Cosmological models with long-lived SUSY particles

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Dark Matter?

Einstein's Cosmological Constant
Or unknown scalar field?

Dark side?

74% Dark Energy

22% Dark Matter

$\Omega_{\text{CDM}} h^2 \leq 0.1$

4% Atoms

Light side (Baryon) 4%

Dark side?

Unknown SUSY particles?

http://map.gsfc.nasa.gov/media/060916
Realistic candidates of particle dark matter in SUSY/SUGRA

- **Neutralino** $\chi$ ($\sim$100% Bino or photino)
  
  Most famous Lightest Supersymmetric Particle (LSP) with $m_\chi \sim$100GeV (appears even in global SUSY)

- **Gravitino** $\psi_\mu$
  
  super partner of graviton with spin 3/2 and $m_{3/2} \lesssim$ 100GeV (massive only in SUGRA (local SUSY))
Contents

• Introduction to Supersymmetry (SUSY) and Supergravity (SUGRA)

• Lightest SUSY Particle (LSP) Dark Matter (DM) in Minimal SUSY Standard Model (MSSM)

• LSP DM in Constrained MSSM (CMSSM) and mSUGRA

• Cosmological and astrophysical constraints on LSP and Next LSP (NLSP)
Introduction to SUSY

**Supersymmetry (SUSY)**

- Solving “Hierarchy Problem”
- Realizing “Coupling constant unification in GUT”

<table>
<thead>
<tr>
<th>Fermion</th>
<th>Boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark</td>
<td>squark</td>
</tr>
<tr>
<td>lepton</td>
<td>slepton</td>
</tr>
<tr>
<td>photino</td>
<td>photon</td>
</tr>
</tbody>
</table>

Depending on SUGRA models

- Highly model-dependent and my review is insufficient

See Kawasaki, Senami, Nakayama (07)
MSSM

- Minimal extension of Standard Model to supersymmetry including two Higgs doublets

\[ W_{\text{MSSM}} = -\bar{u}y_u QH_u + \bar{d}y_d QH_d + \bar{e}y_e LH_d \]

\( \bar{d}y_d QH_u^* \) because of holomorphism in super pot.

\[
H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}
\]

- 105 masses, phases and mixing angles!!!
CMSSM

Constrained MSSM

Simplified into only five parameters from 105:

1. Common scalar mass at GUT scale: $m_0$
2. Unified gaugino (fermion) mass at GUT scale: $m_{1/2}$
3. Ratio of Higgs vacuum expectation values: $\tan \beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$
4. Higgs/higgsino mass parameter (or its signature): $\mu$
5. tri-linear coupling $A_0$
### Super particles in CMSSM

<table>
<thead>
<tr>
<th>Names</th>
<th>Spin</th>
<th>$P_R$</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_u^0$ $H_d^0$ $H_u^-$ $H_d^-$</td>
<td>$h^0$ $H^0$ $A^0$ $H^\pm$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>−1</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>$\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$</td>
<td>$\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>−1</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
<td>(same)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\mu}_L$ $\tilde{\mu}<em>R$ $\tilde{\nu}</em>\mu$</td>
<td>(same)</td>
</tr>
<tr>
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<td>$\tilde{\tau}_L$ $\tilde{\tau}<em>R$ $\tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_1$ $\tilde{\tau}<em>2$ $\tilde{\nu}</em>\tau$</td>
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<td>neutralinos</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$</td>
<td>$\tilde{N}_1$ $\tilde{N}_2$ $\tilde{N}_3$ $\tilde{N}_4$</td>
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<tr>
<td>charginos</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{W}^\pm$ $\tilde{H}_u^+$ $\tilde{H}_d^-$</td>
<td>$\tilde{C}_1^\pm$ $\tilde{C}_2^\pm$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>−1</td>
<td>$\tilde{g}$</td>
<td>(same)</td>
</tr>
<tr>
<td>goldstino (gravitino)</td>
<td>1/2 (3/2)</td>
<td>−1</td>
<td>$\tilde{G}$</td>
<td>(same)</td>
</tr>
</tbody>
</table>

*Martin, “A Supersymmetry Primer”*
Running of Renormalization Group (RG) Equation in CMSSM

Negative Higgs mass term

Martin, “A Supersymmetry Primer”
Mass spectrum in CMSSM

\[
\begin{array}{cccc}
\frac{H^\pm}{H^0 A^0} & \frac{\tilde{N}_4}{\tilde{N}_3} & \tilde{C}_2 & \tilde{g} \\
\tilde{t}_2 & b_\text{b} & b_\text{1} & d_L \tilde{u}_L \\
\tilde{t}_1 & & & \tilde{u}_R \tilde{d}_R \\
\tilde{t}_1 & \tilde{e}_L & \tilde{\nu}_e & \tilde{\nu}_\tau \\
\tilde{\tau}_2 & & & \tilde{\tau}_1 \\
\tilde{\tau}_1 & & & \tilde{\tau}_1 \\
\end{array}
\]
Thermal freezeout

