INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Decaying Dark Matter and cosmic rays

12. Nov. 2009

@KEK

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Collaborators: C-R.Chen, S.Shirai, S.Mandal, T.Yanagida

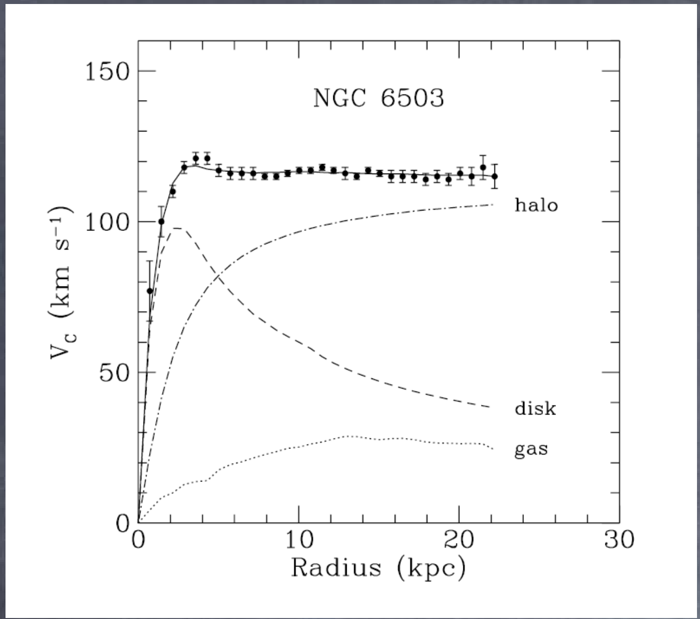
Dark Matter

How can we know the presence of "dark" matter?

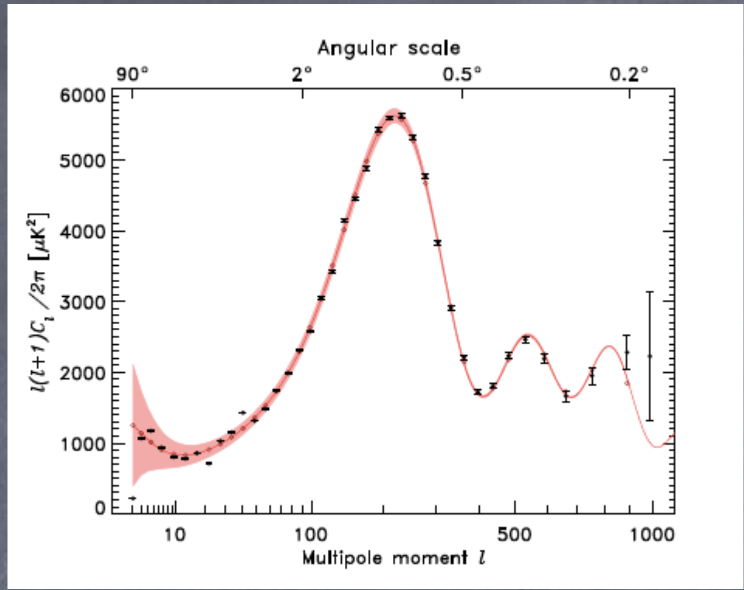
Gravity

It's not just a good idea.
It's the law!

rotation curve

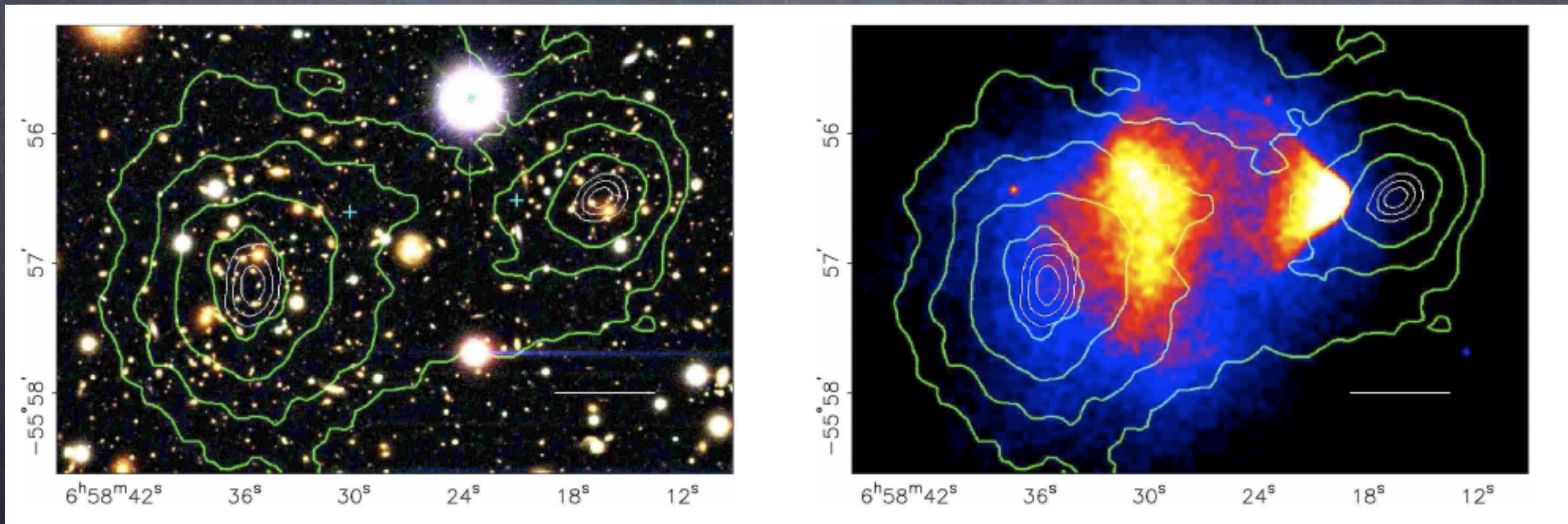


CMB



lensing

Bullet cluster



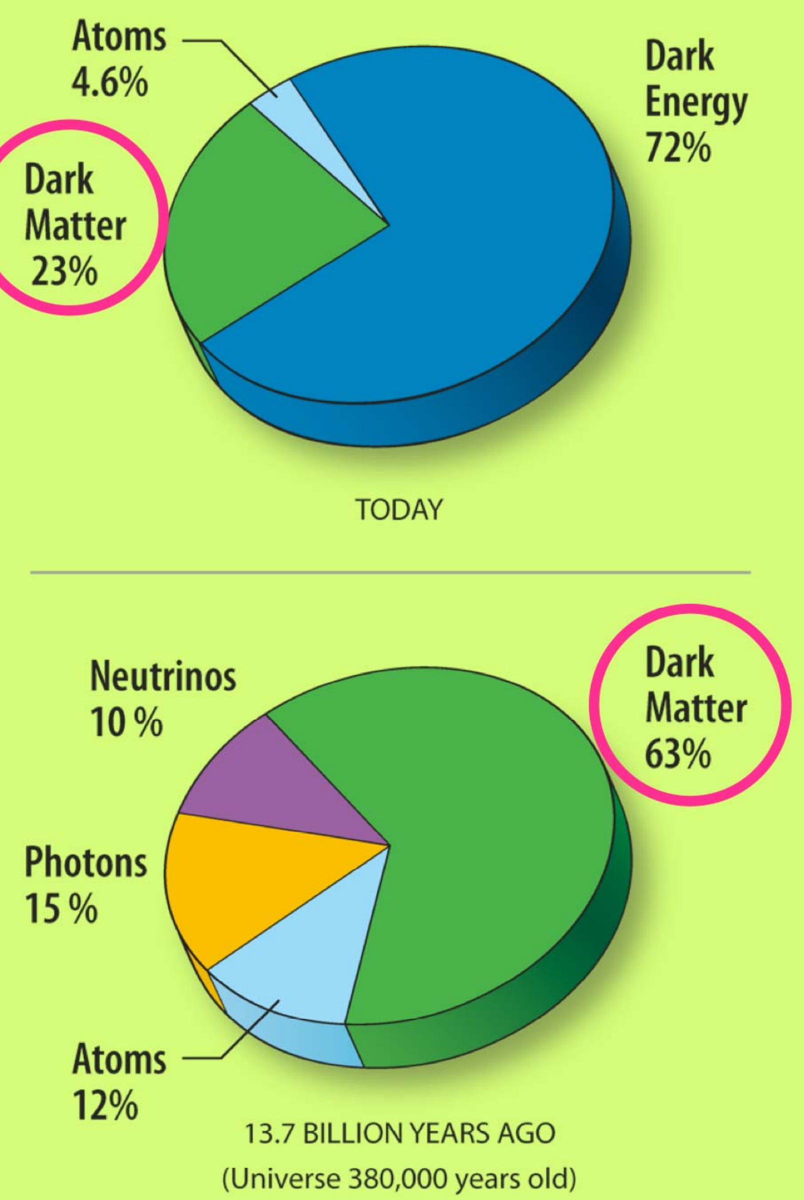
+ large scale structures.

Dark Matter

The presence of DM has been firmly established.

$$\Omega_{DM} \sim 0.2$$

- CMB observation
- Rotation curves
- Structure formation
- Big bang nucleosynthesis



(taken from WMAP webpage)

Dark Matter Candidates

Many

Must be electrically neutral, long-lived and cold.

No DM candidates in SM.

- SUSY

  LSP is long-lived if R-parity is a good symmetry.

  e.g.) neutralino, gravitino, etc. (right-handed sneutrino, axino).

