Cosmic Gamma-ray from inverse-Compton process in unstable dark matter scenario

Koji Ishiwata
(Tohoku University)

In collaboration with
Shigeki Matsumoto (Toyama University)
Takeo Moroi (Tohoku University)

Based on
Phys.Lett.B679:1-5.2009

Assisi, 7th of October 2009

1. Introduction

DM

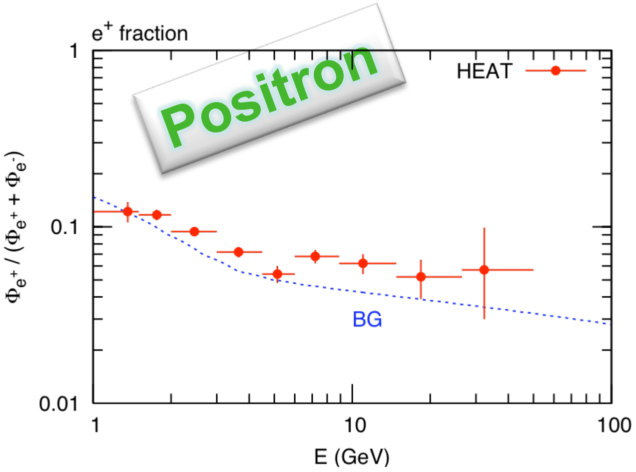
Dark Matter (DM)

The existence is confirmed conclusively [WMAP collaboration] ; however, there is no candidate in the standard model

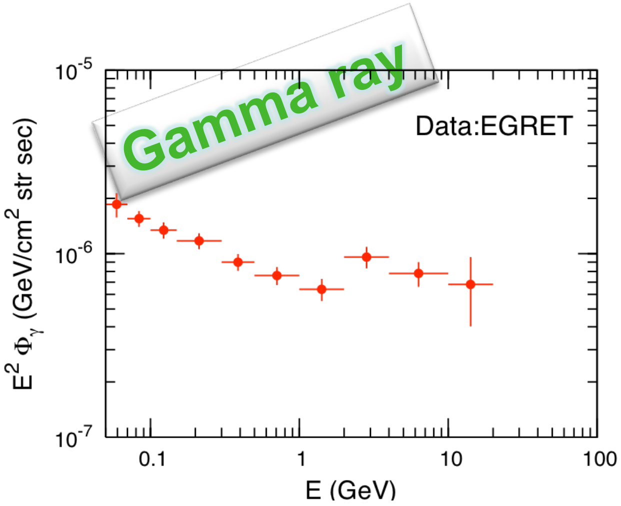
⟹ **Beyond the standard model**

It has been challenging to explore the nature of DM in particle phenomenology; DM scenarios have been studied in cosmology and astrophysics

In particular, the study of DM has been active under various cosmic-ray observations these days



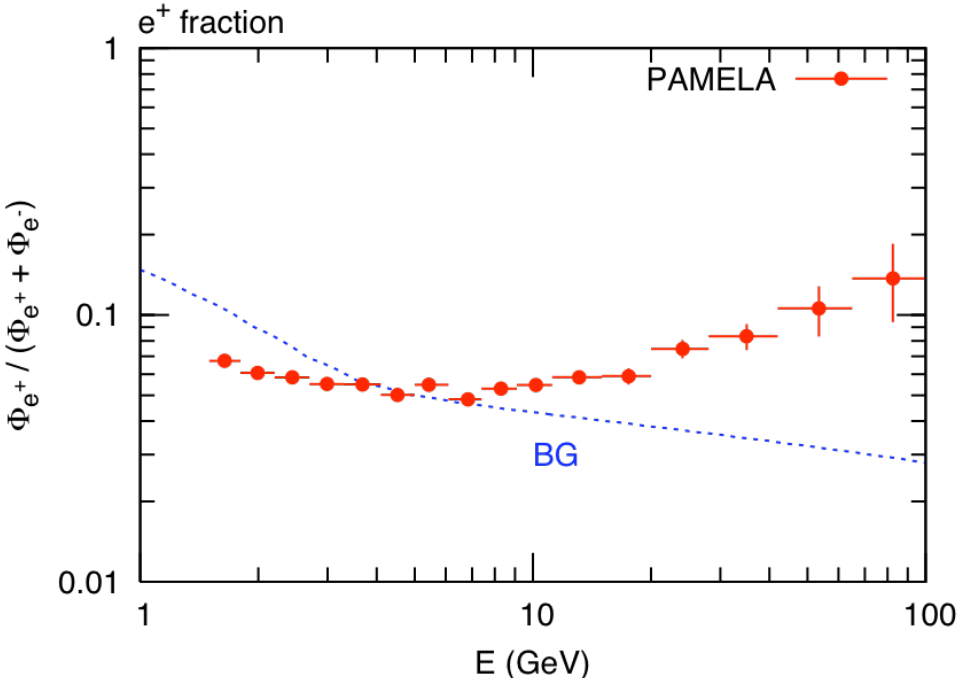
[Barwick *et al.*]



[Sreekumar *et al.*;
Moskalenko,Strong]

⟹ **Signal from DM might have been detected !**

Very recently, PAMELA observations have reported anomaly in cosmic-ray positron



[Adriani *et al.*]

<u>Sharp excess from 10 GeV up to 100 GeV</u>

$\Longrightarrow$ **Exotic source for such high energy e^+ should exist !**

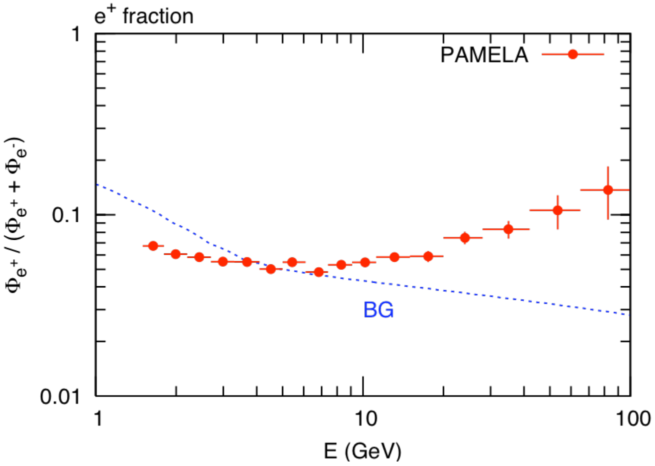
Possible explanations for the anomaly:

Astrophysical origin

- Pulsars [Hooper,Blasi,Serpico; …]
- …

Particle origin

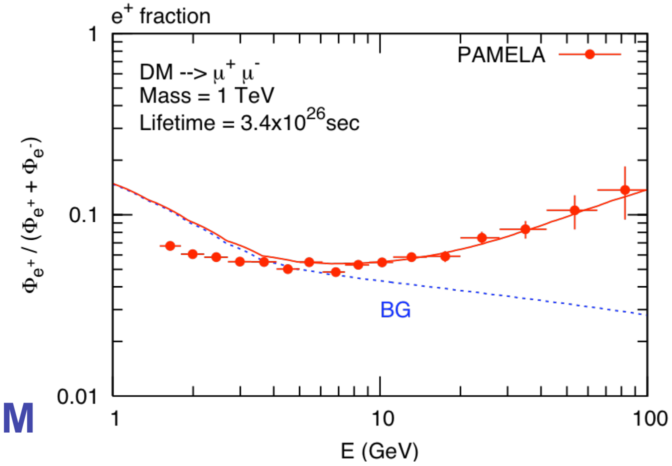
- DM annihilation [Cirelli,Kodastik,Raidal,Strumia;Cholis,Finkbeiner, Goodenough,Weiner; etc…]
- ★ DM decay [KI,Matsumoto,Moroi;Ibarra,Tran; Chen,Takahashi,Yanagida; etc…]