Boltzmann equation

\[ \frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle \left[ (n_\chi)^2 - (n_\chi^{eq})^2 \right] \]

\[ n_\chi \frac{3H}{\langle \sigma v \rangle_{\text{freezeout}}} \]

\[ T_{\text{freezeout}} \approx \frac{m_\chi}{25} \]

\[ \Omega_\chi h^2 \approx 0.1 \left( \frac{\langle \sigma v \rangle}{(0.1/\text{TeV})^2} \right)^{-1} \]

\[ \Omega \text{ does not depend on } m_\chi \]

Predicting TeV Physics!!!
LSP (LOSP) in CMSSM

Neutralino or Scalar tau lepton (Stau) is the Lightest Ordinary SUSY Particle (LOSP)

Ellis, Olive, Santoso, Spanos (2003)
Supergravity (SUGRA)

- Local theory of SUSY (predicting gravitino)
- Models of supersymmetry breaking (gravitino mass production by eating goldstino which appears in spontaneous symmetry breaking)
- Including general relativity (Unifying space-time symmetry with local SUSY transformation)
Gravity mediated SUSY breaking model

Observable sector
quark, squark, ...

Hidden sector
SUSY
$F \sim 10^{20-21} \text{GeV}^2$

Masses of squarks and sleptons

\[ m_{\tilde{q}}, m_{\tilde{t}} = \frac{F}{M_{pl}} = 10^2 - 10^3 \text{ GeV} \]

$F = 10^{20} - 10^{21} \text{ GeV}$

Gravitino mass

\[ m_{3/2} = \frac{F}{M_{pl}} = 10^2 - 10^3 \text{ GeV} \]
SUSY Breaking Models II

- **Gauge-mediated SUSY breaking model**

**Observable sector**
quark, squark, ...

**SUSY breaking sector**

**Messenger sector**

\[ m_{3/2} \sim F / M_p < 10 \text{GeV} \]

Lightest SUSY particle (LSP) may be necessarily the gravitino
Signature of SUSY particles related with Astrophysics and Cosmology

- Direct detection
- Indirect detection
- Big-bang nucleosynthesis (BBN)
- Cosmic Microwave Background (CMB)
- Diffused gamma-ray background
Direct detection of LSP (LOSP) in CMSSM

Annual modulation

June moving around the sun 30km/s

220km/s

December

Gelmini, arXiv:0810.3733v1
Indirect detection of LSP (LOSP)

Annihilation signals of neutralino at Galaxy Center, the Sun, near solar system, etc...

Quite a lot of groups have contributed this topic

\[ \chi \chi \rightarrow WW, ZZ, Z\gamma, 2\gamma, e^+e^- \]
\[ W, Z \rightarrow \text{broad spectrum of } \gamma, e^+e^-, pp \]

Or gravitino/sneutrino decay with R-parity violation

Ibarra, Tran (08), Ishiwata, Matsumoto, Moroi (08), Chen, Takahashi (08)

Or hidden gauge boson decay with kinetic mixing

Chen, Takahashi, Yanagida (08)

- Gamma-ray from a point source
- Anti-proton
- Positron
- 511 keV line gamma
- Neutrinos
- Synchrotron radio
- WMAP HAZE component
- Nucleosynthesis
- etc…
Positron Excess  (PAMELA satellite reported)

Anti-proton flux (PAMELA satellite reported)


Consistent with secondary production of pp or Leptonic DM? by Chen-Takahashi (08)
Gamma-ray anomaly at Galactic Center
(EGRET satellite reported)

Hunter et al (97)
Positron excess in wino DM annihilation

Diffusion model
Fitted to B/C ratio

Solar modulation?