- Little Higgs, UED, etc.

  The lightest T-parity/KK-parity particles

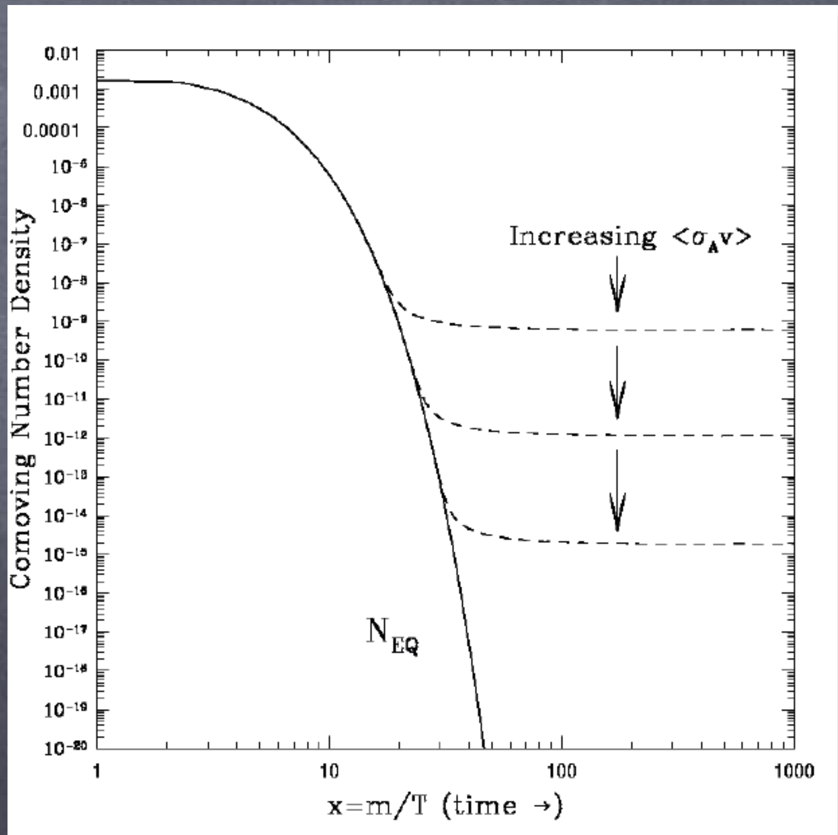
- Others Q-ball, saxion, light moduli, sterile nu, etc...

WIMP "miracle"?

- Thermal relic abundance of WIMPs of mass O(100)GeV - O(1)TeV is close to the observed DM density.

$$\Omega_{\rm WIMP} = \frac{0.3}{\langle \sigma v \rangle / ({\rm pb})}$$

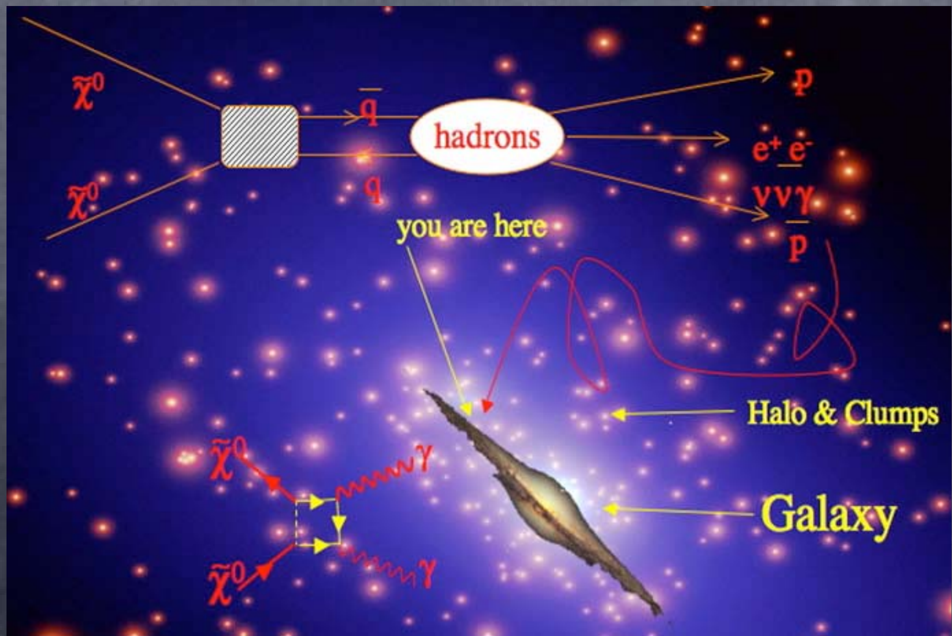
$$\langle \sigma v \rangle_{\rm thermal} \simeq 3 \times 10^{-26}\, {\rm cm}^3/{\rm sec}$$



Sounds reasonable, but it is better keep in mind other possibilities.

Dark matter may not be completely dark.

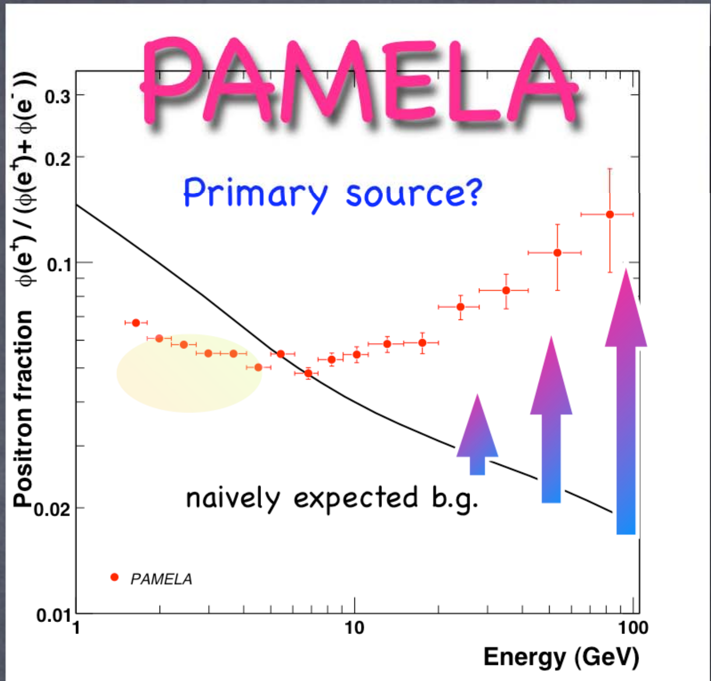
- Collider
- Direct detection
- Indirect search: annihilation/decay of dark matter



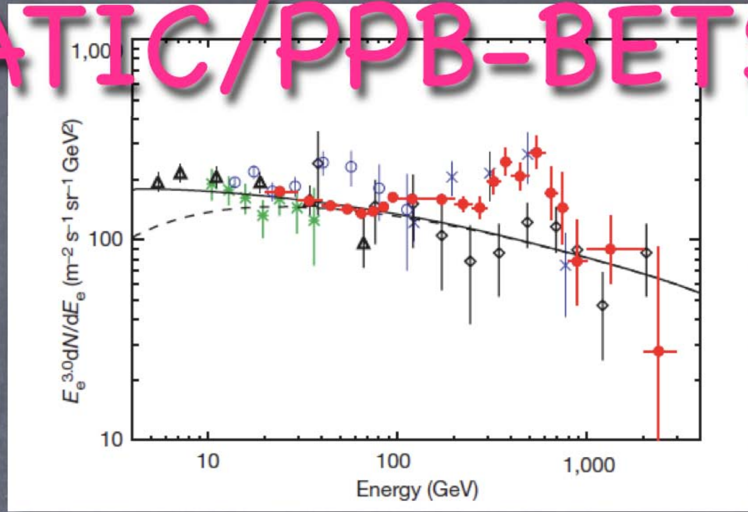
(http://pamela.roma2.infn.it/index.php)

2. PAMELA, ATIC/PPB-BETS, Fermi, and H.E.S.S. results

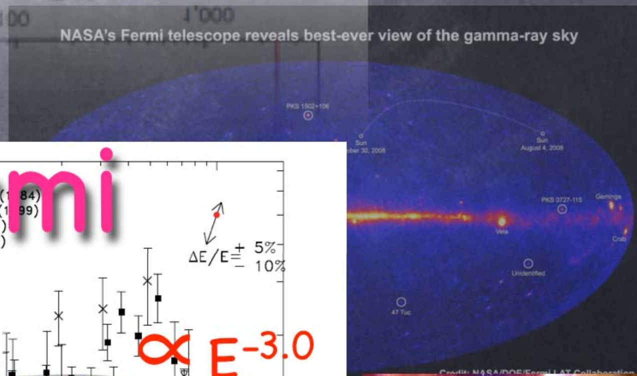
PaMeLa a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