⟹

+

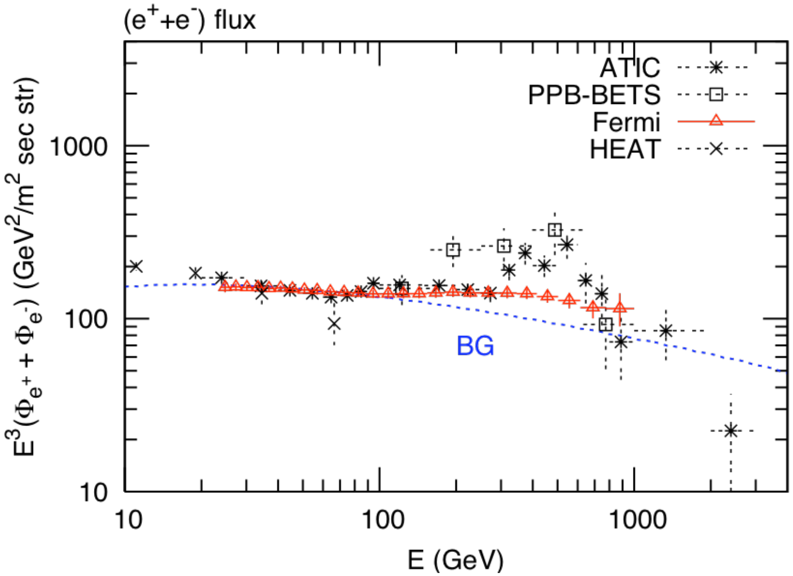
Decaying DM



[KI *et al.*]

On the other hand, no anomaly has been reported in $(e^+ + e^-)$ flux observed by Fermi LAT

- Consistent with the prediction of standard astrophysical cosmic ray ?
- Hard spectrum up to TeV scale indicates heavy DM ?

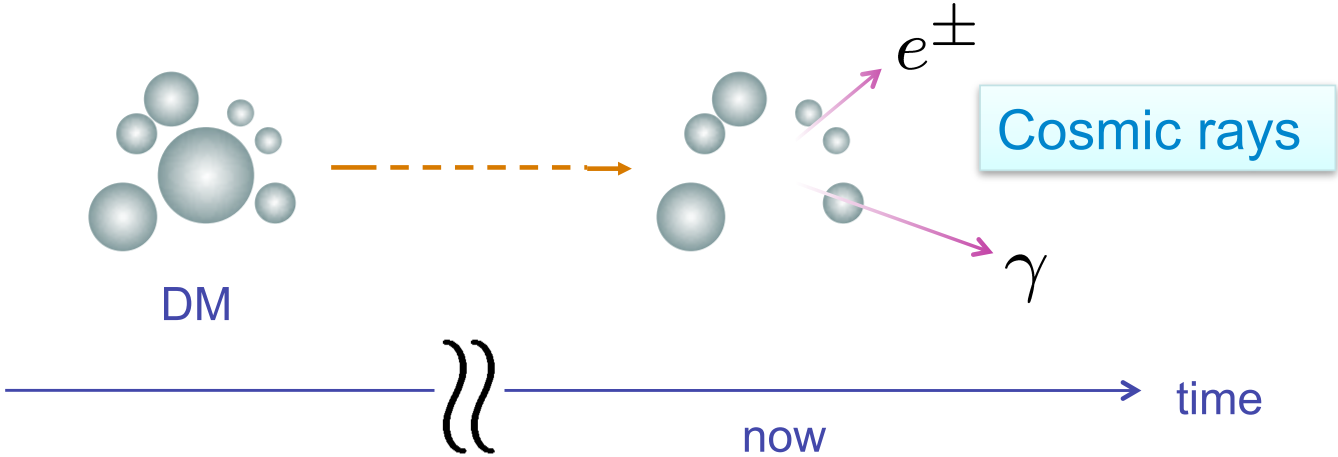


[Abdo *et al.*; Chang *et al.*]

⟹ **Still controversial**

In our study, we focus on γ-ray from inverse-Compton process in decaying DM scenario, then show that

- The PAMELA anomaly can be well explained, being consistent with the Fermi LAT $(e^+ + e^-)$ observation
- $(e^+ + e^-)$ observation might indicate TeV-DM; however, in decaying dark matter scenario, such large DM mass might be constrained by Fermi LAT γ-ray observation



Outline

1. Introduction
2. Cosmic-ray $e^{\pm}$
3. Cosmic γ-ray
4. Summary

2. Cosmic-ray $e^{\pm}$

Cosmic rays that we observe:

$$\Phi_{e^{\pm},\mathrm{tot}} = \Phi_{e^{\pm},\mathrm{DM}} + \Phi_{e^{\pm},\mathrm{BG}}$$

DM decay

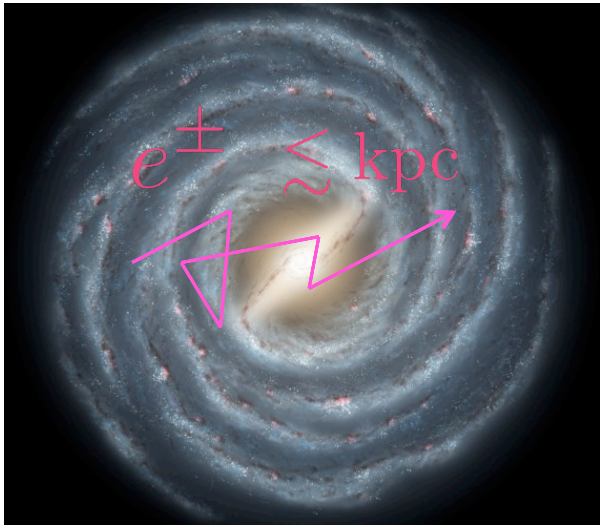
⟹ DM scenario + propagation model in the Galaxy

Astrophysical BG

⟹ We adopt the conventional BG, which is simulated by GALPROP code [Moskalenko,Strong]

DM decay

Propagation of $e^{\pm}$ can be treated as random walk

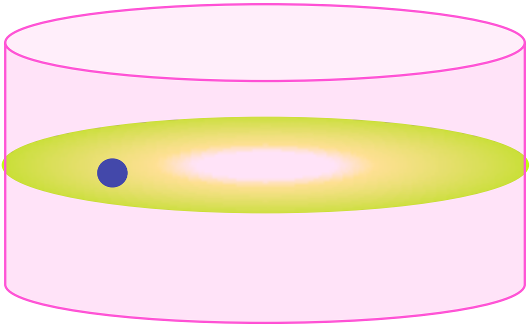


⟹ Diffusion equation;

$$\frac{\partial}{\partial t} f_e(E,\vec{x}) = K_e(E)\nabla^2 f_e(E,\vec{x}) + \frac{\partial}{\partial E}[b_{\mathrm{loss}}(E,\vec{x}) f_e(E,\vec{x})] + Q_e(E,\vec{x})$$

- K_e : Diffusion coefficient
- b_{loss} : Energy-loss rate
- Q_e : $e^{\pm}$ source term (DM-decay)

“Diffusion zone”