Hisano, Kawasaki, Kohri, Nakayama (08) in preparation
See Kazunori Nakayama’s poster talk
Gamma-ray signal in wino DM annihilation


See Kazunori Nakayama’s poster talk
Big-Bang Nucleosynthesis (BBN)

Very strong cosmological tools to study long-lived particles with lifetime of $0.01 \text{ sec} - 10^{12} \text{ sec}$

Theoretical predictions are constrained by observational D, 3He, $^4$He, $^6$Li and $^7$Li abundances with their conservatively-large errors.
Massive particle decaying during/after BBN epoch produces high energy photons, hadrons, and neutrinos

Destruction/production/dilution of light elements

Severer constraints on the number density

Ellis, Kim, Nanopoulos, (1984); Ellis, Nanopoulos, Sarkar (1985)
Kawasaki and Sato (1987)
Kawasaki, Moroi (1994), Sigl et al (95), Holtmann et al (97)
Kawasaki, Kohri, Moroi(04), Jedamzik (06)
Radiative decay scenario

\[ X = \psi_\mu \]

1) Electro-magnetic cascade

\[
\gamma + \gamma_{BG} \rightarrow e^+ + e^- \\
\gamma + e^{-}_{BG} \rightarrow \gamma + e^-, \quad e^- + \gamma_{BG} \rightarrow e^- + \gamma \\
\gamma + \gamma_{BG} \rightarrow \gamma + \gamma
\]

2) many soft photons are produced

3) Photo-dissociation of light elements

\[
D + \gamma \rightarrow p + n, \\
^4\text{He} + \gamma \rightarrow ^3\text{He} + n, \quad T + p, \\
^3\text{He} + \gamma \rightarrow D + p + n, \quad \text{etc.}
\]
Hadronic decay

Hadronic decay

$B_h \approx \frac{\alpha}{4\pi} \approx 10^{-3}$

Two hadron jets with
$E_{\text{jet}} = \frac{m_x}{3}$

One hadron jet with
$E_{\text{jet}} = \frac{m_x}{2}$
(I) Early stage of BBN (before/during BBN)

Extraordinary inter-conversion reactions between $n$ and $p$

cf)  

$$n + \pi^+ \rightarrow p + \pi^0$$  

$$p + \pi^- \rightarrow n + \pi^0$$

\[
\Gamma_{n \leftrightarrow p} = \Gamma_{\text{weak}} + \Gamma_{\text{strong}}
\]

Hadron induced exchange

\[
\Gamma_{n \leftrightarrow p} \uparrow \Rightarrow n/p \uparrow
\]

Even after freeze-out of $n/p$ in SBBN

More He4, D, Li7 …
(II) Late stage of BBN
Hadronic showers and "Hadro-dissociation"

S. Dimopoulos et al. (1988)
Kawasaki, Kohri, Moroi (2004)
Non-thermal Li, Be Production by energetic hadrons

\[ N + ^4\text{He} \rightarrow \begin{cases} ^3\text{He} + \text{X} \\ T + \text{X} \end{cases} \]

\[ N + ^4\text{He} \rightarrow ^4\text{He}^* + \text{X} \]

1. T(He3) - He4 collision

\[ T + ^4\text{He} \rightarrow ^6\text{Li} + n \quad [8.4 \text{ MeV}] \]

\[ ^3\text{He} + ^4\text{He} \rightarrow ^6\text{Li} + p \quad [7.0 \text{ MeV}] \]

2. He4 - He4 collision

\[ ^4\text{He} + ^4\text{He} \rightarrow ^6\text{Li}, ^7\text{Li}, ^7\text{Be} + \ldots \]
Massive particle $X$

Upper bounds on $m_X Y_X$ in both photodissociation and "hadrodiassociations" scenario

$Y_X \equiv n_X / s$

Kawasaki, Kohri, Moroi (04)
Neutralino LSP and gravitino “NLSP”
Upper bound on reheating temperature

\[ T_R \approx 10^9 \text{GeV} \left( \frac{Y_{3/2}}{10^{-12}} \right) \]

\[ m_{3/2} \approx 500 \text{GeV} \left( \frac{\tau_{3/2}}{4 \times 10^5 \text{sec}} \right)^{-1/3} \]

\[ \tau - \approx \frac{51}{3} \frac{3}{2} \frac{3}{2} \frac{500}{4} \frac{1}{10} \text{sec} \]

\[ \text{Case 1} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{1/2} )</td>
<td>300 GeV</td>
</tr>
<tr>
<td>( m_0 )</td>
<td>141 GeV</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>0</td>
</tr>
<tr>
<td>( \tan \beta )</td>
<td>30</td>
</tr>
<tr>
<td>( \mu_H )</td>
<td>389 GeV</td>
</tr>
<tr>
<td>( m_{\chi_1^0} )</td>
<td>117 GeV</td>
</tr>
<tr>
<td>( \Omega_{\text{LSP}}^{(\text{thermal})} h^2 )</td>
<td>0.111</td>
</tr>
</tbody>
</table>
Neutralino (bino) NLSP and gravitino LSP
Gravitino LSP and thermally produced neutralino (Bino) "NLSP" scenario

\[ \Gamma(\tilde{B} \rightarrow \psi \mu \gamma) = \frac{\cos^2 \theta_W}{48\pi M_X^2} \frac{m_{\tilde{B}}^3}{m_{3/2}^2} (1 - x_{3/2}^2)^3 (1 + 3x_{3/2}^2) \]

\[ \tau \equiv \frac{m_3^2}{2} \left( \frac{m_{pl}^2}{m_{NLSP}^5} \right) \]