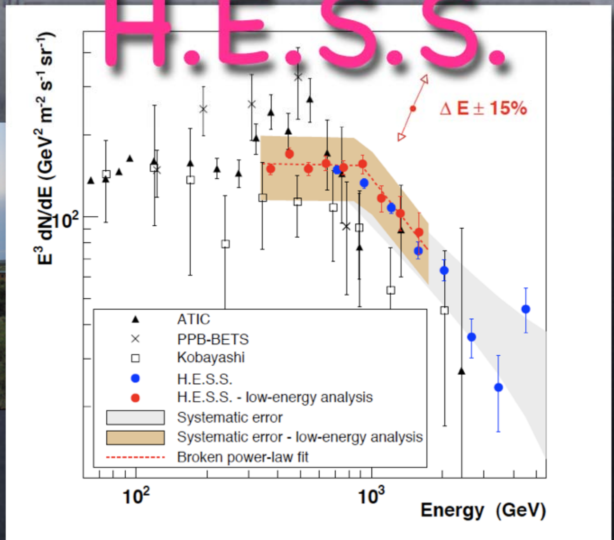


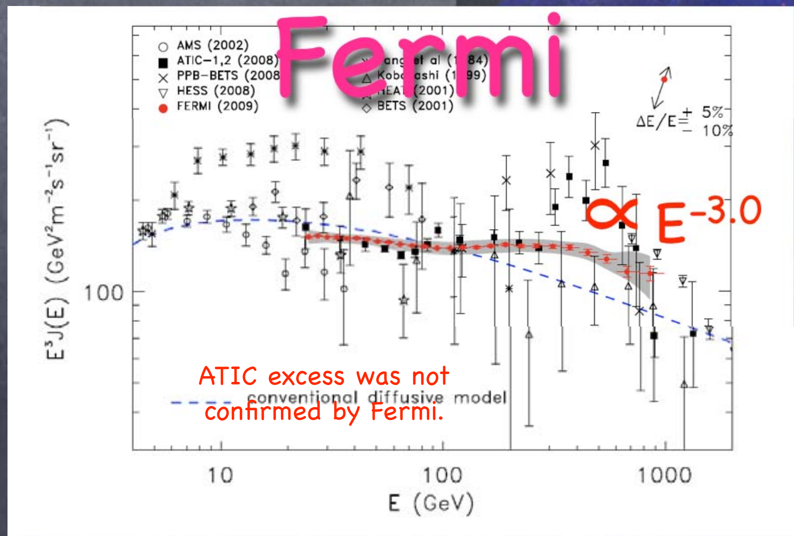
Talk by Casolino



Talk by Torii





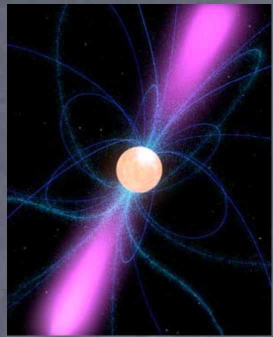


Talk by Uchiyama

Combining the PAMELA, Fermi, and H.E.S.S. results, it is likely that there is an excess in the CR $e^{-}+e^{+}$ from several tens GeV up to 1TeV.

Interpretations of CR $e^{-}+e^{+}$ "excess"

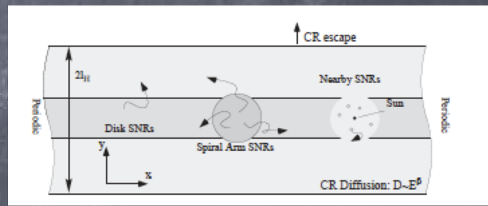
- Pulsars



[Talk by Kawanaka]

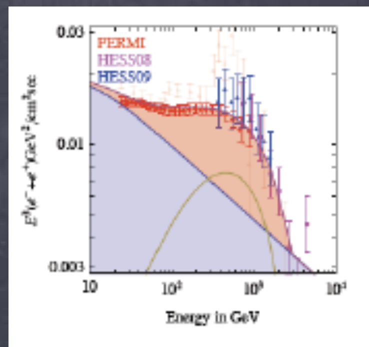
- Modification in propagation or acceleration/production in local SNR

[Talk by Moskalenko, Sarkar]

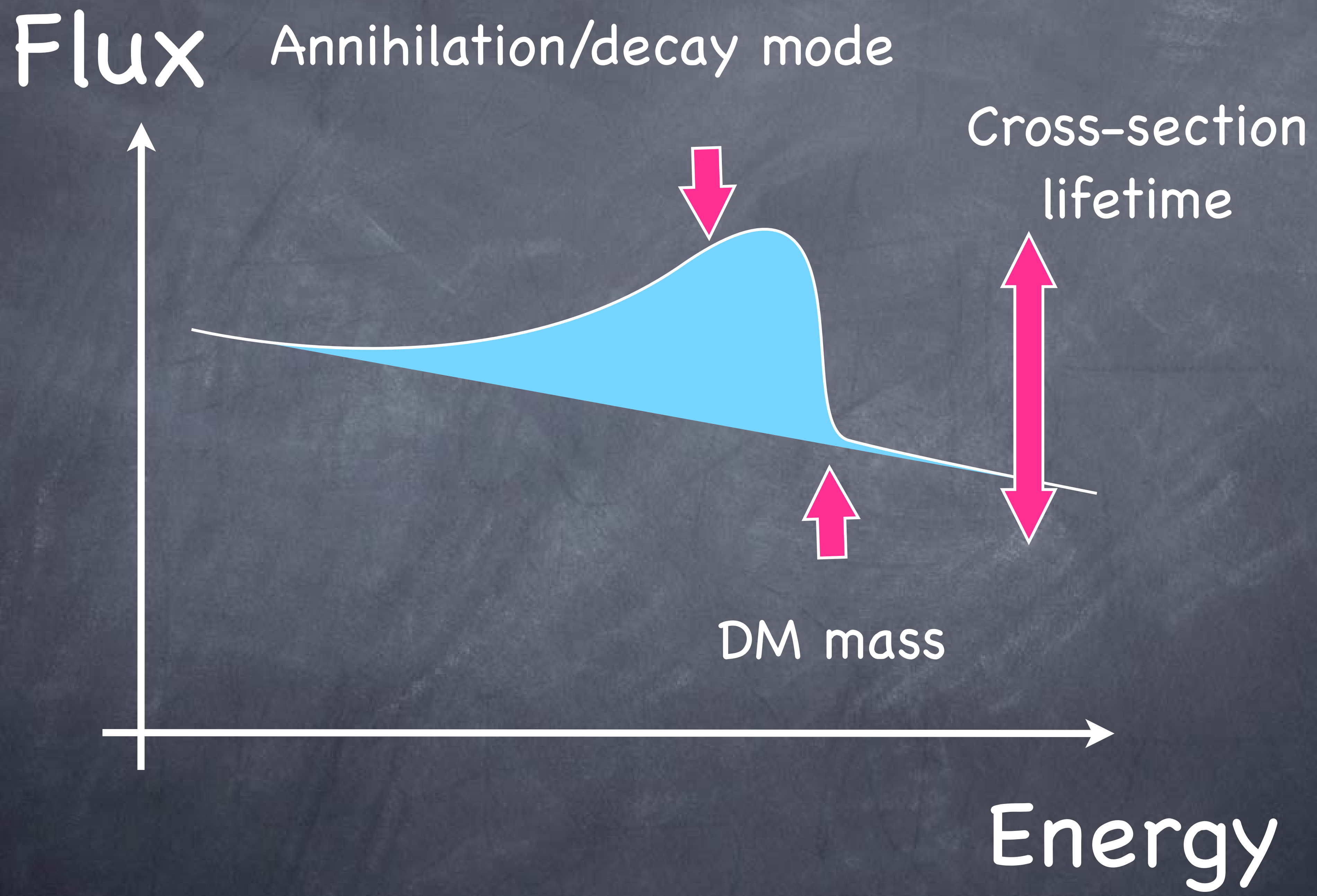


- Dark Matter decay/annihilation

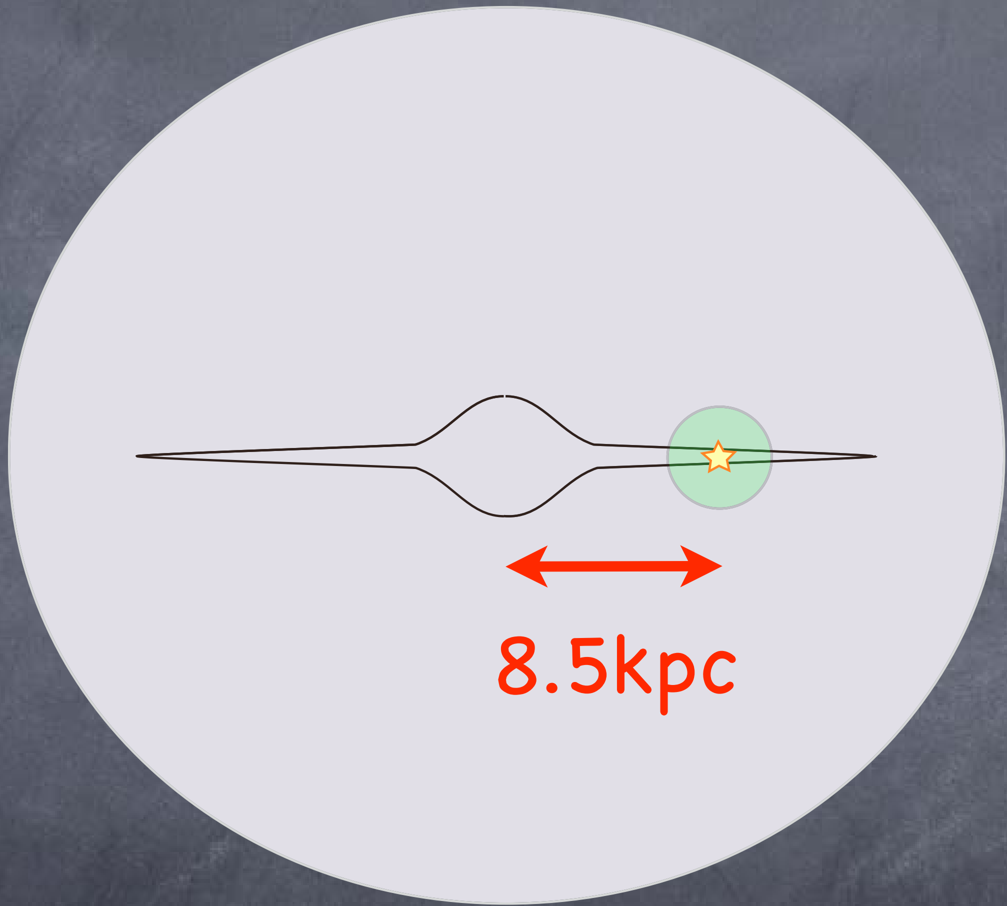
[Talk by Fox, Yamada, Kohri]



