Outline

- Cosmological data and Big-Bang Nucleosynthesis (BBN) constraints
- Lithium puzzle
- A possible explanation and consequences for particle physics and cosmology
- Summary-Prospects
\[ \Omega_{tot} = 1.02 \pm 0.02 \]

\[ \rho_c = \frac{3H_0^2}{8\pi G} \]

\[ \Omega_m h_0^2 = 0.127 \pm 0.008 \]

\[ \Omega_B h_0^2 = 0.0223 \pm 0.0007 \]

\[ \Omega_{DM} h_0^2 = \Omega_m h_0^2 - \Omega_B h_0^2 = 0.104 \pm 0.008 \]

This value of \( \Omega_B \) agrees quite well with the BBN predictions for the abundance of \(^4\text{He}, \ D, \ ^3\text{He}\), but not so good ... with \(^7\text{Li}\) and \(^6\text{Li}\)
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 $\sim 10^{-10}$

- $^2\text{H}$ in quasars absorption systems (and locally):
  abundance by number $\sim 3 \times 10^{-5}$

- $^3\text{He}$ observed in solar wind, meteorites, and in ISM:
  abundance by number $\sim 10^{-5}$
**Neutrino decoupling prepares the beginning of BBN**

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

**BUT ... BBN begins after the D formation**

\[ p + n \rightarrow D + \gamma \quad \Gamma_{\text{prod}} \sim n_B \sigma \quad \text{Deuterium bottleneck} \]

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

Nucleosynthesis begins when

\[ \Gamma_{\text{prod}} \sim \Gamma_{\text{dest}} \Rightarrow \frac{n_\gamma e^{-E_B/T}}{n_b} \sim 1 \Rightarrow T_{\text{BBN}} \sim 100 \text{ KeV} \ (t_{\text{BBN}} = 180 \text{ s}) \]

At this time \( n/p \approx \frac{1}{7} \)

**BBN ends when there are no more neutrons**

BBN is completed when all neutrons present at \( t_{\text{BBN}} = 180 \text{ s} \) have been cooked into nuclei.

This happens at \( t \sim 1000 \text{ s} \).
Main BBN reactions

$A=5,8$ bottlenecks
Light elements production

\[
\begin{align*}
\tau_n &= 887 \text{ sec} \\
N_v &= 3 \\
\Omega_N &= 0.01 h^{-2}
\end{align*}
\]

Sarkar, hep-ph/9602260
Cyburt et al., astro-ph/021258

WMAP value

\[ \Omega_B h^2 \]

\[ \frac{Y}{D/H} \]

\[ \frac{\text{He}}{H} \]

\[ \frac{\text{Li}}{H} \]

baryon-to-photon ratio \( \eta \)
Li problem

$^7$Li data 3 time less than BBN prediction

$^6$Li data 1000 time more than BBN prediction

pre-Galactic PopIII stars can explain $^6$Li
Possible solutions

for \(^{7}\text{Li}\) isotope

- Stelar parameters like \(T, g\)
  - Can account for a factor of 2

- Nuclear rates, for example \(^{3}\text{He} \, (\alpha,\gamma) \,^{7}\text{Be}\)
  - Restricted by solar model

- Particle decays during and after BBN
SUSY Candidates for Dark Matter

- Sneutrino (constrained severely by LEP2 data and direct data)
- Neutralino
- Gravitino, the supersymmetric partner of graviton the mediator of gravity
Gravitino DM scenarios in SUSY models

- Usually the LSP is either the neutralino or stau, and neutralino is the DM particle.

- If gravitino is the LSP, the NSP is either neutralino or stau (for large $A_0$, stop can also play the role of NSP. Y. Santoso’s talk for details).

- In this case we must consider the effect of the “late” gravitational decays $\text{NSP} \rightarrow \text{LSP} + X$, eg $\chi \rightarrow \tilde{G}\gamma$ or $\tilde{\tau} \rightarrow \tilde{G}\tau$.

\[
\Gamma_{\chi \rightarrow \tilde{G}\gamma} \approx \frac{1}{48\pi} \frac{1}{M_P^2} \frac{m_\chi^5}{m_{3/2}^2} \quad \implies \quad \tau \lesssim O(10^8)\text{s}
\]
.. if gravitino is the LSP

\[ h_0 = 0.73 \pm 0.03 \]

\[ H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

\[ \Gamma_{\chi, \tilde{\tau}} \sim \frac{1}{M_P^2} \]
NSP lifetimes in $s$

$m_{3/2} = 100 \text{ GeV}, \tan \beta = 10, \mu > 0$

$m_{3/2} = 0.2m_0, \tan \beta = 10, \mu > 0$
\( \chi \) NSP

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

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

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

(a)