Solar system $\vec{R}_{\odot}$

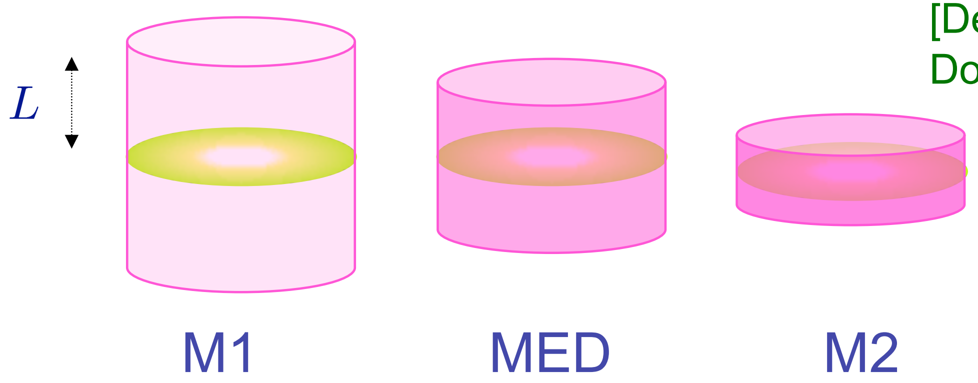
⟹ $\Phi_{e^{\pm},\mathrm{DM}} = \frac{c}{4\pi} f_e(E,\vec{R}_{\odot})$

Propagation models:

parameters: K_e, L

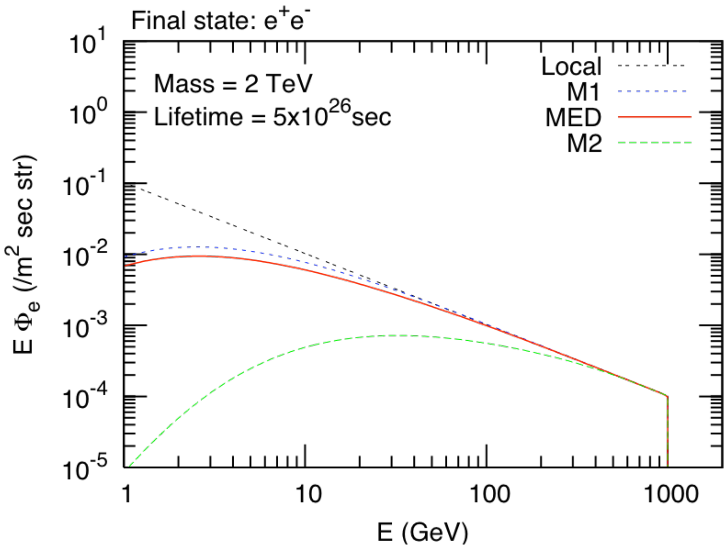
[Delahaye,Lineros,
Donato,Fornengo,Salati]

$\Longrightarrow$



We adopt MED as our benchmark model

cf.)



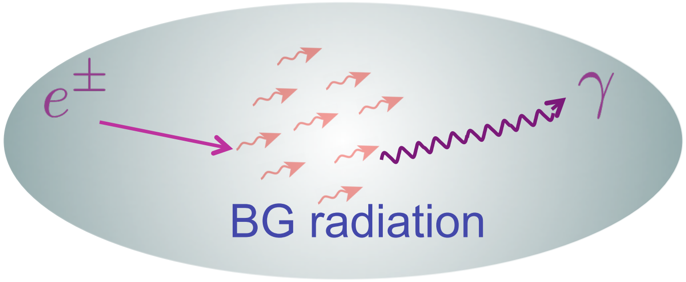
$\Longrightarrow$ M1 $\simeq$ MED $\simeq$ M2
for $E \gtrsim 100\ \mathrm{GeV}$

"Local" :
solution under $K_e \approx 0$

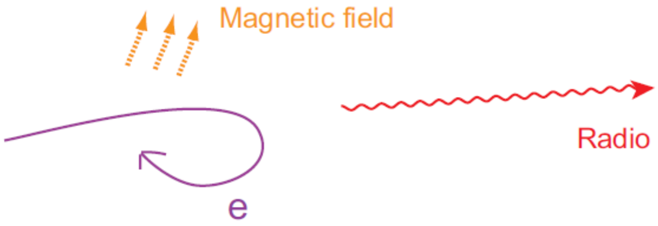
$$f_e^{\mathrm{local}} = \frac{1}{b_{\mathrm{loss}}} \int_E^\infty dE' Q_e$$

Energy-loss rate:

$$b_{\rm loss} = b_{\rm IC} + b_{\rm synch}$$



- Inverse-Compton scattering under BG radiation



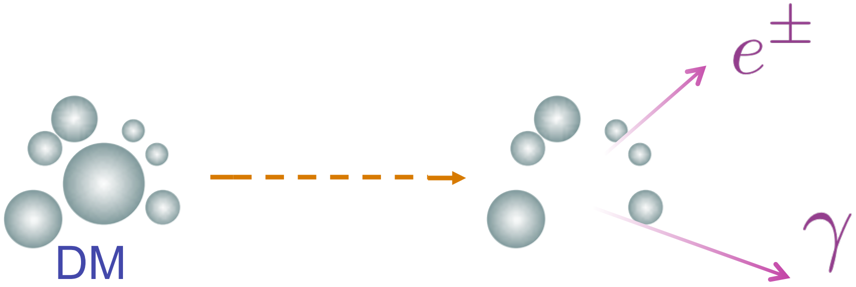
- Synchrotron radiation under magnetic field [Strong,Moskalenko,Reimer]

Decaying DM Scenario:

- Lightest superparticle under R-parity violation [KI,Matsumoto,Moroi; Ibarra,Tran; …]
- Hidden gauge boson [Chen,Takahashi,Yanagida;…]
- …

Here we show two examples:

- Final state: $\mu^+\mu^-$
- Gravitino DM (for comparison)

