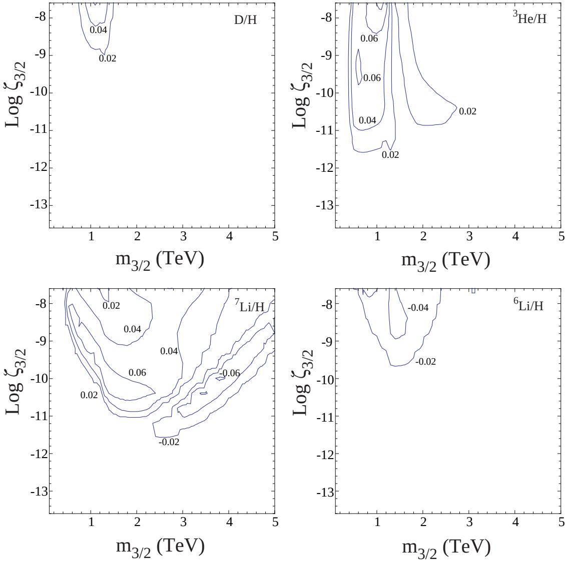


Figure: *For the reaction 21 ($n^4\mathrm{He} \rightarrow npt$, $\epsilon = 20\%$), showing the effects on deuterium (upper left), ^{3}He (upper right), ^{7}Li (lower left) and ^{6}Li (lower right).*

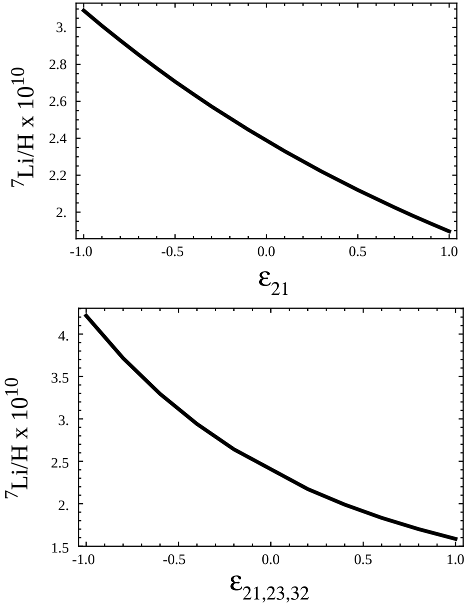


Figure: *The* ^{7}Li *abundance as a function of* ϵ. $\Gamma_i' = (1 + \epsilon_i)\Gamma_i^0$.

χ^2 analysis

$$\chi^2 \equiv \left(\frac{Y_p - 0.256}{0.011}\right)^2 + \left(\frac{\frac{D}{H} - 2.82\times10^{-5}}{0.27\times10^{-5}}\right)^2 + \left(\frac{\frac{^7\mathrm{Li}}{H} - 1.23\times10^{-10}}{0.71\times10^{-10}}\right)^2 + \sum_i s_i^2\,,$$

where $\Gamma_i' = (1 + \epsilon_i\, s_i)\Gamma_i^0$

- $\frac{\mathrm{D}}{\mathrm{H}}$: $(2.82 \pm 0.21)\times 10^{-5}$ (high-redshift quasar absorption systems)
  $(2.52 \pm 0.17)\times 10^{-5}$ (SBBN)
- Y_p: 0.256 ± 0.011 (observations)
  0.2487 ± 0.0002 (SBBN)

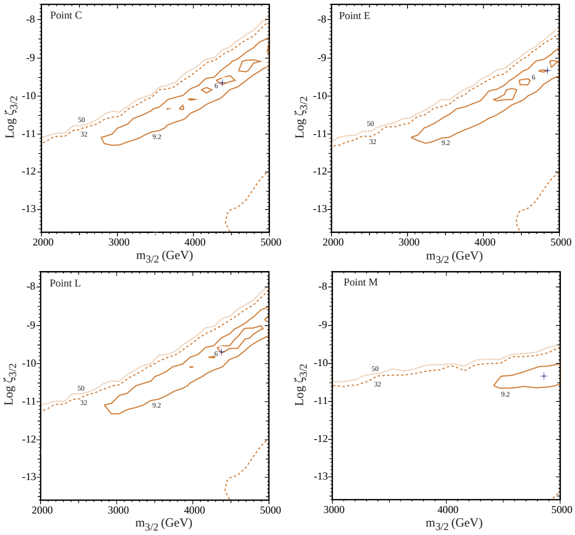


Figure: *Contours of the χ^2 function in the $(m_{3/2}, \zeta_{3/2})$ planes for the benchmark CMSSM scenarios C (upper left), E (upper right), L (lower left) and M (lower right), incorporating the uncertainties.*

Table: Results for the best-fit points for CMSSM benchmarks C, E, L and M. The second set of results for C and M correspond to the globular cluster value for primordial ^{7}Li/H. The third and fourth entries for point C correspond to the higher adopted uncertainty for D/H ($\pm 0.53 \times 10^{-5}$) in field stars and to the globular cluster ^{7}Li abundances, respectively.

