Weak Scale Gravitino Dark Matter

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K. Ishiwata, S. M., T. Moroi (Phys. Rev. D77, 035004)
K. Ishiwata, S. M., T. Moroi (arXiv:0805.1133)

Topics related to Gravitino dark matter having a weak scale mass!

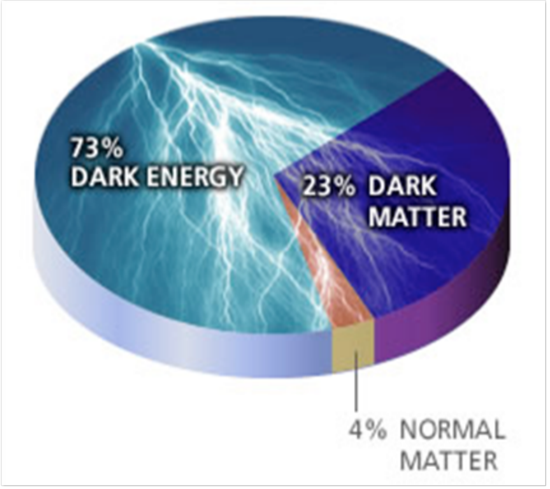
Existence of Dark Matter

Dark Matter and Baryon densities

$$\Omega_{DM}h^2 = 0.1099 \pm 0.0062$$

$$\Omega_b h^2 = 0.02263 \pm 0.00062$$

[WMAP 5yeres (airXiv:0803.0547)]



Existence of Non-baryonic DM

(This result is also supported by BBN)

No Candidate of DM in the SM

(Hot dark matter (ν) is not favored!)

What is DM?

(We have to consider physics beyond the SM)

Dark Matter Candidates

Neutral & Stable

- Supersymmetry
  - Neutralino
  - Gravitino
  - Axino
  - ~~L-sneutrino~~
  - R-sneutrino
- Little Higgs
  - Heavy Photon
- Universal Extra-D
  - 1^{st} KK Photon
  - 1^{st} KK Gravitino
- Gauge-Higgs
  - Anti-periodic mode
- Others
  - Axion
  - Sterile ν

Many people believe

WIMP Dark Matter

$\sigma v(2\text{WIMP} \rightarrow \text{SMs}) \sim \alpha^2/\text{TeV}^2 \sim 1\ (pb)$

$\rightarrow \Omega_{\text{WIMP}} h^2 \sim 0.1\ (pb)/\sigma v \sim 0.1$

However, we focus on

Gravitino Dark Matter,
whose mass is 10 GeV ~ 1 TeV.

The DM is possible to explain

1. Small scale structure problem

OR

2. Cosmic Ray Anomalies.

Productions of the Gravitino DM

→ time

Inflation → **Reheating** → **NLSP decoupled**

Inflation

Gravitino
(Inflaton decay)

It gives a very very severe constraint!

[Endo, Takahashi, and Yanagida, Phys. Rev. D76, 083509 (2007)]

We need some mechanism in a inflation model!

Reheating

Gravitino
(Thermal Scattering)

Gravitino is produced from thermal bath!

In order not to overclose the universe, $T_R < 10^{11}$ GeV!

[Moroi, Murayama, and Yanagida, Phys. Lett. B303, 289(1993)]

NLSP decoupled

Gravitino
(NLSP decay)

NLSP decays after BBN by emitting SM particles!

It gives stringent constraints to the scenario at the TeraScale!

→ Nest Slide

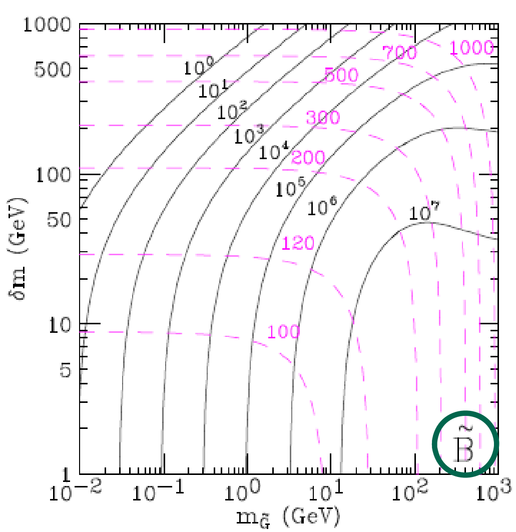
BBN constraints

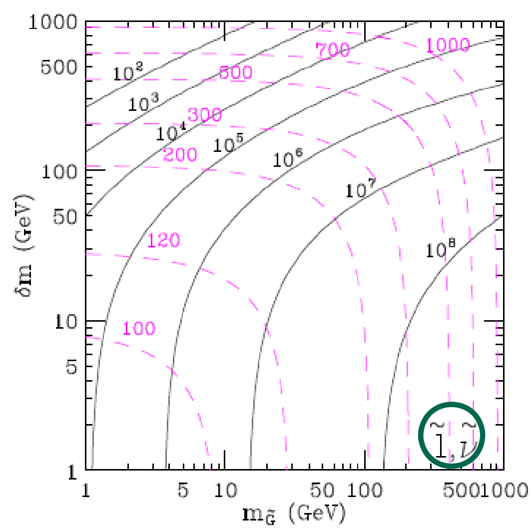
~10^{-8}s ~1s ➡ BBN starts

time

NLSP in thermal equilibrium → **NLSP decoupled (T ~ 10 GeV)** → **NLSP decays into Gravitino**

Life time of NLSP (NLSP = Bino and slepton)





τ_{NLSP} ~ 10^6–10^8 sec. when Gravitino mass is ~ 100 GeV!

BBN constraints

~10^{-8}s ~1s ➡ BBN starts

time

NLSP in thermal equilibrium	NLSP decoupled ($T \sim 10$ GeV)	NLSP decays into Gravitino

Hadronic decay modes are severely constrained by BBN!

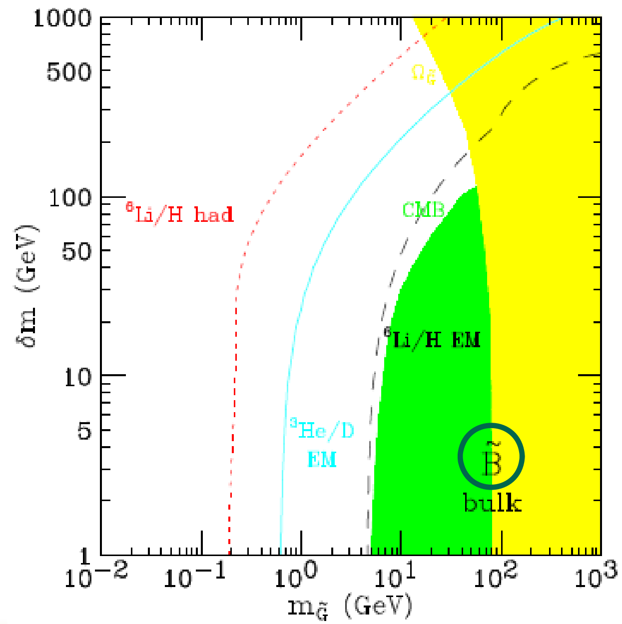
[Kawasaki, Kohri, and Moroi (2005)]

BBN constraints to (Bulk) Bino-like neutralino NLSP

$$\Omega_\chi^{\rm th} h^2 \approx 0.1 \left[\frac{m_\chi}{100\ {\rm GeV}}\right]^2$$

Relic Abundance of the NLSP before it decays into gravitino

[Feng, Su, Takayama, Phys. Rev. D70, (2004)]



BBN constraints

~10^{-8}s ~1s ⇒ BBN starts

time →

NLSP in thermal equilibrium

NLSP decoupled (T ~ 10 GeV)

NLSP decays into Gravitino

Hadronic decay modes are severely constrained by BBN!