Relic abundance

\[ Y_B = 4 \times 10^{-12} \times \left( \frac{m_{\tilde{B}}}{100 \text{ GeV}} \right) \]

No allowed region for DM density

Feng, Su, and Takayama (03)

Steffen (06)

Kawasaki, Kohri, Moroi, Yotsuyanagi (08)
Sneutrino NLSP and gravitino LSP scenario

Stable (left-handed) sneutrino was excluded by the direct detection experiments because of its large cross section directly-coupled with W/Z bosons.

NLSP (left-handed) sneutrino should be unstable
Gravitino LSP and thermally produced sneutrino NLSP scenario

Relic abundance

\[ Y_\tilde{\nu} \simeq 2 \times 10^{-14} \times \left( \frac{m_\tilde{\nu}}{100 \text{ GeV}} \right) \]

Kanzaki Kawasaki, Kohri, Moroi (06)
Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

No allowed region for DM density with 100GeV sneutrinos
Stau NLSP and gravitino LSP scenario

Stable stau with weak-scale mass \((<1\text{TeV})\) was excluded by the experiments of ocean water

NLSP stau should be unstable

Bound-state effect (see next)
Candidates of long-lived CHAMP in modern cosmology

stau, stop ...

“CHAMP recombination” with light elements

\[ T_c \sim \frac{E_{\text{bin}}}{40} \sim 10\text{keV} \]

\[ (E_{\text{bin}} \sim \alpha^2 m_i \sim 100\text{keV}) \]

See also the standard recombination between electron and proton,

\[ (T_c \sim \frac{E_{\text{bin}}}{40} \sim 0.1\text{eV}, E_{\text{bin}} \sim \alpha^2 m_e \sim 13.6\text{eV}) \]

CHAMP captured-nuclei, e.g., \((C, ^4\text{He})\) changes the nuclear reaction rates dramatically in BBN
Pospelov's effect


- CHAMP bound state with $^4$He enhances the rate

$$D + (^4\text{He}, C^-) \rightarrow ^6\text{Li} + C^-$$

- Enhancement of cross section

$$\sim \left( \frac{\lambda_\gamma}{a_{\text{Bohr}}} \right)^5 \sim (30)^5 \sim 10^{7-8}$$

Confirmed by Hamaguchi et al (07), hep-ph/0702274

Catalysis BBN is dangerous!!!
Stau NLSP and gravitino LSP Scenario in gauge mediation

Relic abundance

\[ Y_\tilde{\tau} \approx 7 \times 10^{-14} \times \left( \frac{m_\tilde{\tau}}{100 \text{ GeV}} \right) \]

Kawasaki, Kohri, Moroi PLB 649 (07) 436
Stau NLSP and axino/flatino LSP in DFSZ axion models in Gravity Mediation

Chun, Kim, Kohri, and Lyth (08)

Decaying “flatons” reheats the universe and produce staus

\[ T_R \sim O(10) \text{ GeV} \]

Contrary to gravitino LSP models, lifetime of stau is very short due to milder suppression (\( \propto F_a^{-2} \)) and many couplings.

\[ 10^{-8} \text{ sec} \lesssim \tau_{\tilde{\tau}} \lesssim 10^{-2} \text{ sec} \]

No BBN Catalysis

Stau can be found in LHC!!!
Lifetime of stau NLSP decaying into axino LSP

Chun, Kim, Kohri and Lyth (08)
Can we distinguish gravitino from axino in LHC?

Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (05)
10m
$\tau \sim 10^{-7}\text{sec}$

Large Hadron Collider (LHC)

ATLAS detector in CERN, Geneva, Switzerland
Place another stopper near ATLAS or CMS to stop long-lived charged SUSY particles (even for $c\tau > 10$ m)

- **5 m Iron wall** Hamaguchi, Kuno, Nakaya, and Nojiri (04)
- **Water tank** Feng and Smith (04)
- **Surrounded rock** De Roek, Ellis, Gianotti, Mootgat, Olive and Pape (05)
Lithium Problem