	$m_{3/2}$[GeV]	$\mathrm{Log}_{10}(\zeta_{3/2}/[\mathrm{GeV}])$	Y_p	D/H ($\times 10^{-5}$)	^{7}Li/H ($\times 10^{-10}$)	$\sum s_i^2$	χ^2
BBN	——	——	0.2487	2.52	5.12	——	31.7
C	4380	-9.69	0.2487	3.15	2.53	0.26	5.5
E	4850	-9.27	0.2487	3.20	2.42	0.29	5.5
L	4380	-9.69	0.2487	3.21	2.37	0.26	5.4
M	4860	-10.29	0.2487	3.23	2.51	1.06	7.0
C	4680	-9.39	0.2487	3.06	2.85	0.08	2.0
M	4850	-10.47	0.2487	3.11	2.97	0.09	2.7
C	3900	-10.05	0.2487	3.56	1.81	0.02	2.8
C	4660	-9.27	0.2487	3.20	2.45	0.16	1.1

But recall that we only have 1 d.o.f.

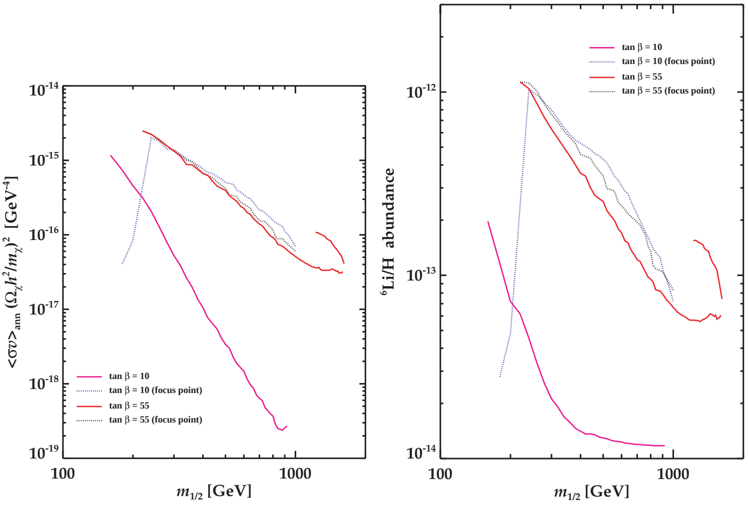
Nevertheless, for $\chi^2 \sim 5.5$, alleviate ^{7}Li from a 4- or 5-σ problem to a $\lesssim 2$-σ issue.

$^6\mathrm{Li}$ problem and residual dark matter annihilations

Idea: *$^6\mathrm{Li}$ abundance is very small, maybe hadronic and electromagnetic showers from dark matter annihilations after freeze-out are enough to cure the $^6\mathrm{Li}$ problem, while leaving the other light element abundances almost unaffected.*

$$
\begin{aligned}
p_{\mathrm{nonthermal}}{}^{4}\mathrm{He} \quad &\rightarrow \quad {}^{3}\mathrm{H}_{\mathrm{nonthermal}} + \cdots \\
& \quad\ \ {}^{3}\mathrm{H}_{\mathrm{nonthermal}} + {}^{4}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + n
\end{aligned}
$$

$$
\Delta Y({}^{6}\mathrm{Li}) \sim 7 \times 10^{-13} \left(\frac{\langle \sigma v \rangle_{\mathrm{ann}}}{10^{-26}\ \mathrm{cm}^{3}\,\mathrm{s}^{-1}} \right) \left(\frac{300\ \mathrm{GeV}}{m_{\chi}} \right)^{2}
$$



10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
<σv>ann (Ωχh²/mχ)² [GeV⁻⁴]
tan β = 10
tan β = 10 (focus point)
tan β = 55
tan β = 55 (focus point)
100
1000
m1/2 [GeV]
10^-12
10^-13
10^-14
⁶Li/H abundance
tan β = 10
tan β = 10 (focus point)
tan β = 55
tan β = 55 (focus point)
100
1000
m1/2 [GeV]

Conclusions and future work

- heavy particle decays or/and annihilations scenarios are constrained by BBN
- $^{7}\mathrm{Li}$ and/or $^{6}\mathrm{Li}$ problems point to new physics?
- uncertainties of non-thermal nuclear reaction rates needed to be pin down to help constrain the scenarios better
- Future work: both decay and annihilations, bound state effects

Thank You :)