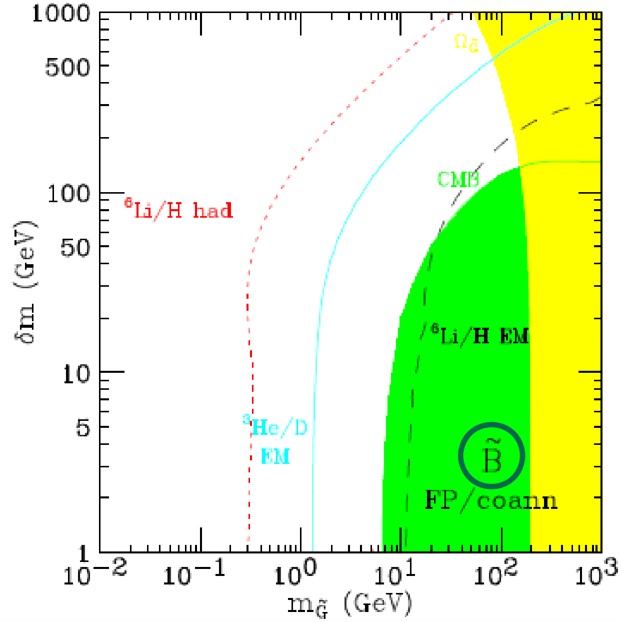
[Kawasaki, Kohri, and Moroi (2005)]

BBN constraints to (FP/coann) Bino-like neutralino NLSP

$$\Omega_\chi^{\rm th} h^2 \approx 0.1 \left[\frac{m_\chi}{200\ \mathrm{GeV}}\right]^2$$

Relic Abundance of the NLSP before it decays into gravitino

[Feng, Su, Takayama, Phys. Rev. D70, (2004)]



BBN constraints

~10^{-8}s ~1s ➡ BBN starts → time

NLSP in thermal equilibrium

NLSP decoupled ($T \sim 10$ GeV)

NLSP decays into Gravitino

Hadronic decay modes are severely constrained by BBN!

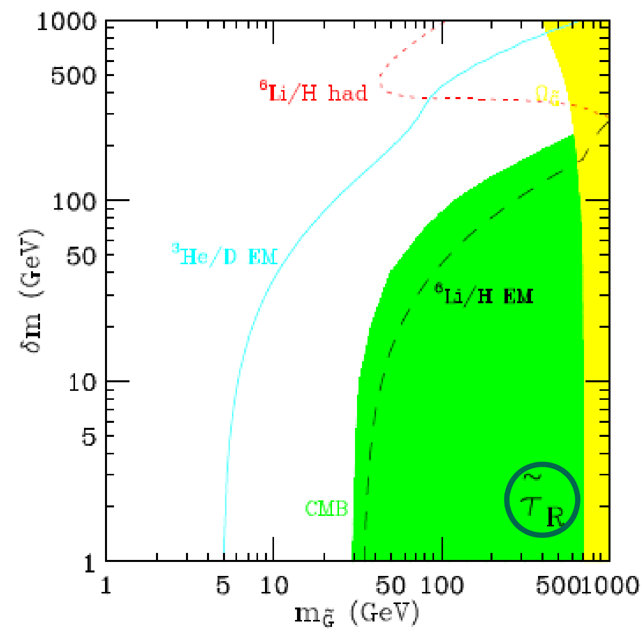
[Kawasaki, Kohri, and Moroi (2005)]

BBN constraints to stau NLSP

$$\Omega^{\rm th}_{\tilde{l}_R} h^2 \approx 0.2 \left[\frac{m_{\tilde{l}_R}}{\rm TeV}\right]^2$$

Relic Abundance of the NLSP before it decays into gravitino

[Feng, Su, Takayama, Phys. Rev. D70, (2004)]



BBN constraints

~10^{-8}s ~1s ➡ BBN starts

time

NLSP in thermal equilibrium

NLSP decoupled (T ~ 10 GeV)

NLSP decays into Gravitino

Hadronic decay modes are severely constrained by BBN!

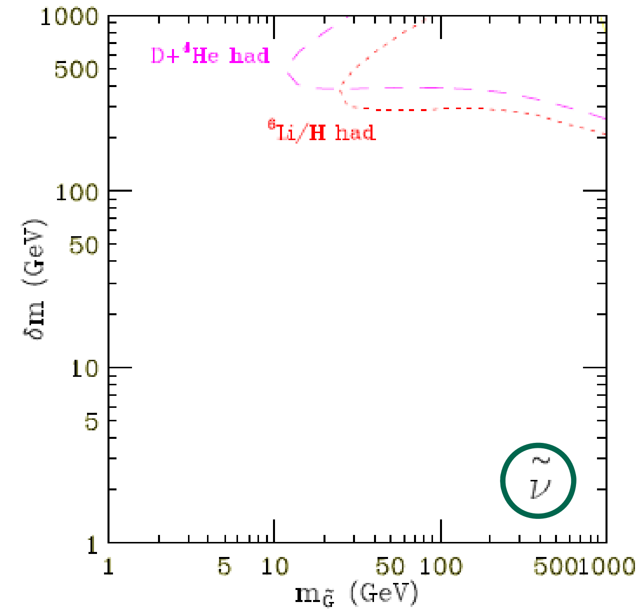
[Kawasaki, Kohri, and Moroi (2005)]

BBN constraints to sneutrino NLSP

$$\Omega_{\tilde{\nu}}^{\rm th} h^2 \approx 0.06 \left[\frac{m_{\tilde{\nu}}}{\rm TeV}\right]^2$$

Relic Abundance of the NLSP before it decays into gravitino

[Feng, Su, Takayama, Phys. Rev. D70, (2004)]



Way out

In order to avoid the BBN constraints
to the weak scale gravitino DM,
we consider following two scenarios.

1. Introduction of weak scale Right handed neutrinos
   ($\tilde{\nu}_R$ = NLSP, MSSM-LSP such as $\tilde{B}$ = NNLSP)

→ Cosmology at the late time can be drastically changed.
→ It is also possible to realize the "SuperWIMP scenario" where all DM abundance is coming from the MSSM-LSP decay.
→ Small scale structure problem can be solved.

2. Introduction of tiny R-parity violating (RPV) interactions

→ Weak scale Gravitino can still be DM.
→ The scenario is compatible with the thermal leptogenesis.
→ The DM can be a source of cosmic rays, because a fraction of the DMs have decayed until today.
→ It is possible to account for EGRET & HEAT anomalies.

The scenario 1

Model example: **MSSM with right-handed neutrinos, where neutrino masses are *purely Dirac type*.**

Super Potential & Soft-breaking terms

$$W = W_{\rm MSSM} + y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c$$
$$\mathcal{L}_{\rm soft} = -M_{\tilde{L}}^2 \tilde{L}^\dagger \tilde{L} - m_{\tilde{\nu}_R}^2 \tilde{\nu}_R^* \tilde{\nu}_R + (A_\nu H_u \tilde{L} \tilde{\nu}_R^c + {\rm h.c.}) + \cdots$$

- R-sneutrino can be relatively light among super-particles, because there is no EW scale corrections for its mass.
- Never thermalized due to small neutrino Yukawa couplings!

In the following discussion, we assume

- Three right-handed sneutrino masses are degenerate
- A_ν is parameterized as $A_\nu = a_\nu y_\nu M_{\tilde{L}}$ with $a_\nu \sim \mathcal{O}(1)$
- $y_\nu \sin\beta = 3.0 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.8 \times 10^{-3}\ {\rm eV}^2} \right)^{1/2}$