See also Keith Olive’s talk

If we adopted smaller systematic errors for observational data for $^6$Li and $^7$Li, the theoretical values do not agree with those observational ones.
\[ SBBN \]

\[
\begin{align*}
\gamma & \equiv (4-5) \times 10^{-10} \\
\gamma & \equiv 5 \times 10^{-5}
\end{align*}
\]
Lithium 7

**a factor of two or three smaller !!!**

- Expected that there is little depletion in stars.

\[
^7\text{Li} / \text{H} = 2.19^{+2.2}_{-1.1} \times 10^{-10} \ (1\sigma)
\]

Bonifacio et al. (2002)

\[
^7\text{Li} / \text{H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \ (1\sigma)
\]

Melendez, Ramirez (2004)

\[
^7\text{Li} / \text{H} = \ (1\sigma)
\]

Ryan et al. (2000)
Lithium 6

- Observed in metal poor halo stars in Pop II
- $^{6}\text{Li}$ plateau?

Astrophysically, factor-of-two depletion of $^{7}\text{Li}$ needs a factor of $O(10)$ $^{6}\text{Li}$ depletion (Pinsonneault et al '02)

$^{6}\text{Li} / ^{7}\text{Li} = 0.022 - 0.090$

$^{7}\text{Li} / \text{H} \approx (1.1 - 1.5) \times 10^{-10}$
still disagrees with SBBN

We need more primordial $^{6}\text{Li}$?
Can decaying particles solve the Li Problem?

- Neutralino LSP and stau NLSP with small mass deference (<100 MeV)  
  Bird, Koopmans, Pospelov (07), Jittoh et al (07, 08)

- Residual annihilation of wino-like neutralino LSP with more massive gravitino  
  Hisano et al (08)  
  See K. Nakayama’s RESCEU talk

- Stop NLSP and gravitino LSP scenario  
  Kohri and Santoso (08)
Residual annihilation of wino LSP

Hisano, Kawasaki, Kohri, Nakayama (08)
See Kazunori Nakayama’s RESCEU talk

• Non-thermal production of wino LSP by decaying massive such as gravitinos (> O(10) TeV)

\[ \psi_\mu \rightarrow W + \tilde{\nu} \]

• Annihilating even after wino’s freeze-out time with its larger annihilation rate than bino’s

\[ \langle \sigma v \rangle >> 3 \times 10^{-26} \, cm^3 / s \]

Even during/after BBN epoch!!!
Reduction of $^7$Li and production of $^6$Li

Jedamzik (04), Cumberbatch et al. (08)

- Copious neutrons and tritiums are produced in hadronic shower process with decay/annihilation
- Reducing Be7 through
  
  $^7$Be(n,p)$^7$Li(p,$^4$He)$^4$He
  
  (Li is produced later by $^7$Be + e$^-$ → $^7$Li + $\nu_e$)
- Tritium scatters off the background He4 and produces Li6

$^7$Be(n,p)$^7$Li(p,$^4$He)$^4$He

$^7$Li is produced later by $^7$Be + e$^-$ → $^7$Li + $\nu_e$

$T+4He \rightarrow ^6$Li+n
Residual annihilation of wino LSP

We need nonthermal wino production by gravitino decay
Stop NLSP and gravitino LSP

- Stop is confined into “messino” after QCD phase transition

- Second annihilation of stopa occurs just after QCD phase transition through strong interaction

- Stop number density is highly suppressed, but it is appropriate to solve the Li problem

\[ m_f n_f / s \sim 10^{-14} \text{ GeV} - 10^{-13} \text{ GeV} \]
Stop NLSP and gravitino LSP

Kohri and Santoso arXiv:0811.1119v1 [hep-ph]
Conclusion

• Direct and indirect detections of DM will become more attractive in near future to get information for SUSY and SUGRA

• BBN is a strong tool to investigate the long-lived SUSY particles, such as gravitino, neutralino, stau, stop, or axino

• In neutralino LSP and unstable gravitino scenario in gravity mediated SUSY breaking models, the constraint on reheating temperature after primordial inflation is very stringent,

\[ T_R \leq 3 \times 10^5 \text{GeV} - 10^7 \text{ GeV} \]

(for \( m_{3/2} = 100 \text{ GeV} - 1\text{TeV} \))

• In gauge mediation, thermal-relic NLSP fails to produce DM gravitino density for natural scales of NLSP masses (100GeV - 1TeV). We need thermal or nonthermal production of LSP gravitino by the decay of Inflaton, moduli etc.

See Moroi, Murayama, Yamaguchi (93) for thermal production, and Endo, Takahashi, Yanagida (07) for non-thermal production of LSP gravitino.
Another ideas

- positrons produced in pulsars

Hooper, Blasi, Serpico (08)