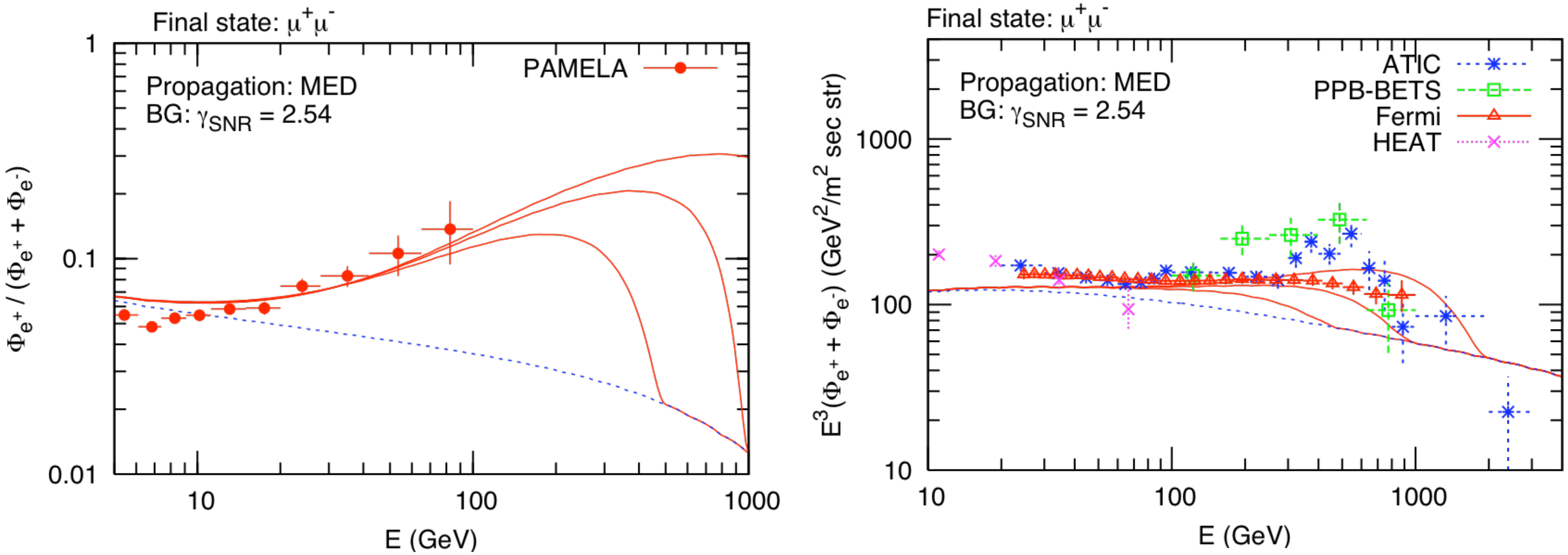


Numerical Results

- Final state: $\mu^+\mu^-$

$$m_{\rm DM} = 1, 2, 4\ {\rm TeV}$$

$$\tau_{\rm DM} = 6.6, 3.4, 1.7 \times 10^{26}{\rm sec}$$

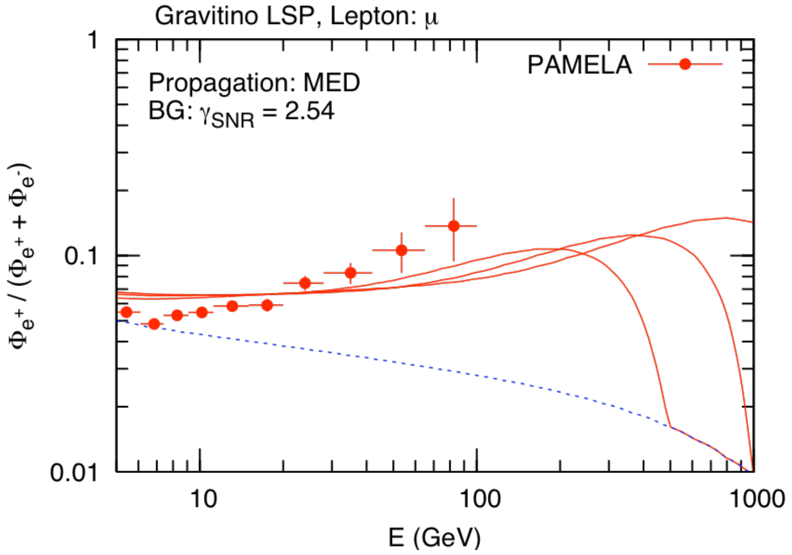


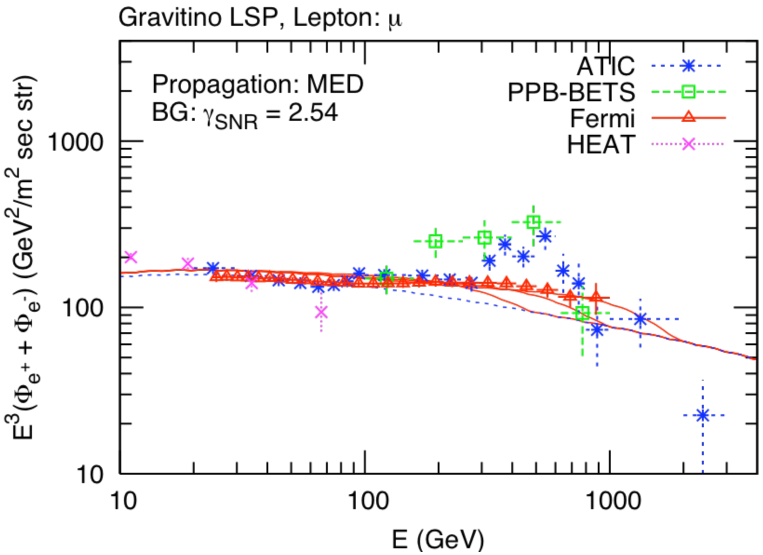
BG: rescaled by 0.93

- PAMELA anomaly can be well explained
- Fermi LAT prefers $m_{\rm DM} \gtrsim 2\ {\rm TeV}$
  ($\because$ No bump or drop up to $1\ {\rm TeV}$)

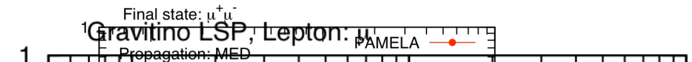
- Gravitino DM

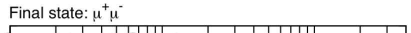
$\tau_{\rm DM} = 2.0, 1.8, 1.6 \times 10^{26}{\rm sec}$





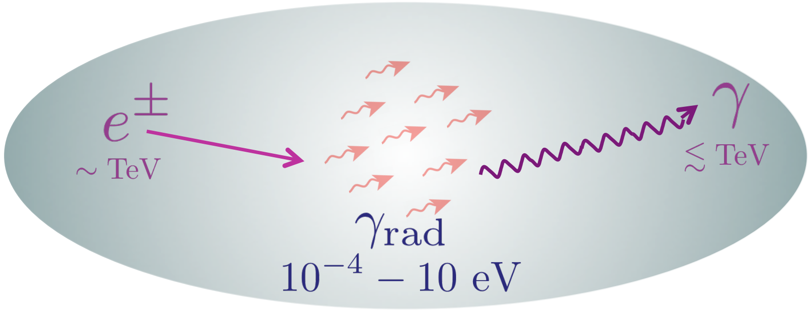
Fit with PAMELA becomes a little bit worse; it still is a possible explanation for the anomaly, being consistent with Fermi LAT





3. Cosmic γ-ray

$$\Phi_{\gamma_{\rm DM}} = \Phi_\gamma^{\rm (IC)} (+\Phi_\gamma^{\rm (prim)})$$



Inverse-Compton process

$e^\pm$ emitted by DM decay inevitably produces γ-ray in inverse-Compton (IC) scattering

Primary emission from DM

⟹ Gravitino-DM case

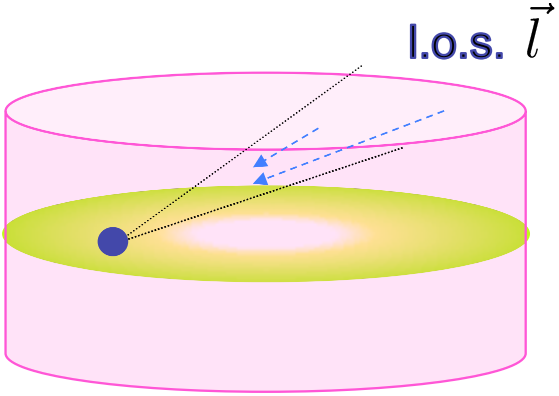
Notice that the uncertainty of estimating astrophysical BG; we calculate DM contribution and compare is with observation

IC process:

$$\Phi_\gamma^{(\mathrm{IC})} = \Phi_\gamma^{(\mathrm{Galaxy})} + \Phi_\gamma^{(\mathrm{Cosmo})}$$

- Galaxy (anisotropic)

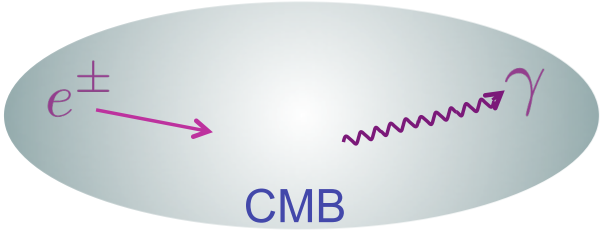
$$\Phi_\gamma^{(\mathrm{Galaxy})} = \frac{1}{4\pi}\int_{\mathrm{l.o.s}} d\vec{l} L_{\mathrm{IC}}(E_\gamma, \vec{l})$$



where $L_{\mathrm{IC}} = \int dE_e dE_{\gamma_{\mathrm{rad}}} \frac{d\sigma_{\mathrm{IC}}}{dE_\gamma} f_{\gamma_{\mathrm{rad}}} f_e$

$f_{\gamma_{\mathrm{rad}}}$: Interstellar radiation field spectrum [Porter,Strong]

f_e : Solution of the diffusion Eq.