The scenario 1

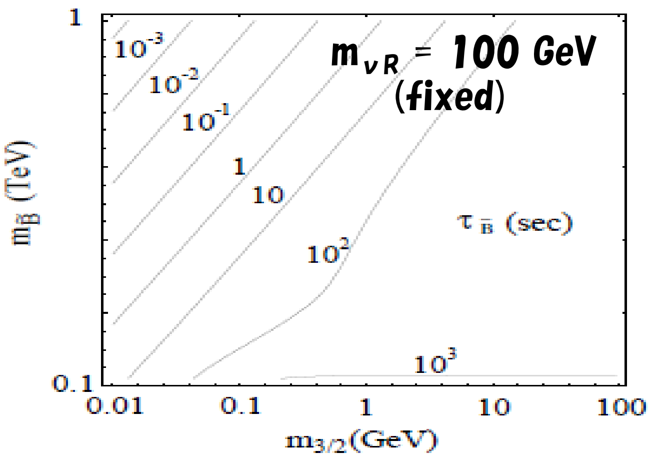
time

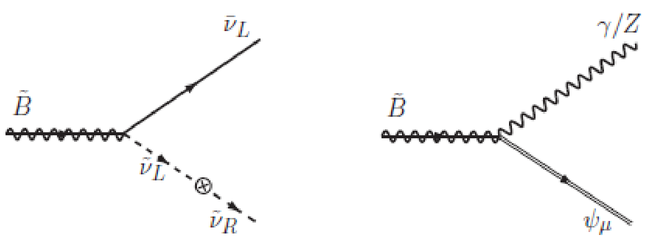
MSSM-LSP such as Bino decoupled

MSSM-LSP decays into R-sneutrino

R-sneutrino decays into Gravitino

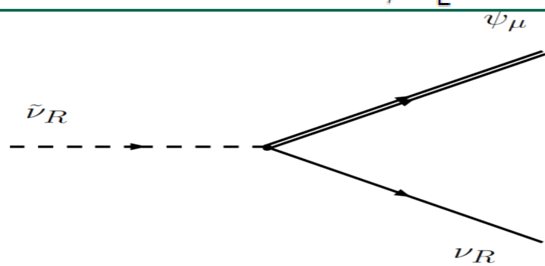
Bino decay





R-Sneutrino decay

$$\Gamma_{\tilde{\nu}_R \to \psi_\mu \nu_R} = \tau_{\tilde{\nu}_R}^{-1} = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\nu}_R}^5}{m_{3/2}^2} \left[1 - \frac{m_{3/2}^2}{m_{\tilde{\nu}_R}^2} \right]^4$$



$\tau \sim 10^6$ s $(m_{3/2}/10 \text{ GeV})^2$

No visible particles are emitted!

The scenario 1

time →

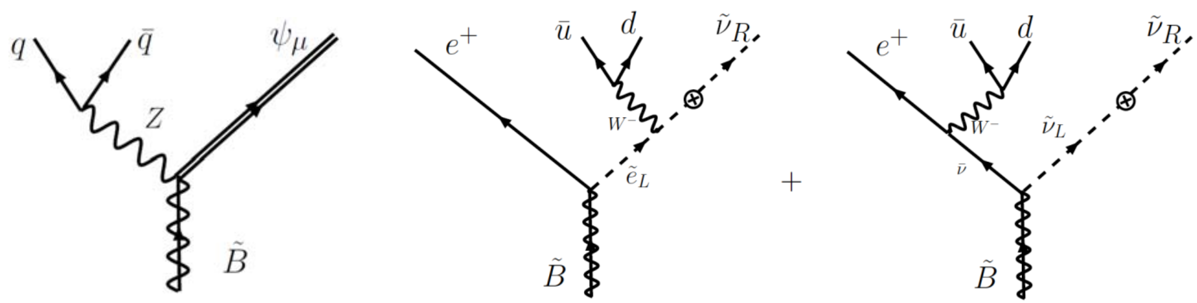
MSSM-LSP such as Bino decoupled

MSSM-LSP decays into R-sneutrino

R-sneutrino decays into Gravitino

This decay is still constrained by the BBN due to following sub-leading processes.

$$\tilde{B} \to \psi_\mu q\bar{q}$$
$$\tilde{B} \to \tilde{\nu}_R e^+_L q\bar{q}'$$
$$\tilde{B} \to \tilde{\nu}_R \bar{\nu}_L q\bar{q}$$



Three- or four- body decays to produce hadrons

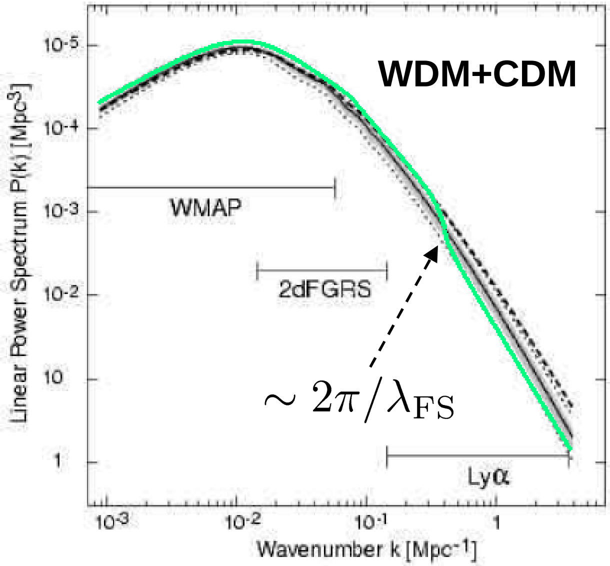
The scenario 1

time

MSSM-LSP such as Bino decoupled → MSSM-LSP decays into R-sneutrino → R-sneutrino decays into Gravitino

The decay is constrained by the structure formation of the universe!
(Gravitino acts as an warm dark matter:
Free-streaming length ~ 6 Mpc when $m_{\nu R}$ = 100 GeV)

On the other hand, Gravitino is also produced by thermal scatterings, and it acts as cold dark matter.
→ Constraints on WDM+CDM scenario

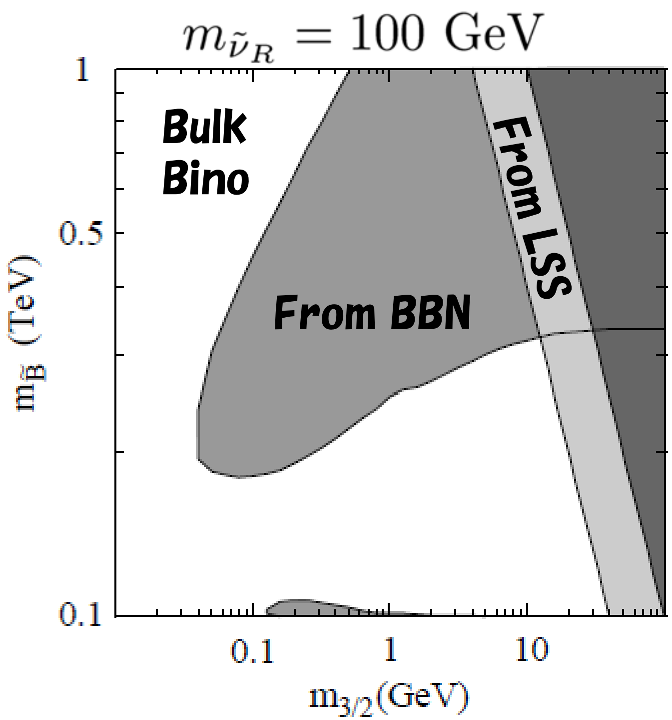


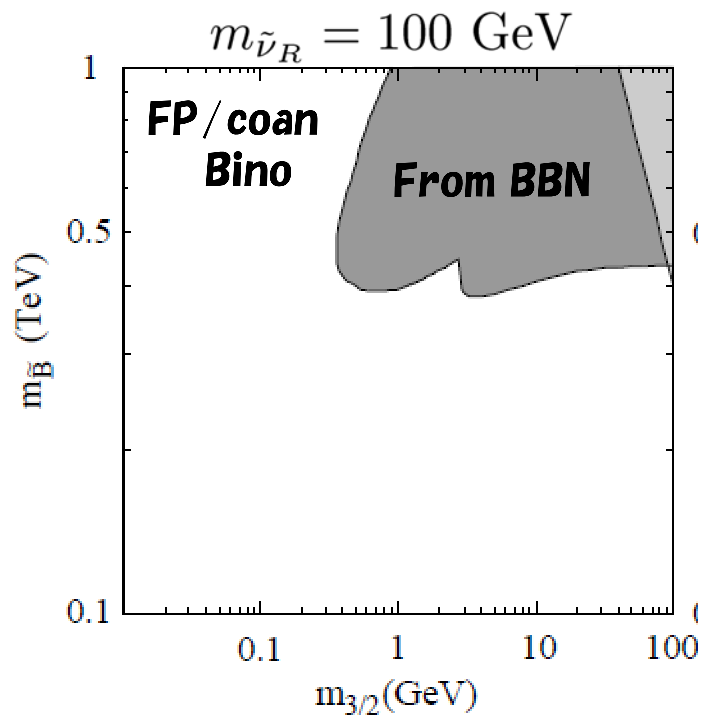
[D.N.Spergel (2003)]

Not to distort the power spectrum,

$$\Omega_{3/2}^{\rm dec} \lesssim 0.4\Omega_{\rm DM}$$

The scenario 1





Constraints on the Gravitino mass is drastically relaxed!