3. Dark Matter


Flux
Annihilation/decay mode
Cross-section
lifetime
DM mass
Energy

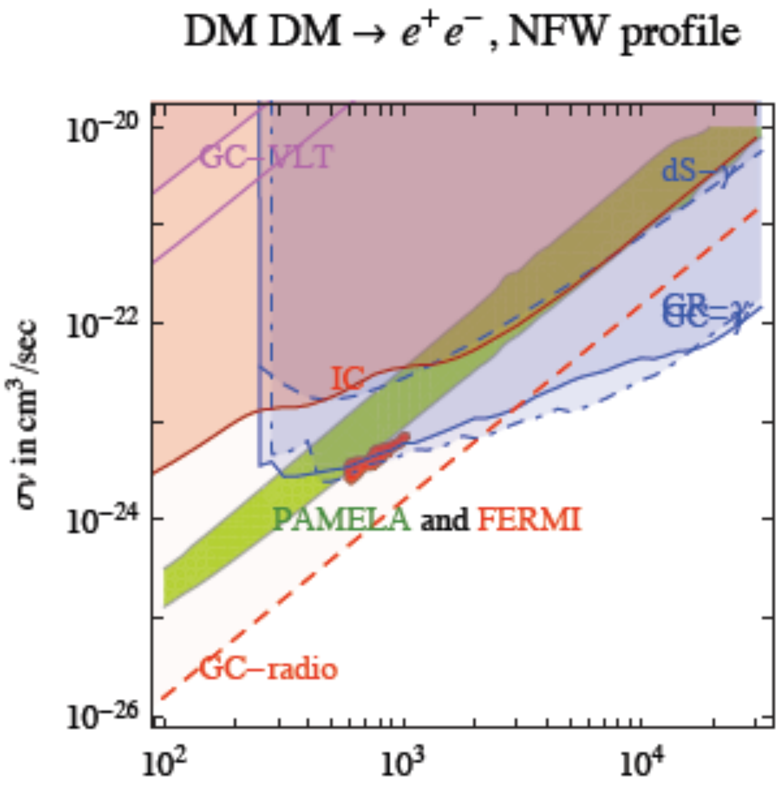
The cosmic-ray particles diffuse in our Galaxy.

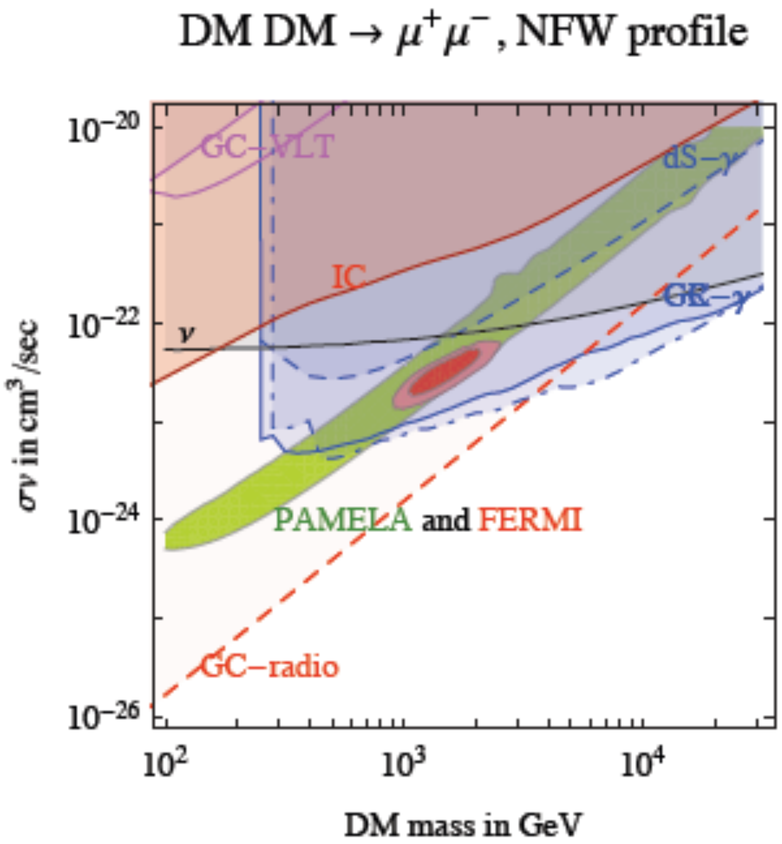


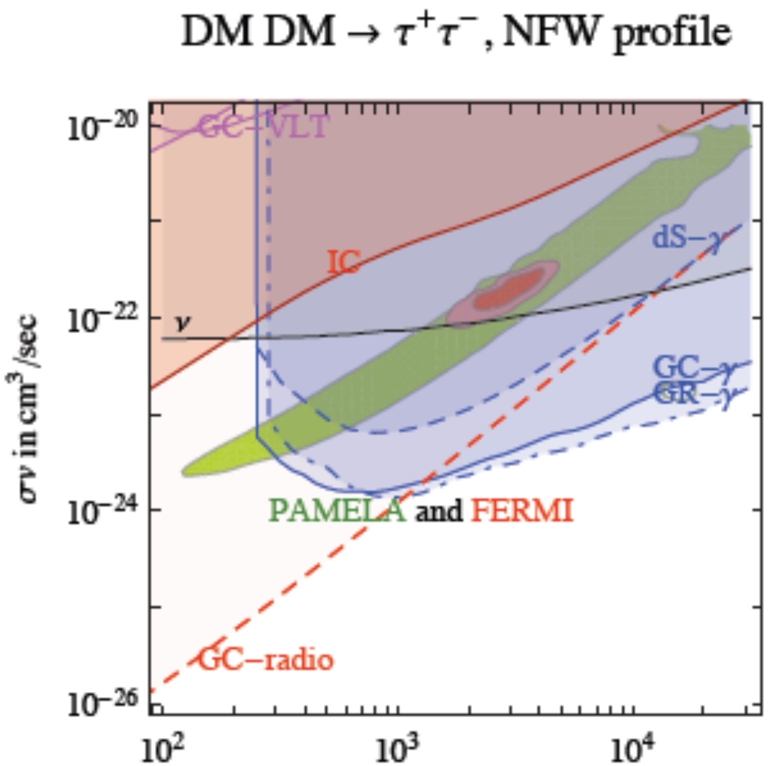
1 pc = 3.26 lyr

= 3×10^{16} m

In particular, 1TeV electron/positron loses its most of the energy in 10^5yrs, traveling about 1kpc.