- Extra-Galaxy (isotropic)

$$\Phi_{\gamma}^{(\mathrm{Cosmo})} = \frac{c}{4\pi}\int dt \frac{1}{(1+z)^3} L_{\mathrm{IC}}(t, E_{\gamma})$$

$f_{\gamma_{\mathrm{rad}}}$: Cosmic microwave background (CMB)

f_e : No diffusion (no propagation model dependence); determined only by the IC energy-loss rate

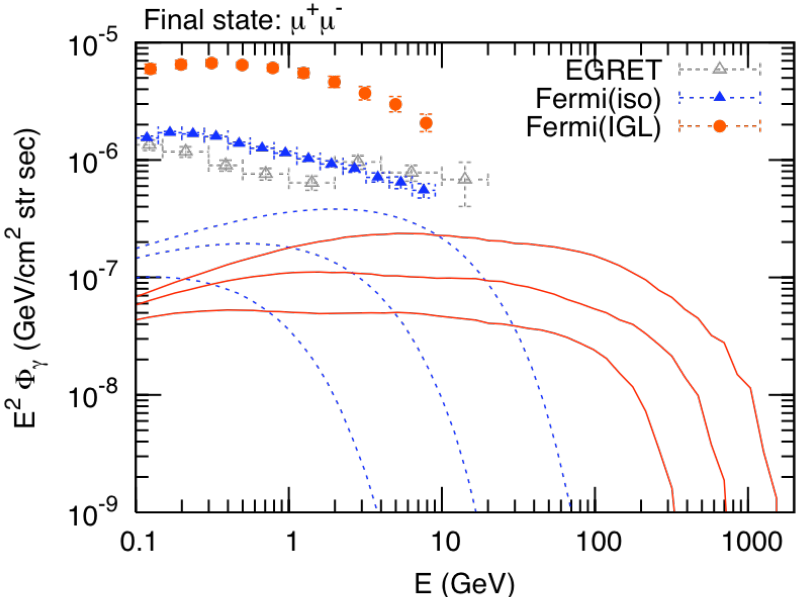
⟹ **No astrophysical uncertainty !**

Numerical results

- Final state: $\mu^+\mu^-$

$m_{\rm DM} = 1, 2, 4\ {\rm TeV}$

$\tau_{\rm DM}$: PAMELA best fit



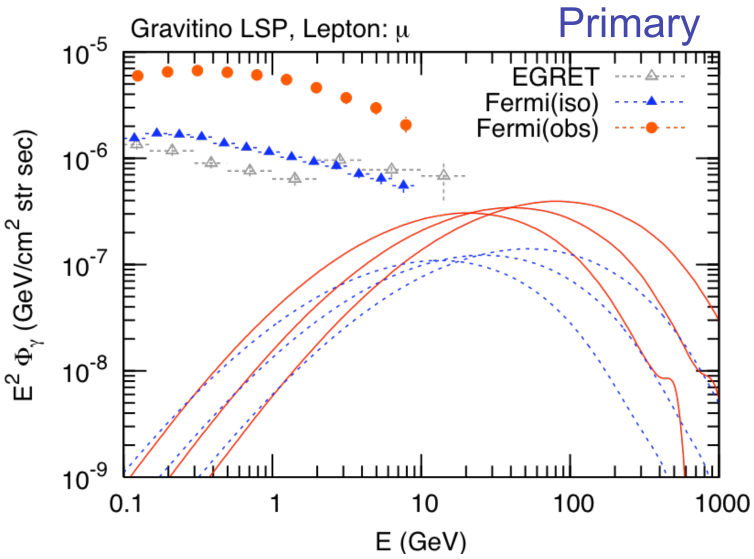
iso: isotropic

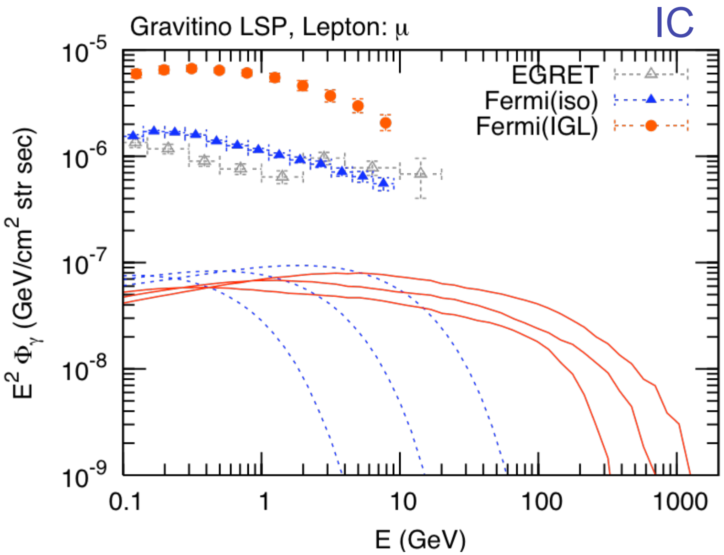
IGL: $10^\circ < b < 20^\circ$

- Cosmo: may be comparable to Fermi(iso) for large DM mass
- Galactic: less than Fermi(IGL)

$m_{\rm DM} \gtrsim 4\ {\rm TeV}$ may be constrained by the present observation of isotropic γ-ray although $m_{\rm DM} \gtrsim 2\ {\rm TeV}$ is indicated by Fermi $(e^+ + e^-)$ observation

- Gravitino DM





For primary contribution,

- Cosmo: comparable to IC
- Galactic: larger than IC

$m_{\rm DM} \gtrsim 1\ \mathrm{TeV}$ may be constrained by (future) IGL γ-ray observation up to $\sim 100\ \mathrm{GeV}$