The mechanism works when the MSSM-LSP is the stau.
(In this case, stau decays into W + Gravitino.)

The scenario 1

Most interesting possibility in this setup is the realization of the "SuperWIMP" scenario, where all DM abundance comes from MSSM-LSP decay.

time →

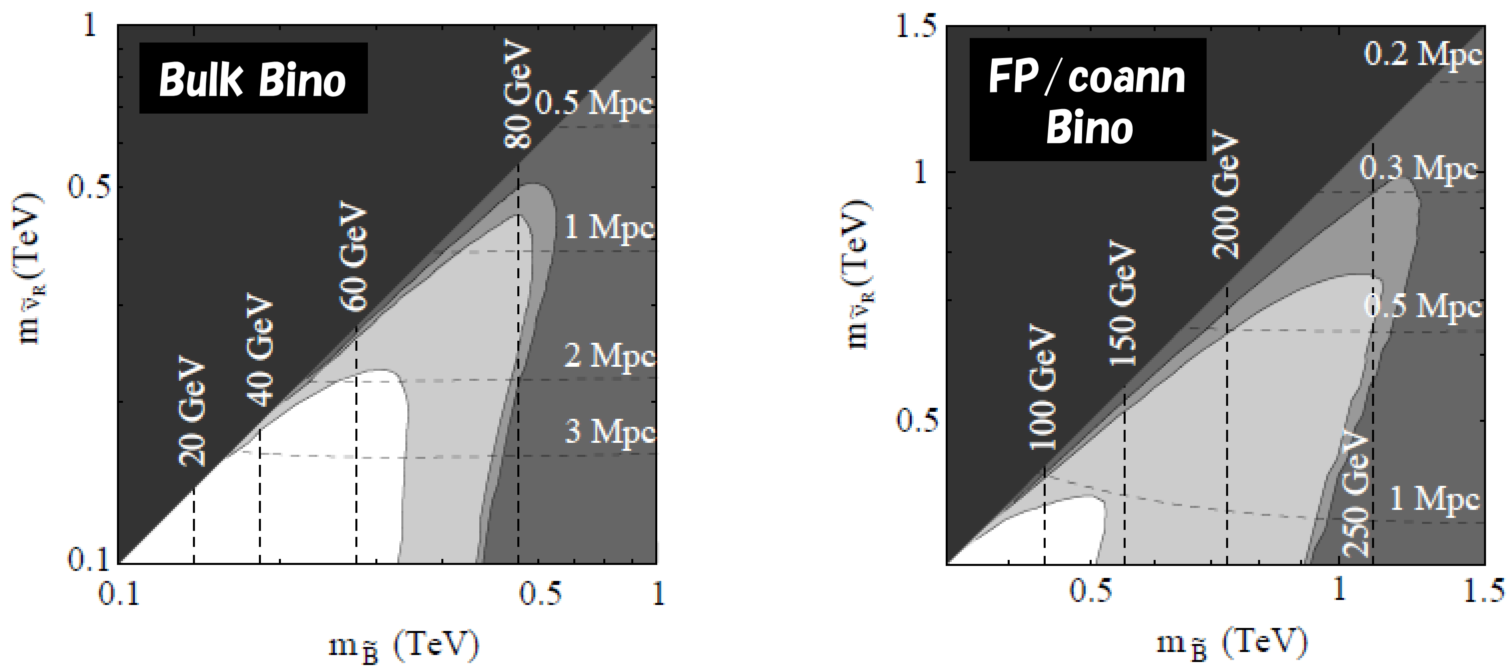
Inflation → Reheating → MSSM-LSP decoupled → Gravitino

Reheating temperature is assumed to be low!

$$\Omega_{\rm SuperWIMP} = \frac{m_{\rm SuperWIMP}}{m_{\rm MSSM-LSP}} \Omega_{\rm MSSM-LSP}$$

Since $\Omega_{\rm MSSM\text{-}LSP} \sim 0.1$, the relic abundance of the gravitino dark matter can be explained naturally when $O(m_{\rm SuperWIMP}) \sim O(m_{\rm MSSM\text{-}LSP})$.

The scenario 1

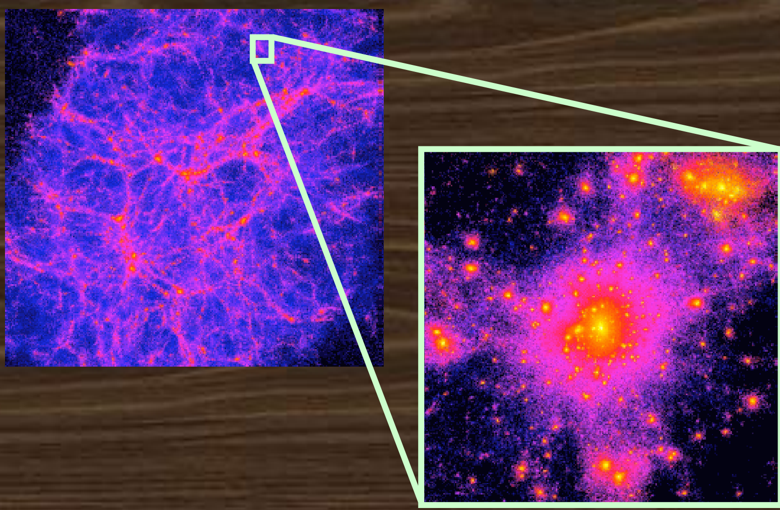


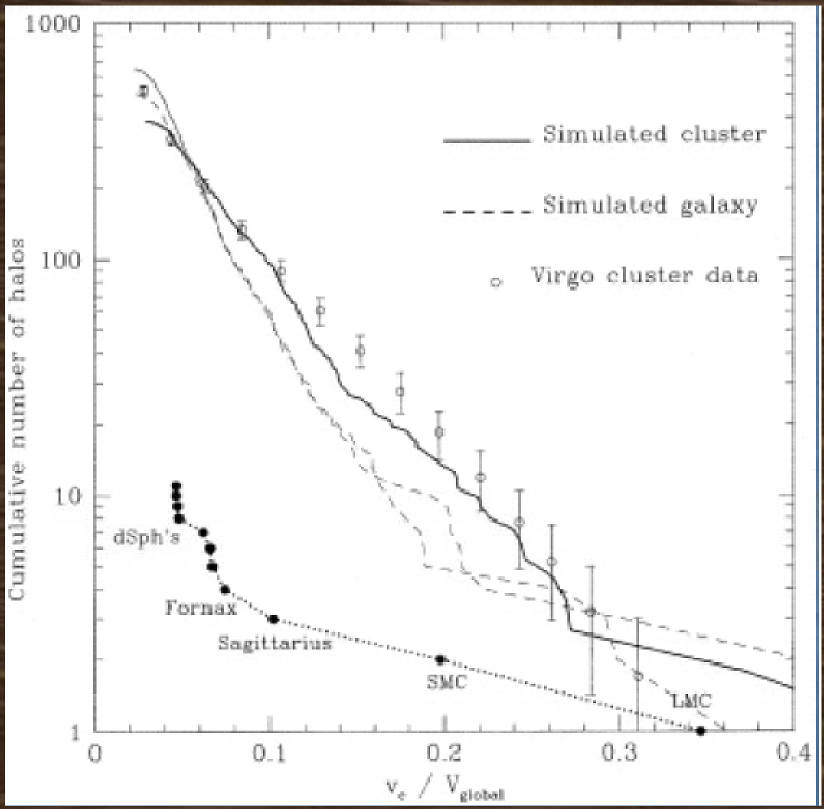
1. Gravitino mass is fixed using the relation
   $\Omega_{SuperWIMP} = (m_{SuperWIMP}/m_{MSSM-LSP})\,\Omega_{MSSM-LSP}$.
2. Without the R-sneutrino, it is impossible to realize the SuperWIMP scenario even if the L-sneutrino is LSP.
3. The gravitino dark matter act as an warm dark matter. Its free-streaming length is about 1 Mpc.