(b)

(c)

Figure 1: Hadronic 3-body decays...
$\tilde{\tau}$ NSP

$\tilde{\tau} \rightarrow \tilde{G} \tau$

(a) $\tilde{G}$

(b) $\tilde{G}$

(c) $\tilde{\chi}$

(d) $\tilde{G}$

V.C. Spanos, Univ. of Minnesota VCMSSM 39
Method

- Calculate the partial and the total widths for the NSP decays
- Calculate the NSP relic density, that eventually will become gravitino relic density
- 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
Bound-state effects for stau NSP

* $\tilde{\tau}$ NSP can form bound states with various nuclei, $^4$He, $^7$Li and $^7$Be

* The presence of these bound states changes the light elements abundance in two ways:
  1. reduces the Coulomb barrier of the nuclear reactions
  2. enhances particular channels, for example $^4$He($d, \gamma$)$^6$Li

Similar for $^3$He($\alpha, \gamma$)$^7$Be and $^7$Li($p, \gamma$)$^8$Be.

Pospelov, hep-ph/0605215
**Procedure**

- Solve numerically the corresponding Boltzmann eqs for the BS abundances
  Kohri, Takayama, hep-ph/0605243

- We apply this for BS effects associated with $^4\text{He}$, $^7\text{Li}$ and $^7\text{Be}$ nuclei

- The BS effects affect significantly the values of various cross-sections and consequently the light elements abundances.
w/o BS

$m_{3/2} = 100 \text{ GeV}, \tan \beta = 10, \mu > 0$

$^7\text{Li} = 4.3$

$^3\text{He}/^4\text{He} = 1$

$^6\text{Li}^7\text{Li} = 0.15$

$D = 4.0$

$4.0$

$2.2$

$0.15$

$0.01$

w/ BS

$m_{3/2} = 100 \text{ GeV}, \tan \beta = 10, \mu > 0$

$^7\text{Li} = 4.3$

$^3\text{He}/^4\text{He} = 1$

$^6\text{Li}^7\text{Li} = 0.15$

$D = 4.0$

$4.0$

$2.2$

$0.15$

$0.01$

Compatible with BBN
Rich Cyburt, John Ellis, Brian Fields, Keith Olive, VS, JCAP 0611 (2006) 014

w/o BS

\[ m_{3/2} = 0.2m_0, \tan \beta = 10, \mu > 0 \]

w/ BS

\[ m_{3/2} = 0.2m_0, \tan \beta = 10, \mu > 0 \]

\( ^7\text{Li} = 4.3 \)

\( ^6\text{Li}/^7\text{Li} = 0.15 \)

\( ^6\text{Li}/^7\text{Li} = 0.15 \)

\( \mu = 0.2 \)

\( \mu = 0.2 \)

Compatible with BBN

Solution of Li problem
\[ m_{3/2} = 0.2m_0, \tan \beta = 57, \mu > 0 \]

\[ ^7\text{Li} = 4.3 \]

\[ m_0 = 0.01 \text{ (GeV)} \]

\[ m_{1/2} = \text{ (GeV)} \]

The meanings of the other lines and contours are explained in the text.

\[ \mathbb{B} \] Compatible with BBN
\[ \text{w/o BS} \]
\[ m_{3/2} = m_0, A_0 = 3 - \sqrt{3}, \mu > 0 \]

\[ \text{w/ BS} \]
\[ m_{3/2} = m_0, A_0 = 3 - \sqrt{3}, \mu > 0 \]

- \( \text{\textcolor{yellow}{Compatible with BBN}} \)
We present a new BBN calculation including the effects of the EM and HD decays of the NSP.

Including the **bound-states effects** in the stau NSP case.

NSP decays probably **can not** solve the lithium problem.

The bound states effects for the stau NSP case are important and exclude regions of the parameter space with lifetimes longer than $10^4$ s. And can explain the lithium isotopes discrepancies for $\tau \leq 1000$ s !

Work in progress and for the future:

- Unstable gravitino effects of neutralino DM models
- Detailed scan of the parameter space
- SUSY searches at LHC