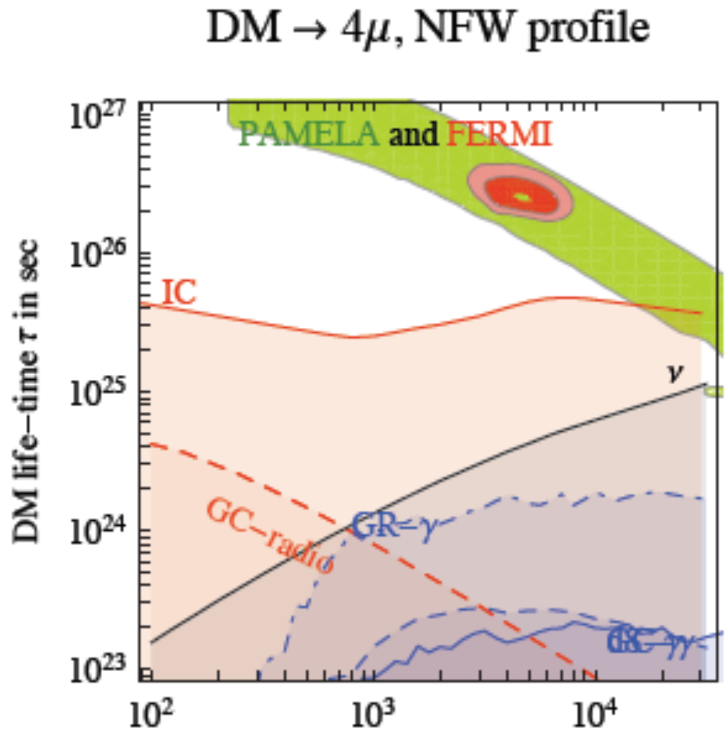


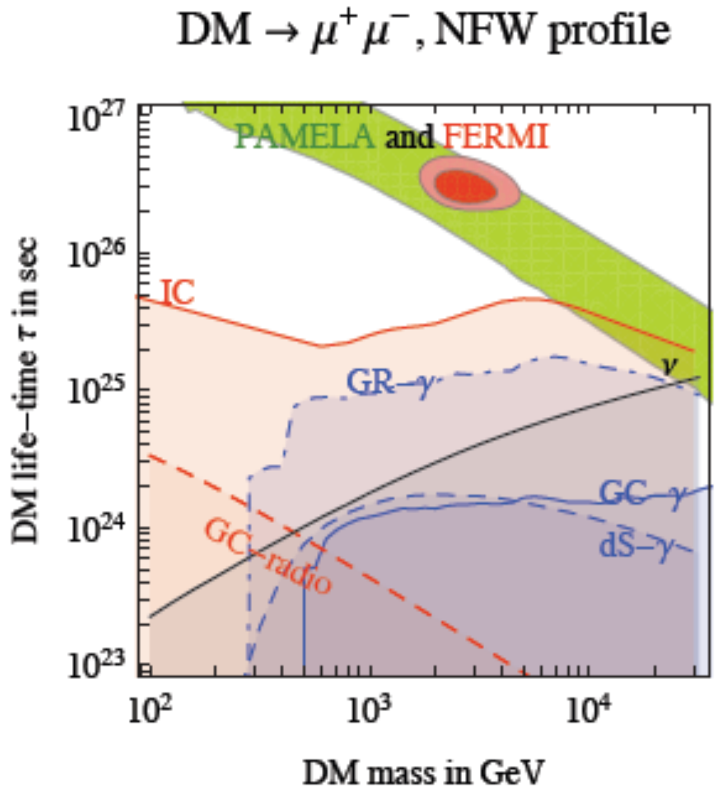


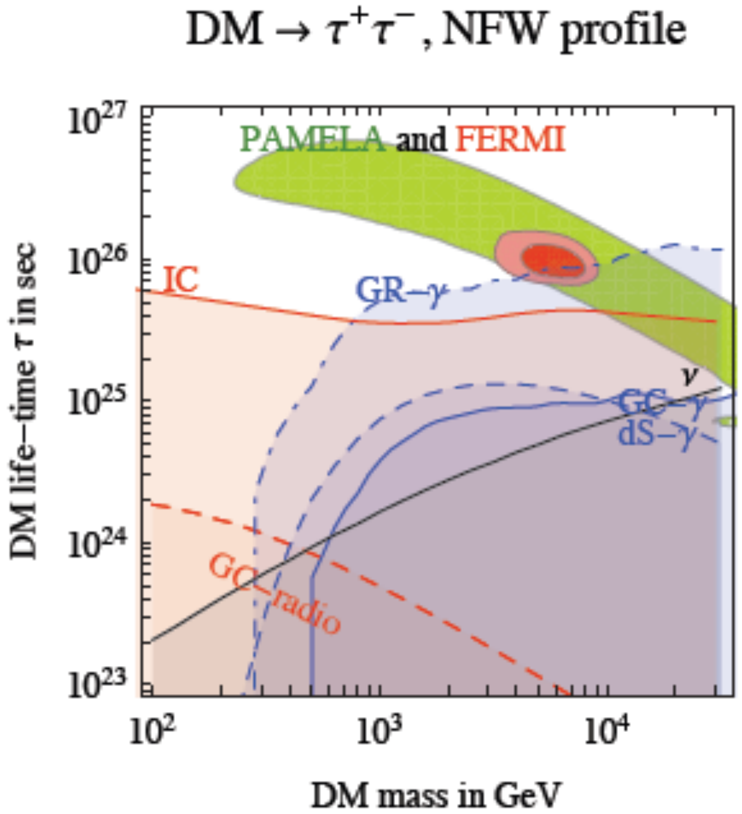


NFW Annihilation

Meade et al, arXiv:0905.0480







NFW Decay

Meade et al, arXiv:0905.0480

- Monochromatic electron production gives a poor fit to the Fermi data. (Good for ATIC)
- Softer spectrum, e.g. (mu, tau) production is favored by Fermi.
- DM annihilation scenario is disfavored.
- DM decay scenario can satisfy the observational constraints.
- DM mass must be in the TeV scale!

Decaying DM scenario

Dark matter particle with

Mass: a few TeV (or heavier)

Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

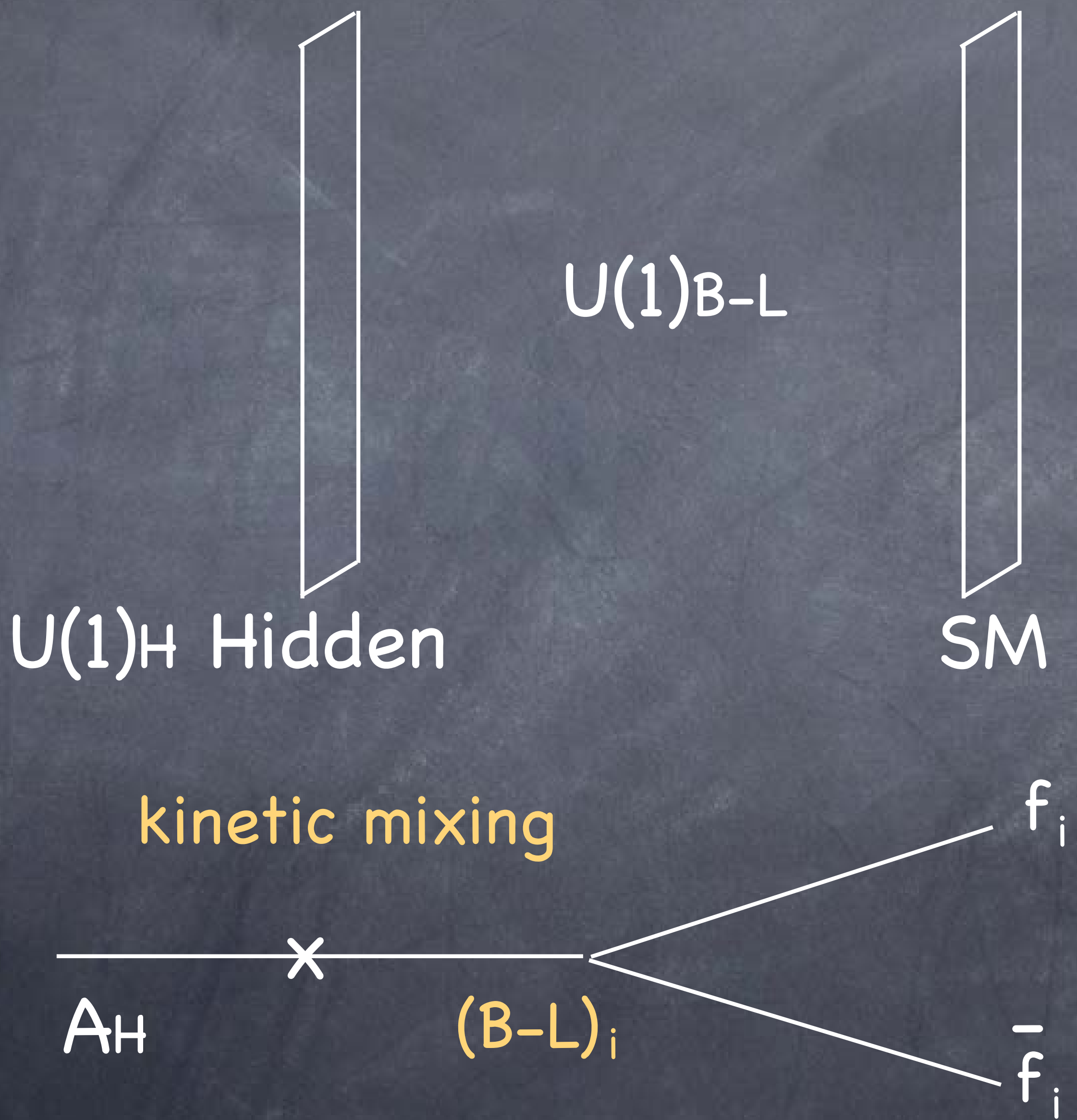
Insensitive to the clumpy structure.

The longevity of DM may be a puzzle, especially if the mass is above 1TeV.

Hidden U(1) Gauge Boson

Hidden-gauge-boson DM

Chen, Takahashi, Yanagida (2008)
arXiv:0809.0792, 0811.0477



Lifetime OK

$$\mathcal{L}_{(4D)} = -\frac{1}{4}F^{(H)}_{\mu\nu}F^{(H)\mu\nu} - \frac{1}{4}F^{(B)}_{\mu\nu}F^{(B)\mu\nu} + \frac{\lambda}{2}F^{(H)}_{\mu\nu}F^{(B)\mu\nu}$$

$$+\frac{1}{2}m^2 A_{H\mu}A^\mu_H + \frac{1}{2}M^2 A_{B\mu}A^\mu_B,$$

kinetic mixing

We can make A's canonical and express them in terms of the mass-eigenstates:

$$A_B \simeq A'_B - \lambda\frac{m^2}{M^2}A'_H,$$

- Coupling to SM fermions:

$$\mathcal{L}_{\rm int} = q_i A^\mu_B\,\bar\psi_i\gamma_\mu\psi_i \supset -\lambda\, q_i\frac{m^2}{M^2}A'^\mu_H\,\bar\psi_i\gamma_\mu\psi_i,$$