Small scale structure problem

Small scale structure of Universe (< 1 Mpc)

Clump Problem





Simulation predicts too many substructures (dwarf galaxies) in a host galaxy!!

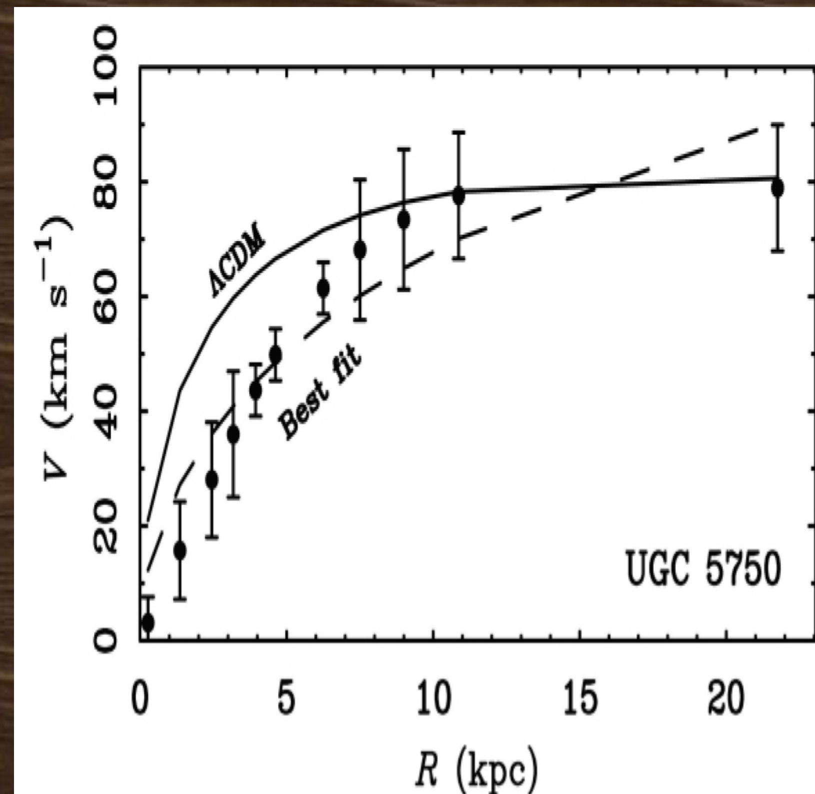
Small scale structure problem

Small scale structure of Universe (< 1 Mpc)

Cusp Problem

DM profile

Simulation predicts
over-dense cores
in a galaxy.



The scenario 2

Model example: MSSM with R-parity violating interactions.

Super Potential

R-parity violation
bi-linear LH ⊂ W

Baryon # is conserved.

⇒ No mixing terms in fermion mass

↑ Redefinition of L and H

Soft-breaking terms

$$\mathcal{L}_{\rm RPV} = B_i \tilde{L}_i H_u + m^2_{\tilde{L}_i H_d} \tilde{L}_i H_d^* + {\rm h.c.}$$

↓

Sneutrino has VEV through EW symmetry breaking

→ Lepton & χ mixed

↓

$$\kappa_i \equiv \frac{\langle \tilde{\nu}_i \rangle}{v}$$

$$10^{-11} \lesssim \kappa_i \lesssim 10^{-7}$$

The scenario 2

BBN starts → time

Thermal Scattering | NLSP decoupled | NLSP decays | Gravitino Almost stable

NLSP decay

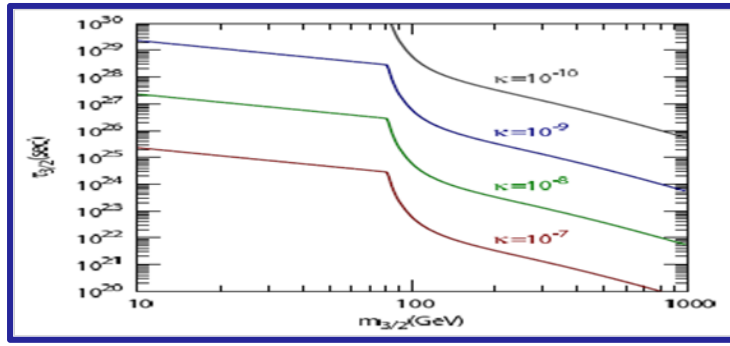
$$\tau_{\tilde B} \simeq 0.07\ \text{sec} \times \left(\frac{\kappa}{10^{-11}}\right)^{-2} \left(\frac{m_{\tilde B}}{200\ \text{GeV}}\right)^{2}$$

$$\tau_{\tilde\tau_R} \simeq 0.3\ \text{sec} \times \left(\frac{\kappa}{10^{-11}}\right)^{-2} \left(\frac{m_{\tilde\chi^0}}{300\ \text{GeV}}\right)^{2} \left(\frac{m_{\tilde\tau_R}}{200\ \text{GeV}}\right)^{-1}$$

$\tau_{NLSP} \ll 1$ s when $\kappa > 10^{-11}$

NLSP decays before BBN!
→ No BBN constraints

Gravitino decay



$\tau_{Gravitino} \gg 10^{17}$ s (Age of Universe)

[Takayama, Yamaguchi, Phys. Lett. B485 (2000)]

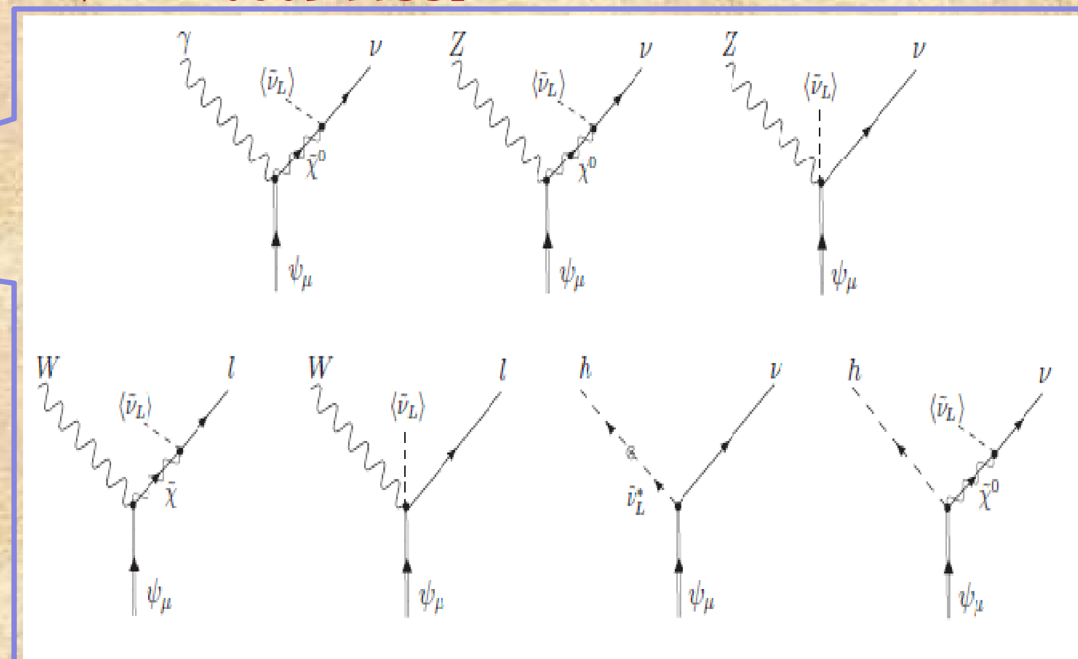
This scenario is very attractive, because it is compatible with the thermal leptogenesis scenario.

[Fukugida, Yanagida, Phys. Lett. B174, (1986)]

The scenario 2

Most interesting possibility in this setup is that the gravitino DM can be a source of cosmic rays.

[A. Ibarra, D. Tran, Phys. Rev. Lett. 100, (2008)]
[A. Ibarra, D. Tran, arXiv:-804.4596]
[Ishiwata, S.M. Moroi, arXiv:0805:1133]



1. There also exists extragalactic gamma-rays from the DM decay.
2. No extragalactic positrons due to the loss of their energy during the propagation. Only the DM within a few kpc around the solar system can be the source of energetic positrons.