4. Summary

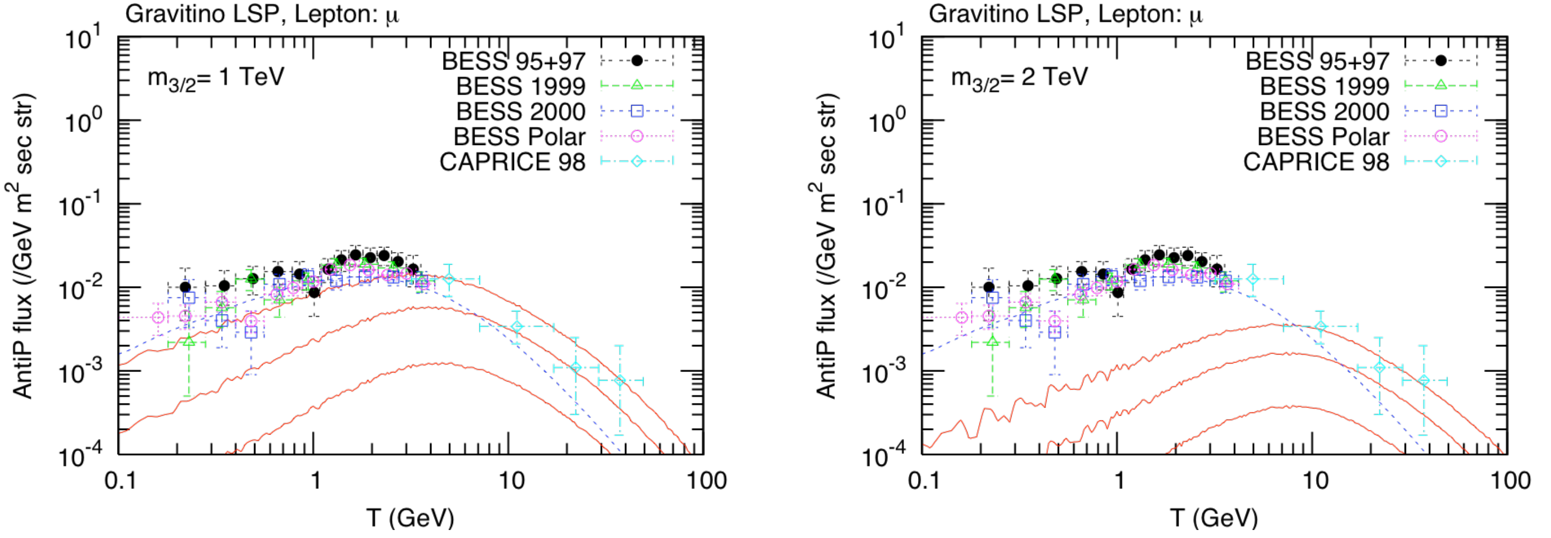
We studied decaying DM scenario for a solution of PAMELA anomaly, focusing on γ-ray in IC process, and found that

- The PAMELA anomaly can be well explained when $\tau_{\mathrm{DM}} \sim O(10^{26\text{-}27}\mathrm{sec})$, being consistent with Fermi LAT $(e^+ + e^-)$ observation
- Especially $(e^+ + e^-)$ observation might indicate $m_{\mathrm{DM}} \gtrsim 2\ \mathrm{TeV}$; however, $m_{\mathrm{DM}} \gtrsim 4\ \mathrm{TeV}$ might be constrained by the present Fermi LAT γ-ray observation

γ

Backup

Anti-proton



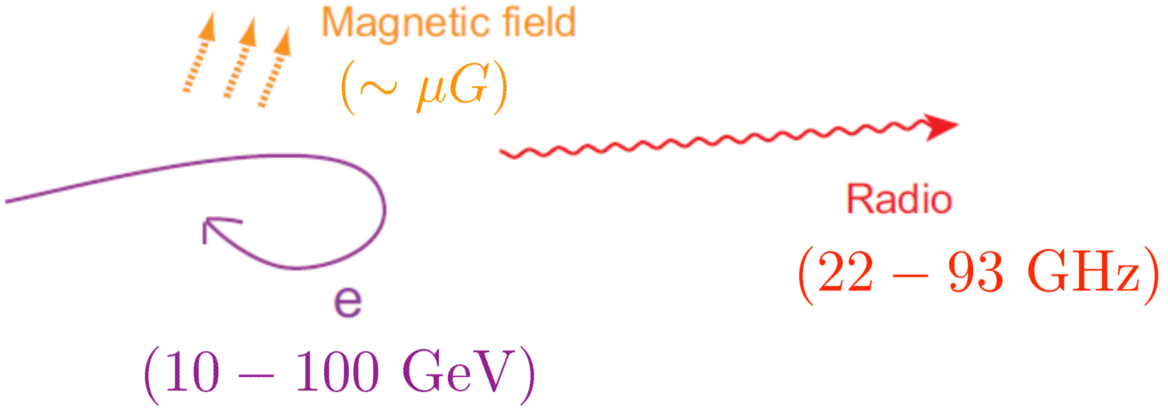
Model: MAX,MED,MIN
Lifetime: PAMELA best-fit

Constrain from observation is no so severe

(PAMELA preliminary results might constrain $m_{3/2} \gtrsim 1 \text{ TeV}$)

Synchrotron Radiation Flux

On the other hand, $e^{\pm}$ induces synchrotron radiation under the magnetic field in the Galaxy



Magnetic field

$(\sim \mu G)$

Radio

$(22 - 93\ \mathrm{GHz})$

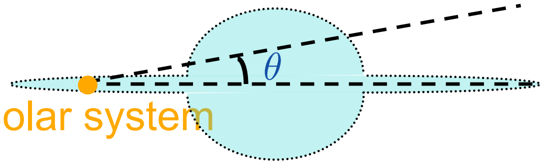
e

$(10 - 100\ \mathrm{GeV})$

In the frequency band, remnant flux of $O(1\ \mathrm{kJy/str})$ from the Galactic center, which is called "WMAP Haze", is reported

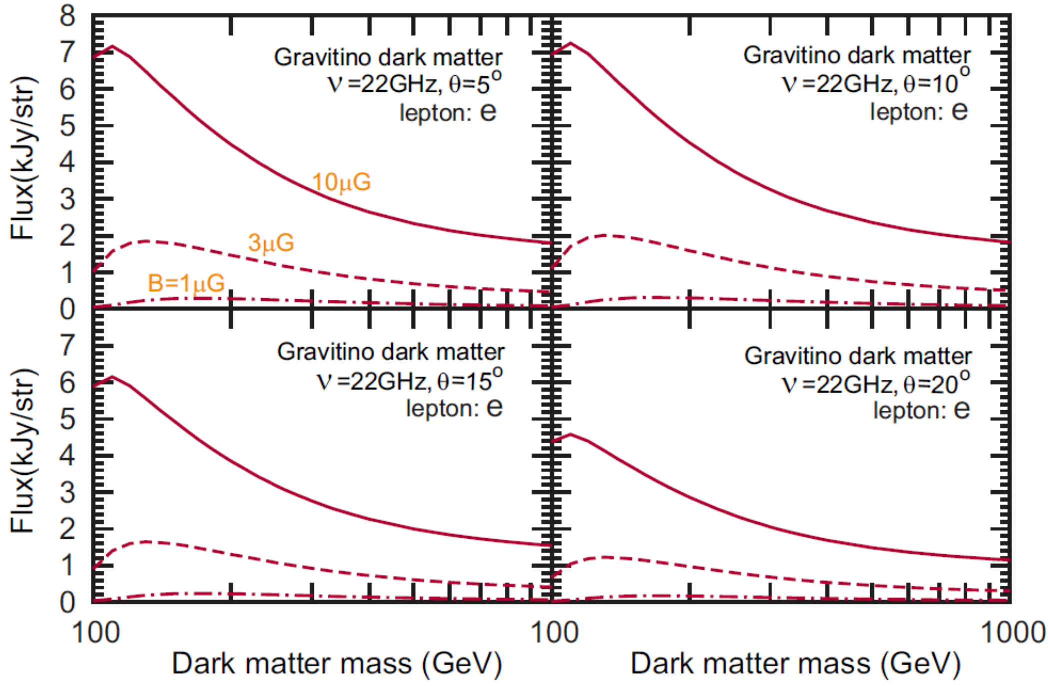
[Hooper,Finkbeiner,Dobler]

Numerical Results



Side view of Galaxy

Synchrotron Radiation Flux



[KI,Matsumoto, Moroi]