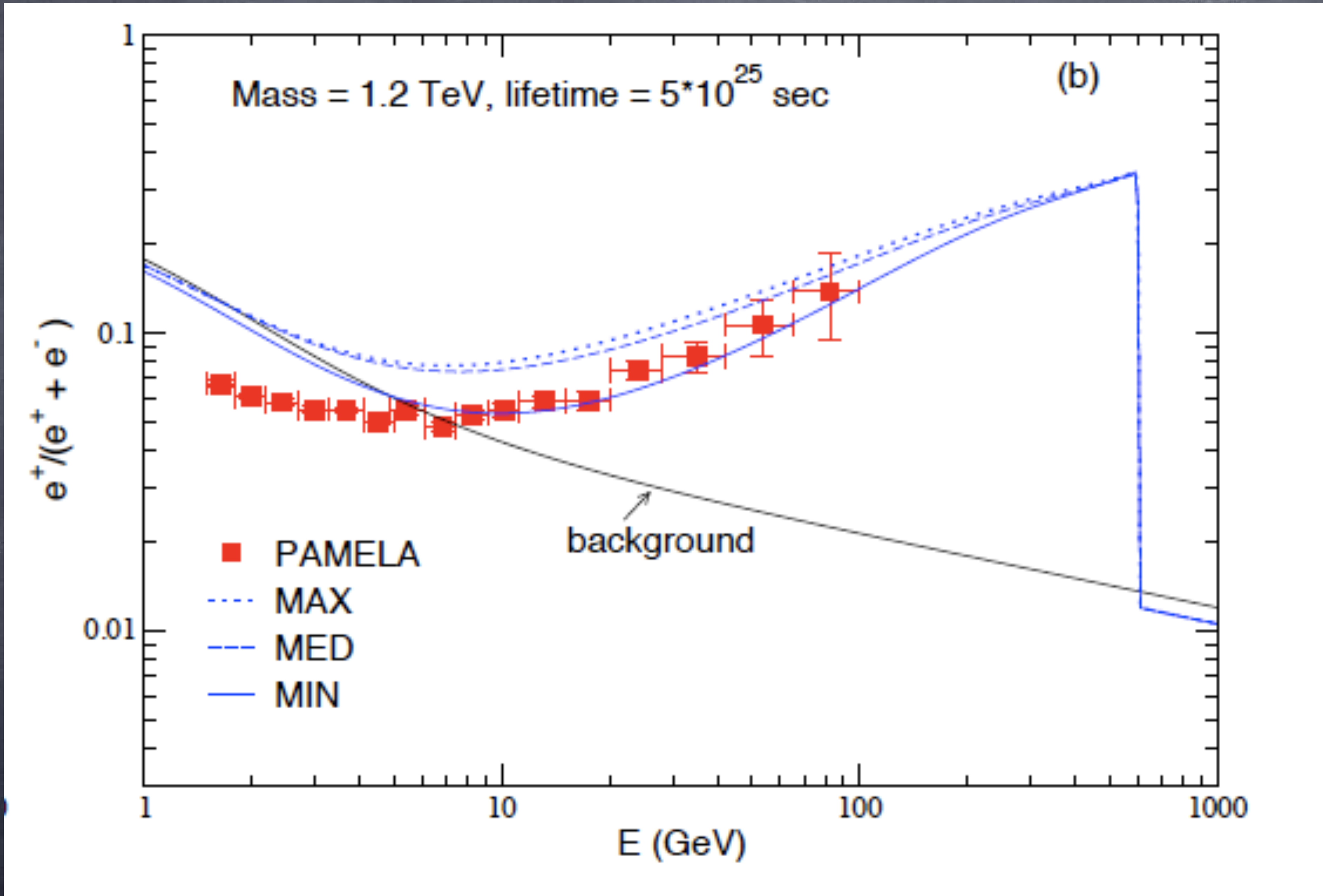
B-L charge

$$\tau \simeq 1\times 10^{26}\,{\rm sec}\left(\sum_i N_i q_i^2\right)^{-1}\left(\frac{\lambda}{0.01}\right)^{-2}\left(\frac{m}{1.2\,{\rm TeV}}\right)^{-5}\left(\frac{M}{10^{15}{\rm GeV}}\right)^4,$$

Lepton dominated decay modes!