The scenario 2

Most interesting possibility in this setup is that the gravitino DM can be a source of cosmic rays.

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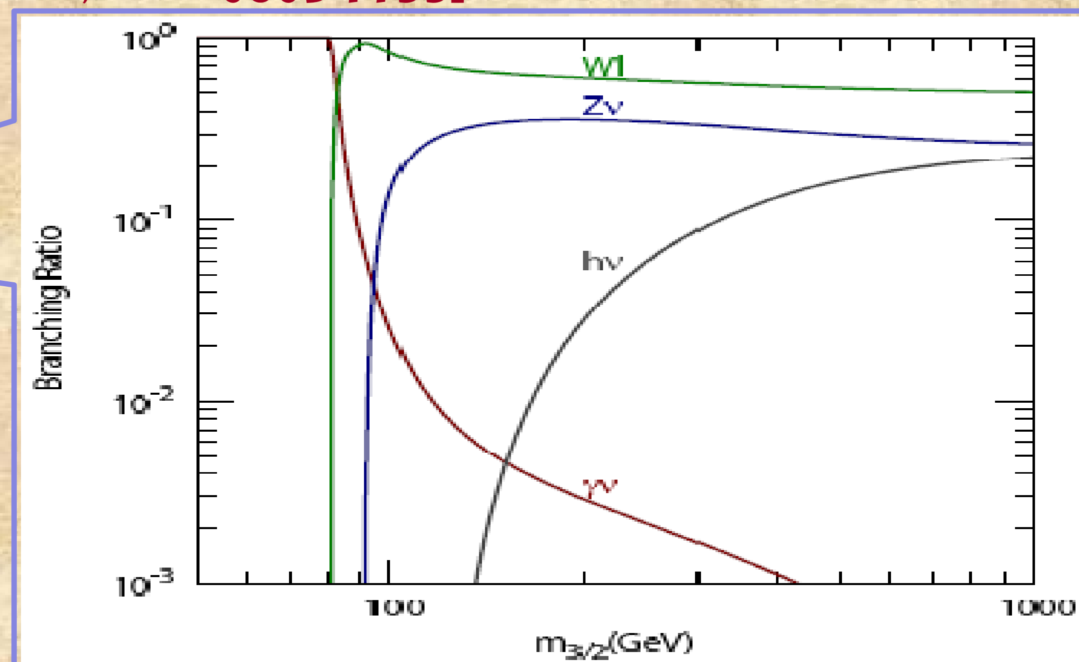