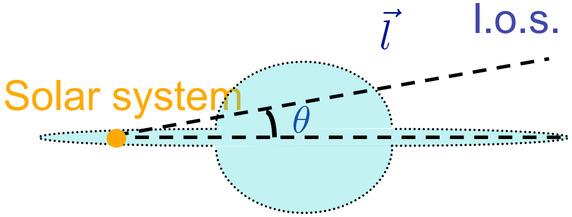
$\tau_{3/2} = 5 \times 10^{26}$ sec

Radiation flux in decaying gravitino-DM scenario is $\lesssim 1\ \mathrm{kJy/str}$, which is consistent with "WMAP Haze"

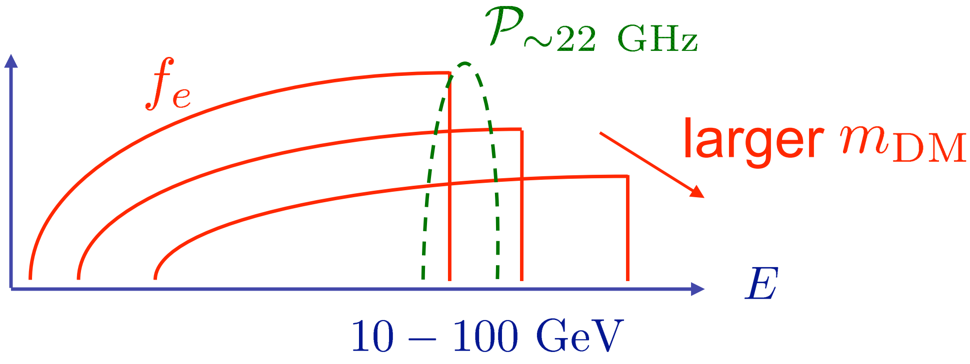
Formalism

$$J_\nu(\theta,\phi) = \frac{1}{4\pi}\int_{\mathrm{l.o.s.}} d\vec{l} \int dE\ \mathcal{P}(\nu, E)\ f_e(E,\vec{l})$$

$\mathcal{P}$: Synchrotron radiation energy per unit time and unit frequency from single electron



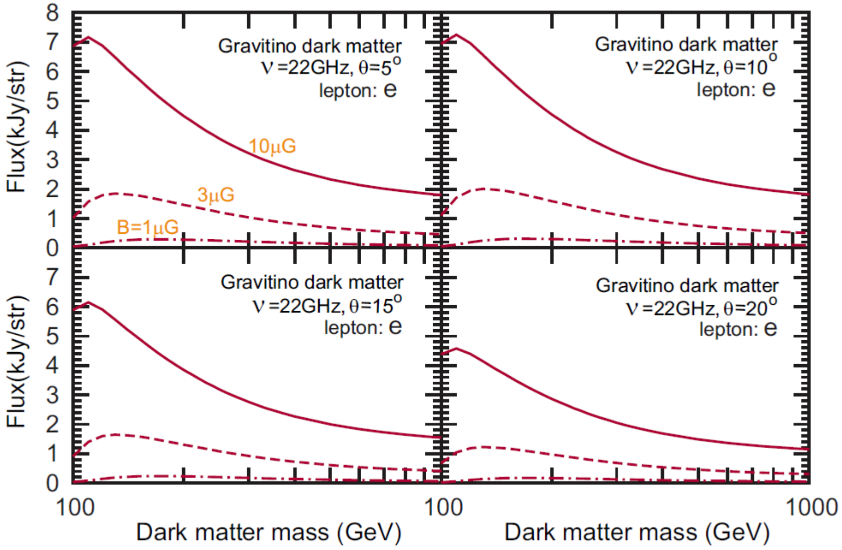
Side view of Galaxy

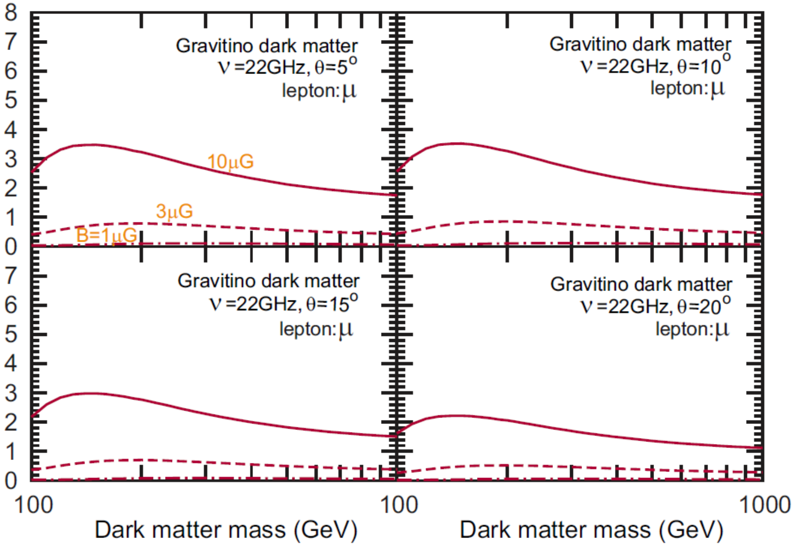


⟶ J_ν is expected to have a peak at $m_{\mathrm{DM}} \sim 100\ \mathrm{GeV}$ and suppressed by m_{DM}^{-1} in $m_{\mathrm{DM}} \gtrsim 100\ \mathrm{GeV}$

Numerical Results

- Gravitino DM



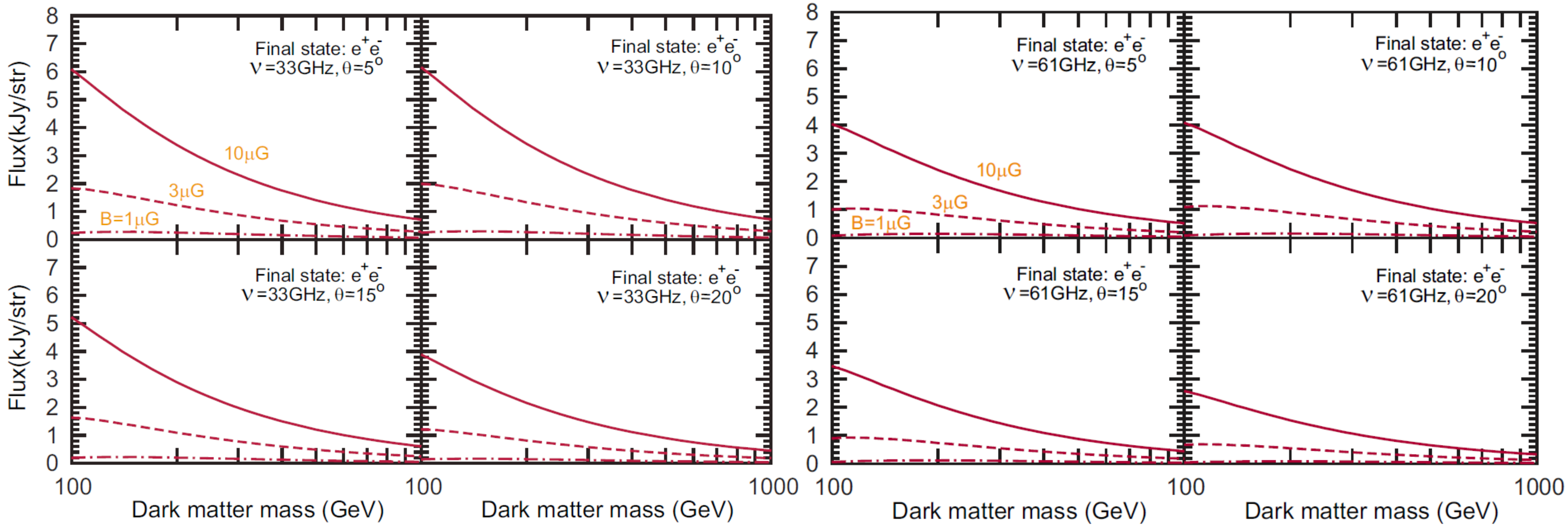


$$\tau_{3/2} = 5 \times 10^{26}\ \mathrm{sec}$$

Radio flux in decaying gravitino DM scenario is $\lesssim 1\ \mathrm{kJy/str}$, which is consistent with WMAP Haze