	Quarks	Leptons
Nc (B-L)^2	1/3	1
BR	0.25	0.75

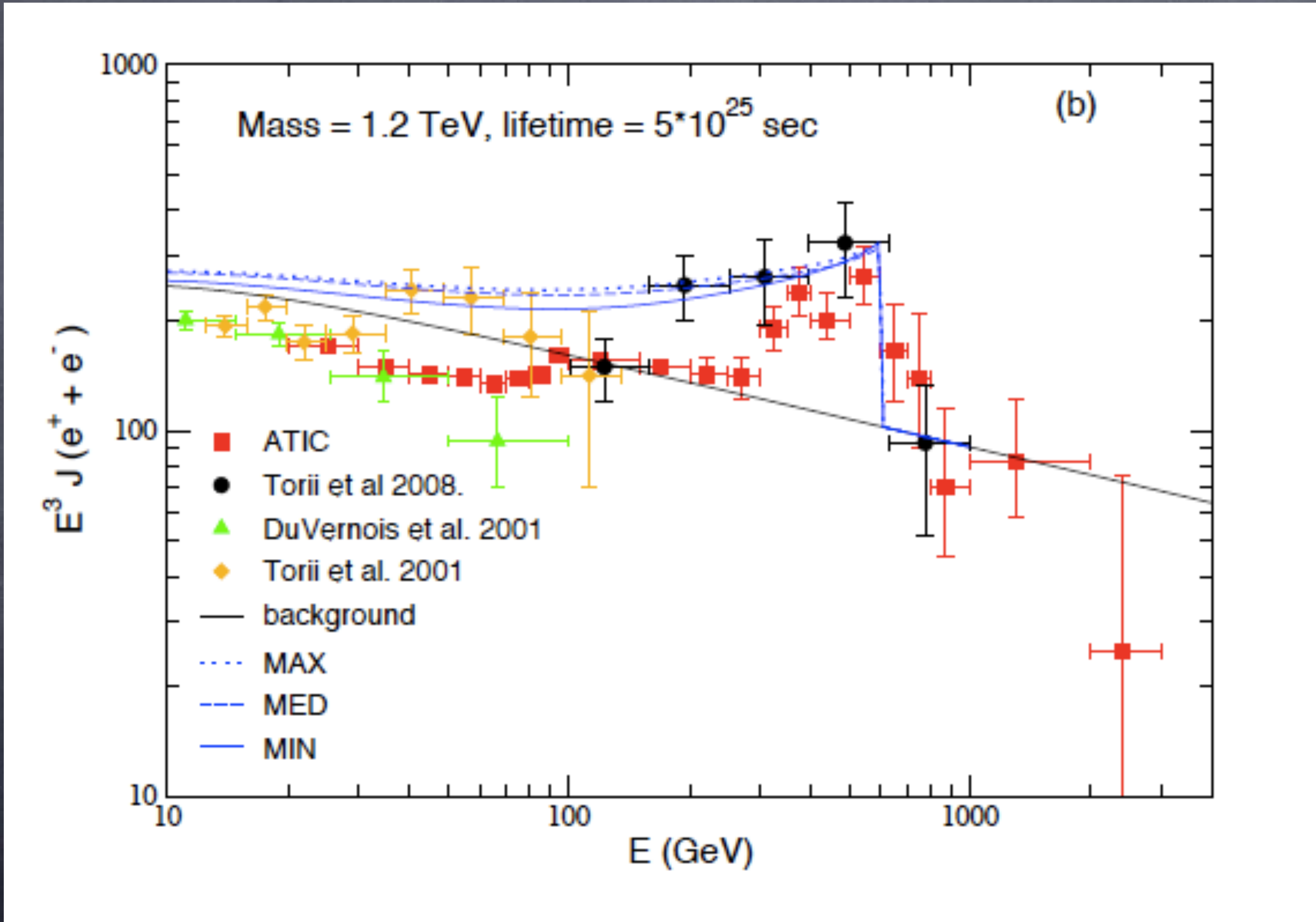
Positron Fraction



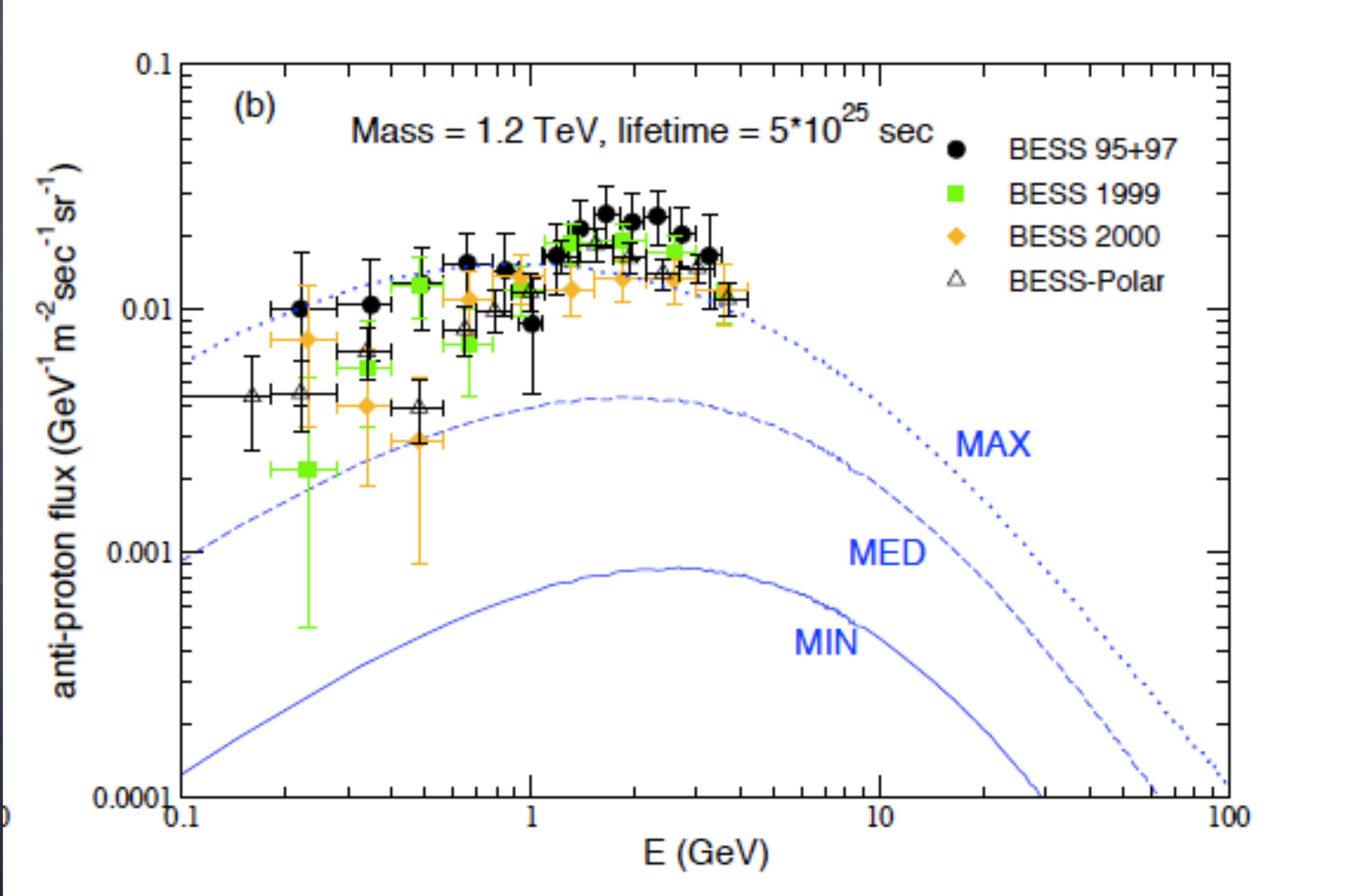
Chen, Nojiri, Takahashi, Yanagida (2008)

- Electron + positron spectrum:

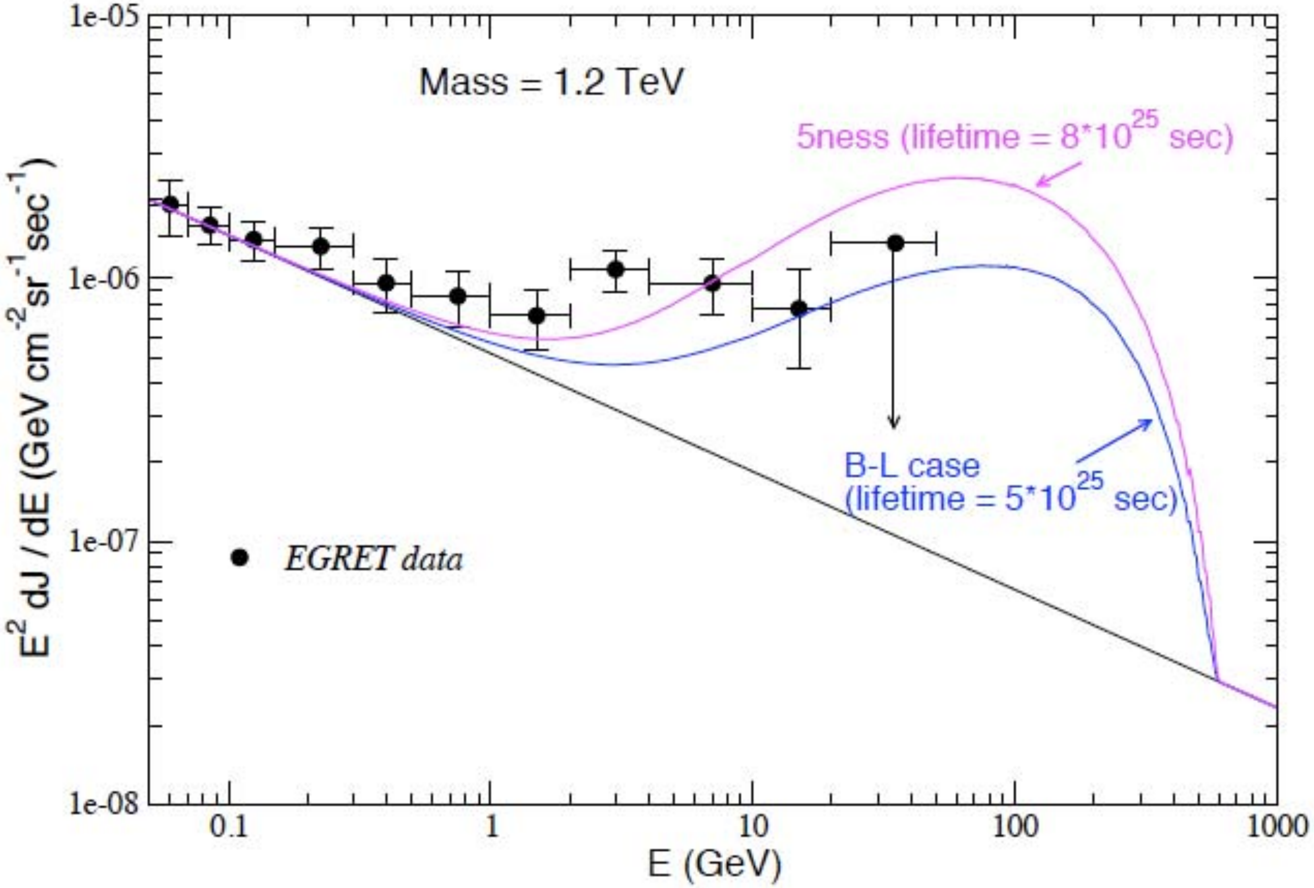
Chen, Nojiri, Takahashi, Yanagida (2008)



Hidden-gauge-boson DM

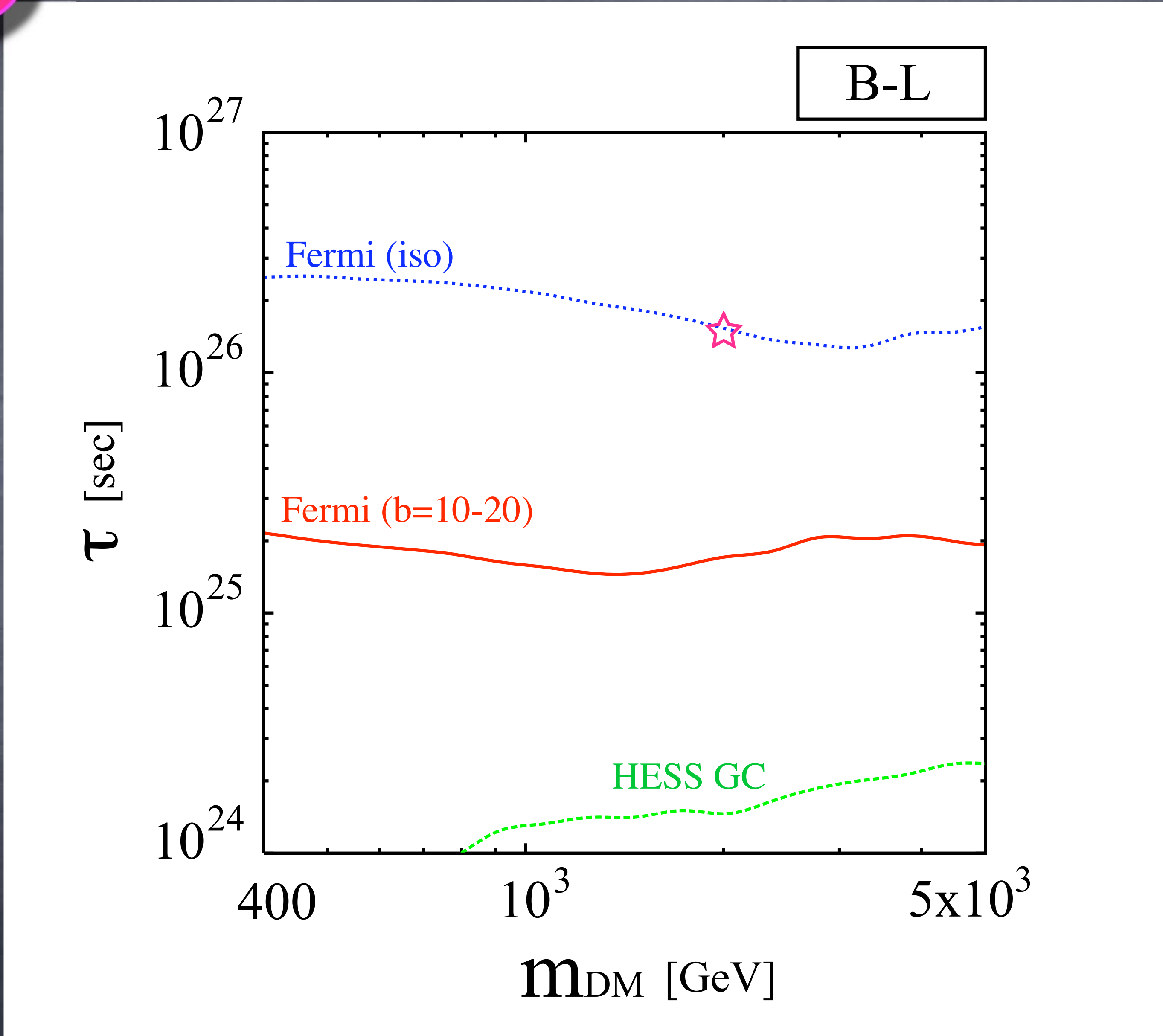


Diffuse Gamma-ray background



Gamma-ray constraints

Updated



C-R.Chen, S. Mandal, FT, arXiv:0910.2639

Wino LSP DM

Shirai, FT, Yanagida, arXiv:0905.0388

Phys.Lett.B680:485-488,2009.