$\tilde{G} \to W(Z) + l$

$\quad\quad \hookrightarrow \pi^0 \to 2\gamma$

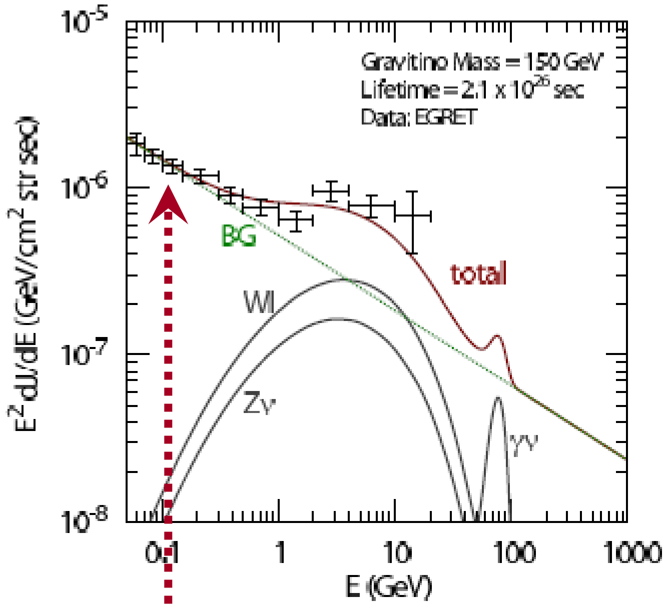
$\to \gamma + \nu$

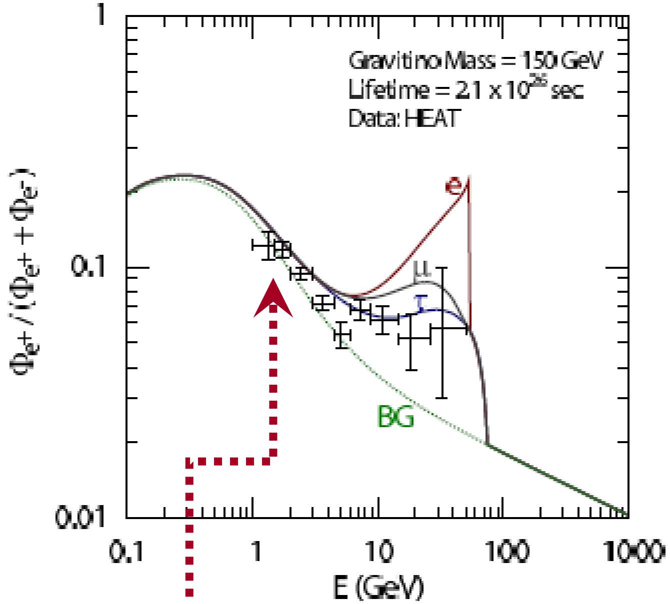
$\tilde{G} \to W(Z) + l$

$\quad\quad \hookrightarrow \pi^\pm \to l$

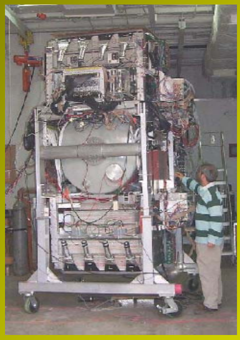
The scenario 2

Gravitino mass = 100 GeV





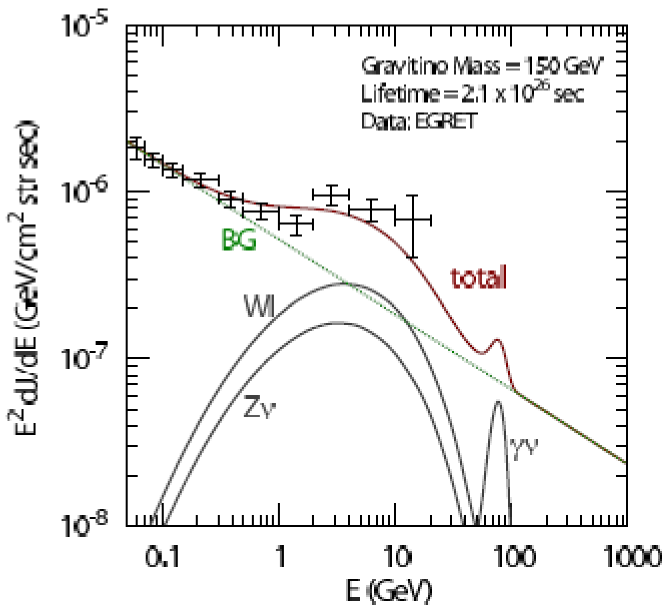
EGRET

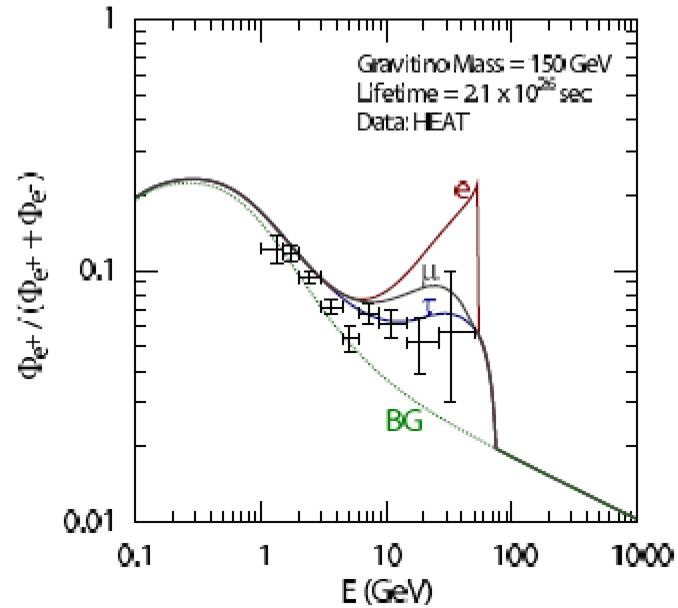


HEAT

The scenario 2

Gravitino mass = 100 GeV

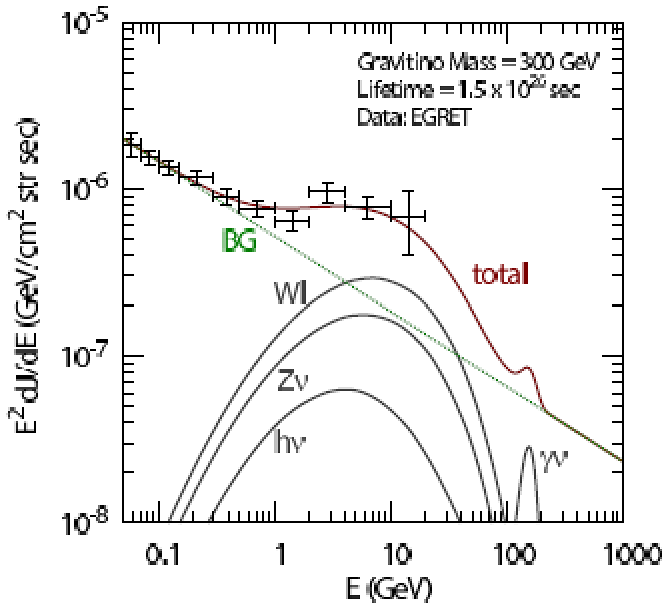


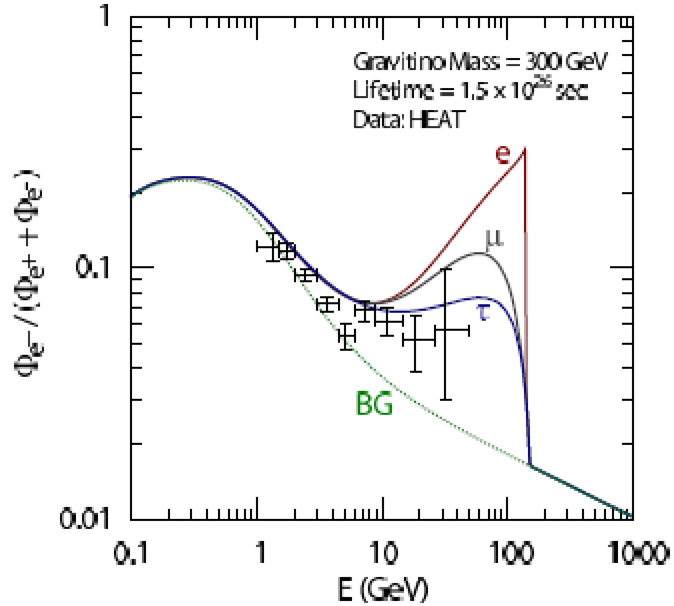


1. The gravitino DM can explain gamma (EGRET) and positron (HEAT) anomalies simultaneously.
2. The decay mode G → W τ is preferred. Other modes such as G → W e, W μ are not so good.
3. Line-gamma-ray signal coming from G → γ ν is difficult to observe when $m_{3/2}$ is large.

The scenario 2

Gravitino mass = 300 GeV

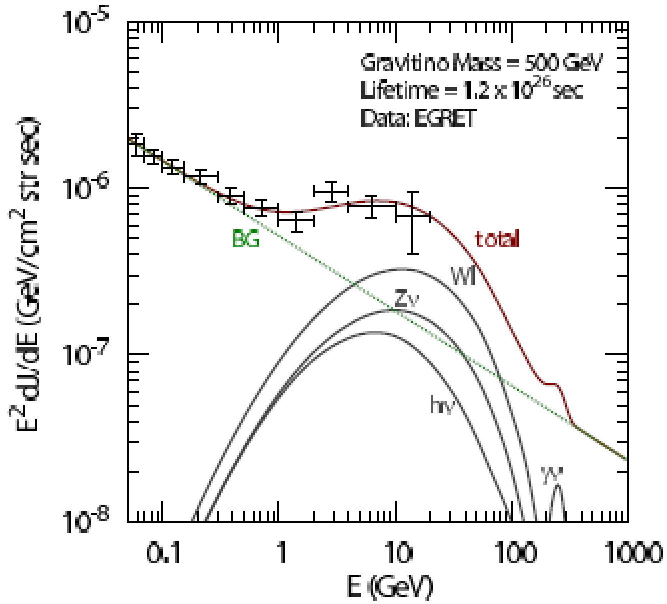


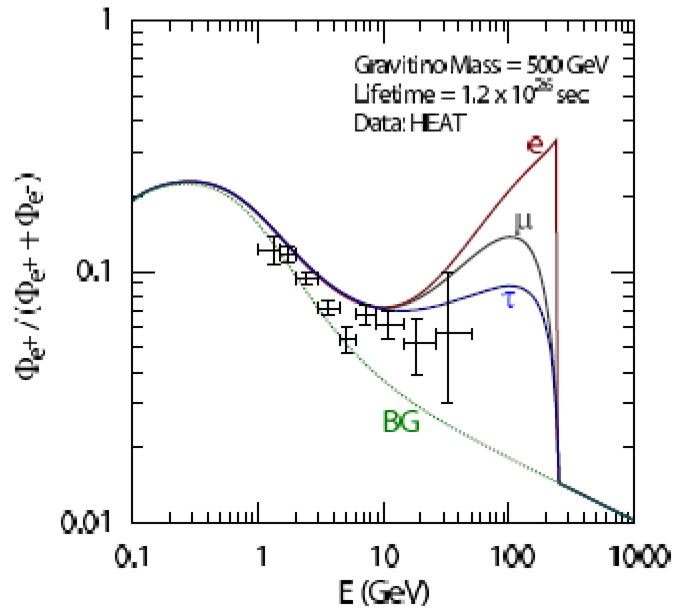


1. The gravitino DM can explain gamma (EGRET) and positron (HEAT) anomalies simultaneously.
2. The decay mode $G \to W\ \tau$ is preferred. Other modes such as $G \to W\ e$, $W\ \mu$ are not so good.
3. Line-gamma-ray signal coming from $G \to \gamma\ \nu$ is difficult to observe when $m_{3/2}$ is large.

The scenario 2

Gravitino mass = 500 GeV





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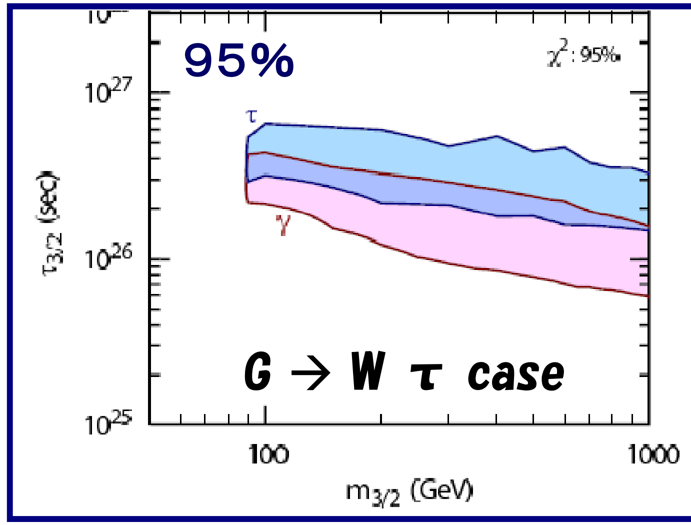
The scenario 2

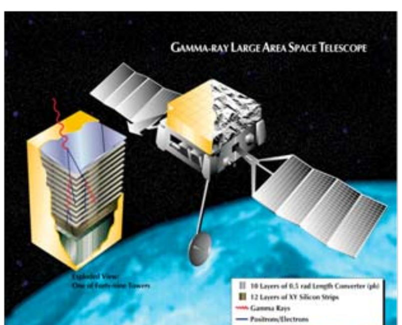
χ^2 analysis

$$\langle \chi^2 \rangle = \left\langle \sum_{i=1}^{N} \frac{(N_{\mathrm{th},i} - N_{\mathrm{BG},i})^2}{\sigma_{\mathrm{BG},i}^2} \right\rangle$$