Numerical Results

- Final state: e^+e^- $(X \to e^+e^-)$



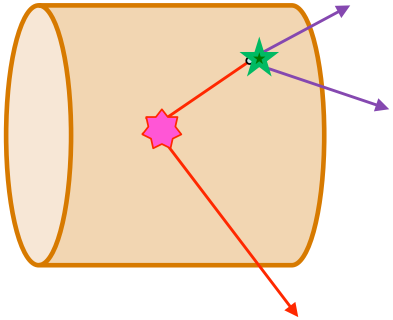
$\tau_X = 5 \times 10^{26}$ sec

Flux of $O(1\ \mathrm{kJy/str})$ is expected in leptonically decaying DM scenario

NLSP decay at the LHC

NLSP decay at LHC

In the gravitino DM scenario, NLSP decay can be detected at the LHC although its decay length is much larger than the detector size



When $\tau \lesssim 10^{-(3-5)}$ sec , the number of decaying NLSP is expected to be $\gtrsim O(10)$ for $\chi_1^0, \tilde{\tau}$ cases

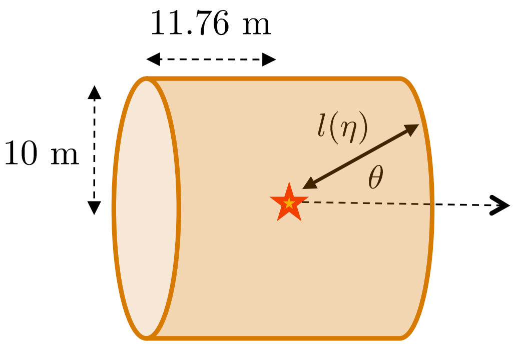
[K.I.,Ito,Moroi]

- χ_1^0 -NLSP: $\tau \simeq 1 \times 10^{-6} \text{ sec} \times \left(\frac{\kappa}{10^{-9}}\right)^{-2} \left(\frac{m_{\chi_1^0}}{200 \text{ GeV}}\right)^{-1}$
- $\tilde{\tau}$ -NLSP: $\tau \simeq 3 \times 10^{-5} \text{ sec} \times \left(\frac{\kappa}{10^{-9}}\right)^{-2} \left(\frac{m_{\tilde{\tau}}}{200 \text{ GeV}}\right)^{-1} \left(\frac{m_{\tilde{B}}}{300 \text{ GeV}}\right)^{2}$

→ The number of NLSP decay is expected to be $\gtrsim O(10)$ for the wide parameter region in this scenario

Moreover, with the numbers of decaying and total NLSP, lifetime can be determined when $\tau \lesssim 10^{-(3-5)}\ \mathrm{sec}$ with statistical uncertainty 30% [K.I.,Ito,Moroi]

$$\begin{aligned} N_{\mathrm{dec}} &= N_{\mathrm{tot}} \int d\eta dv\, f(\eta, v)(1 - e^{-l(\eta)/v\gamma\tau}) \\ &\simeq N_{\mathrm{tot}} \int d\eta dv\, f(\eta, v) \frac{l(\eta)}{v\gamma} \frac{1}{\tau} \\ &\equiv N_{\mathrm{tot}} \frac{L_{\mathrm{eff}}}{c\tau} \end{aligned}$$



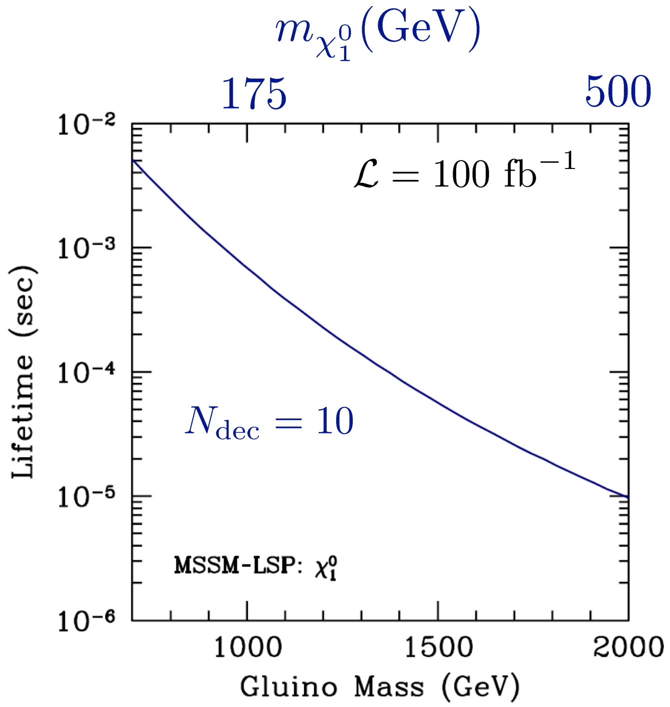
$\eta = -\ln\tan(\theta/2)$

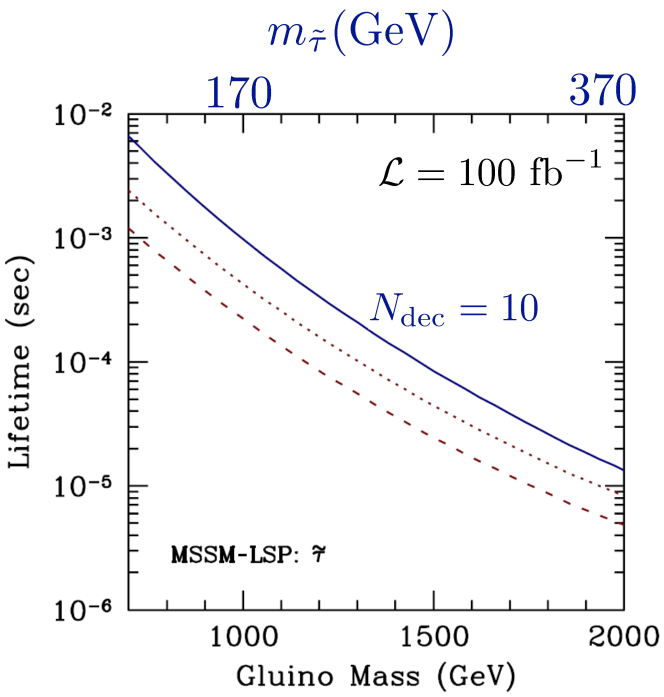
$N_{\mathrm{dec/tot}}$: Number of (decaying/total) NLSP
$f(v, \eta)$: Momentum distribution of NLSP
$1 - e^{-l(\eta)/v\gamma\tau}$: Decay probability within $l(\eta)$

In SUSY event, $L_{\mathrm{eff}} \sim 10\ \mathrm{m}$,which is not sensitive to mass spectrum [simulated by HERWIG and ISAJET packages], thus

Observables: $N_{\mathrm{dec}}, N_{\mathrm{tot}} \longrightarrow \tau$

NLSP decay at LHC





SUSY event simulated by HERWIG package in minimal gauge mediation (mass spectrum is given by ISAJET package)