To estimate how well the DM decay can explain both anomalies

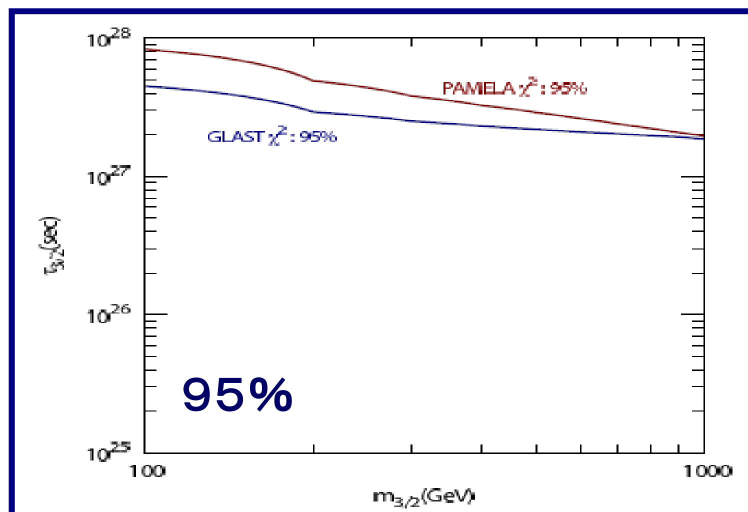


Sensitivity to detect the signal in future observations



GLAST


PAMELA



The scenario 2

Some issues related to the DM scenario

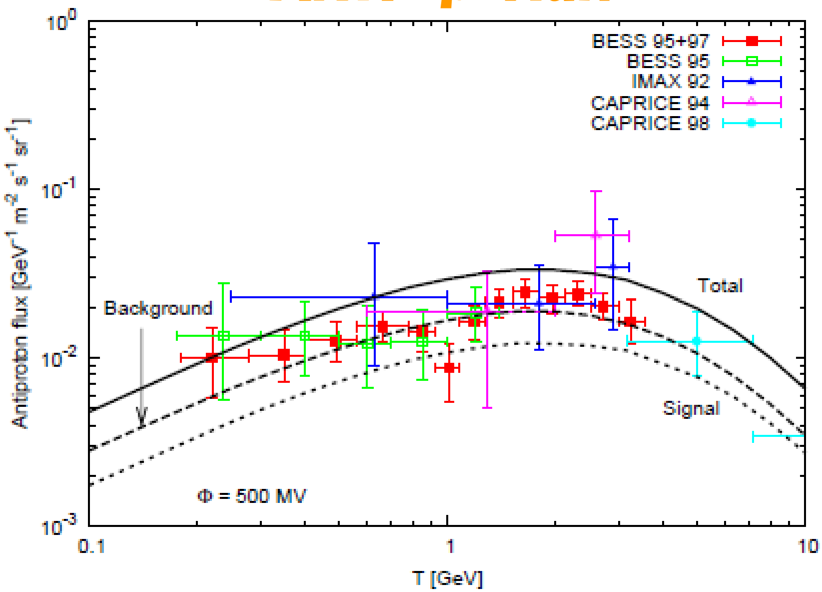
1. Anti-proton production
2. Preliminary PAMELA result
3. Dark Matter Haze (Synchrotron)

The scenario 2

Some issues related to the DM scenario

1. Anti-proton production
2. Preliminary PAMELA result
3. Dark Matter Haze (Synchrotron)

Anti-p flux



[A. Ibarra, D. Tran, arXiv:-804.4596]

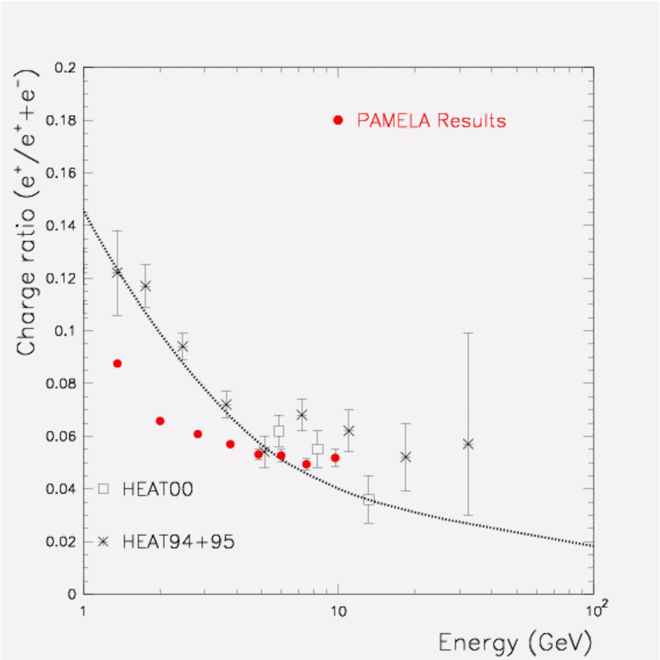
Predicted anti-p flux seems to be too large. However the flux depends strongly on parameters of diffusion model such as how deep the magnetic field penetrates to the direction perpendicular to the galactic disc.

The scenario 2

Preliminary PAMELA result

Some issues related to the DM scenario

1. Anti-proton production
2. Preliminary PAMELA result
3. Dark Matter Haze (Synchrotron)



Hard spectrum is shown in PAMELA result. Also the result seems to be inconsistent with the HEAT result even at the low energy range.

The scenario 2

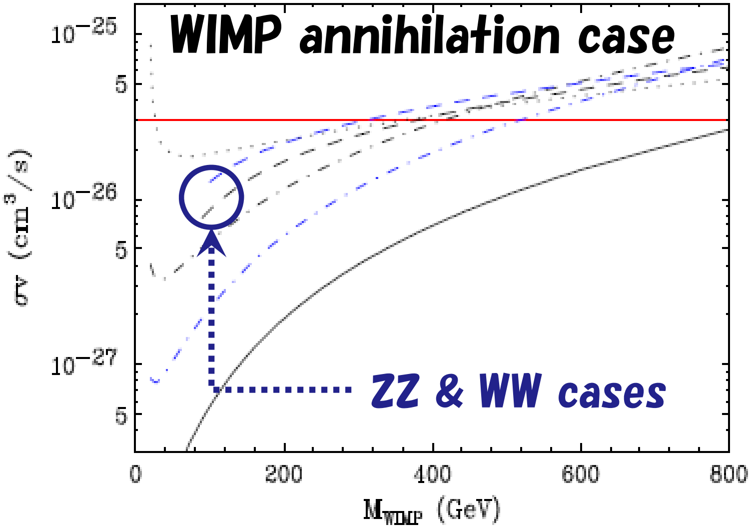
Some issues related to the DM scenario

1. Anti-proton production
2. Preliminary PAMELA result
3. Dark Matter Haze (Synchrotron)

DM Haze: Synchrotron γ from DM annihilation/decay

[Hooper, Douglas P, Dobler, Phy. Rev. D, 2007]

Dark Matter Haze



Production rate of $e^{\pm}$

$$2\text{WIMPs} \to WW:\ \Gamma = 1/2(\sigma v)\, n_{DM}^2$$

$$\tilde{G} \to W\tau:\ \Gamma = n_{DM}/\tau_{3/2}$$

$$\tau_{3/2} = 5\times 10^{26}\ s \times[m_{3/2}/(100\ \text{GeV})] \times[(10^{-26}\ cm^3/s)/\sigma v] \times[(10\ \text{GeV}/cm^3)/\rho_{DM}]$$

Summary

1. Cosmology of the Weak Scale Gravitino DM scenario has been studied.

2. Though the scenario is severely constrained by the BBN, it is possible to avoid the constraints by introducing (i) weak scale right-handed neutrinos or (ii) tiny RPV interactions.

3. In case (i), the SuperWIMP scenario can be realized, and the gravitino act as an warm DM.
4. In case (ii), the DM decay can be a source of cosmic rays, and it is possible to account for EGRET, HEAT, and Haze anomalies.