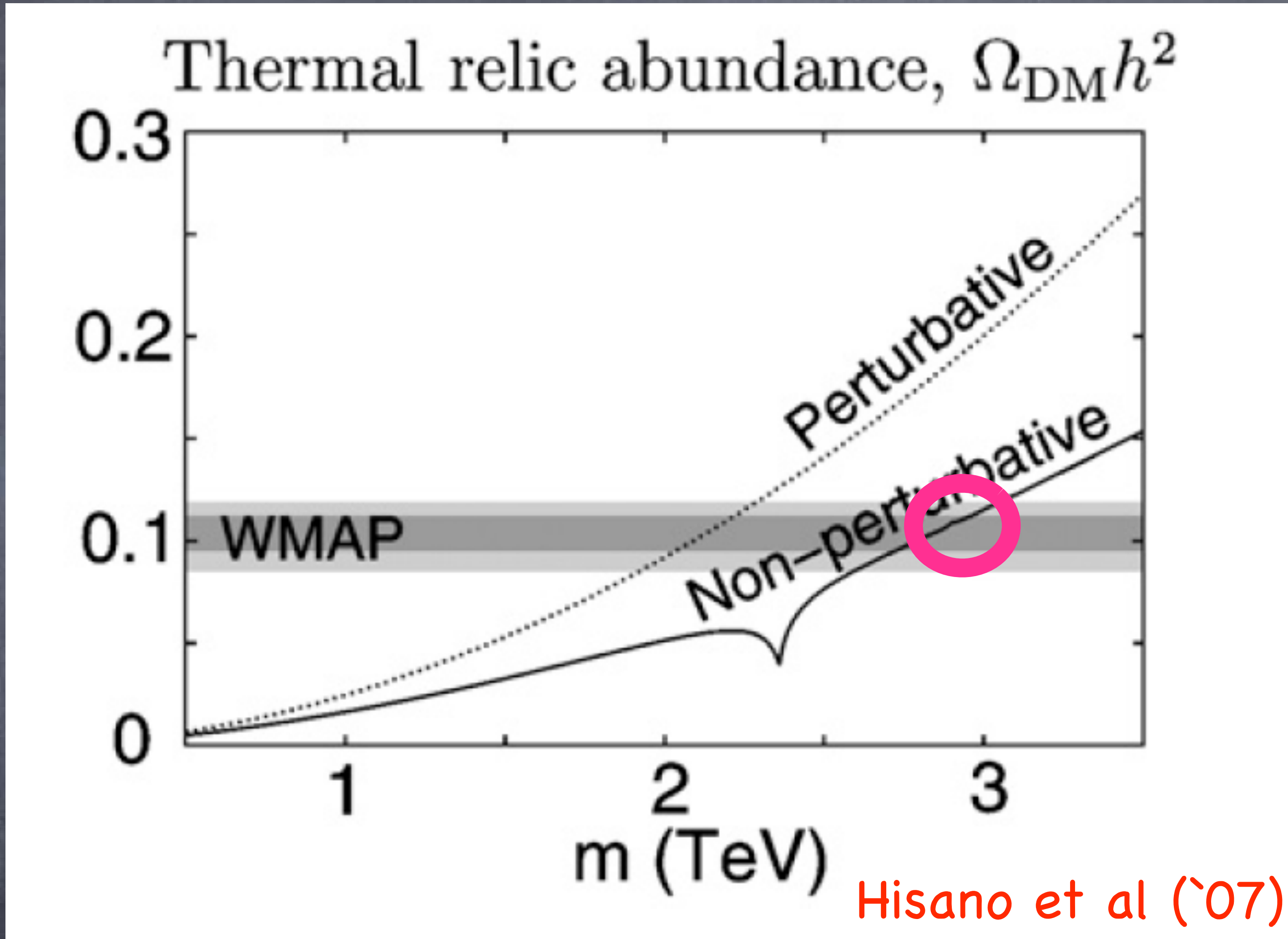
The neutralino LSP scenario is interesting, because thermal relic production can naturally explain the DM abundance.

The lightest neutralino is Bino-, Higgsino-, or Wino-like, or a certain mixture of those.

Let us focus on the **Wino LSP** scenario,

which is realized in anomaly-mediation.

Thermal relic Wino DM



$$m_{\tilde{W}} \sim (2.7 - 3)\,\mathrm{TeV}$$

The R-parity must be a good symmetry for the Wino LSP to account for the observed DM.

Is the R-parity an exact symmetry or just an approximate one?

In order to have a (almost) vanishing cosmological constant, the superpotential must have a constant term:

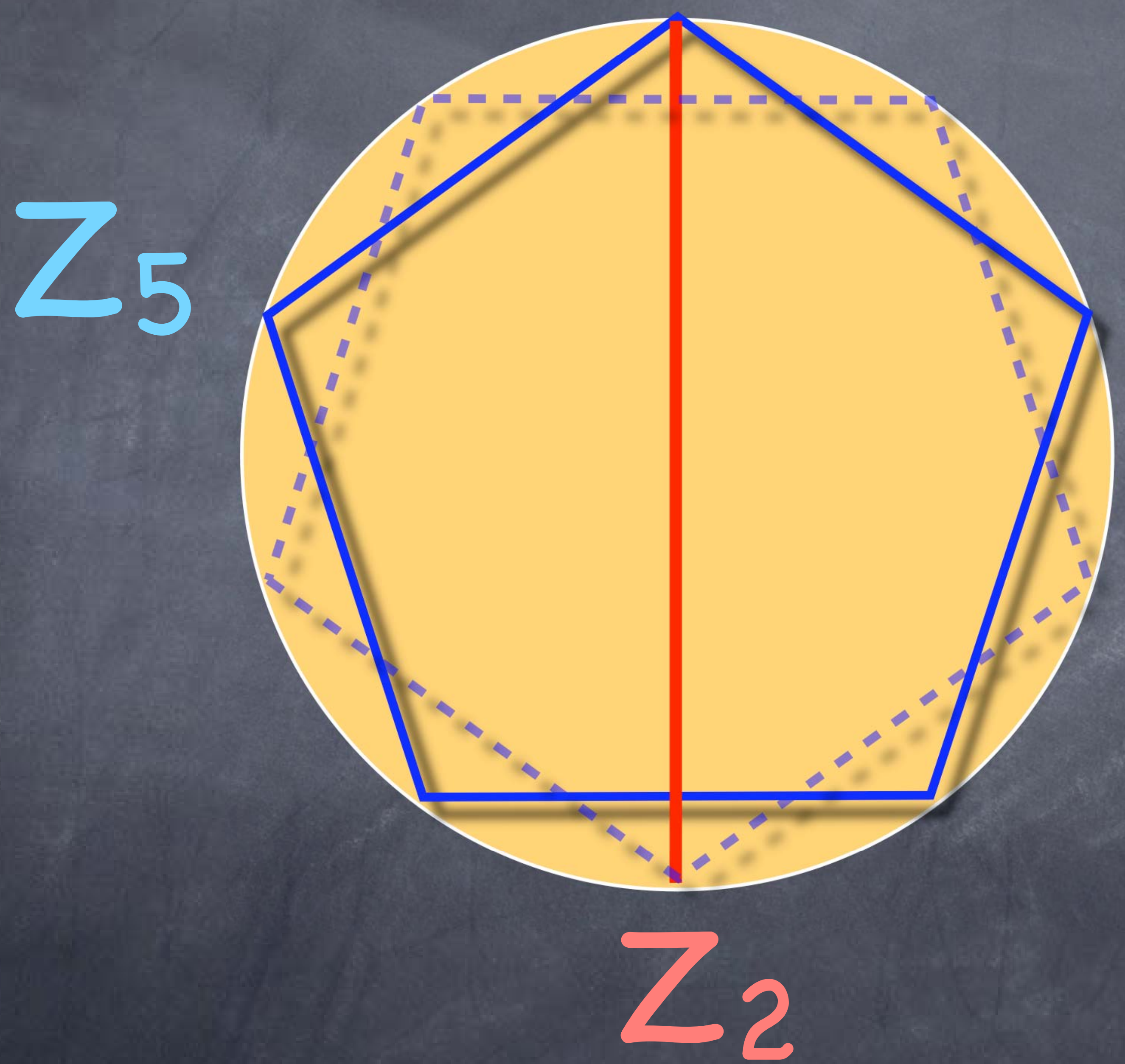
$$W \supset C_0 = m_{3/2} M_P^2$$

The constant term breaks a continuous U(1)R symmetry down to the Z_2 symmetry (R parity).

However, a continuous $U(1)_R$ may not be the symmetry of the theory at high energies.

If the R symmetry in the high energy is a discrete one (e.g. Z_{2k+1}), the R parity is broken by C_0.

As an example, let us consider the case of k = 2, namely, Z_5 R symmetry.


Z5
Z2

R-parity violation

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$	H_u	H_d	C_0
R	1	1	1	1	1	0	0	2

In addition to the SM Yukawa interactions, the following operator is allowed by the symmetry.

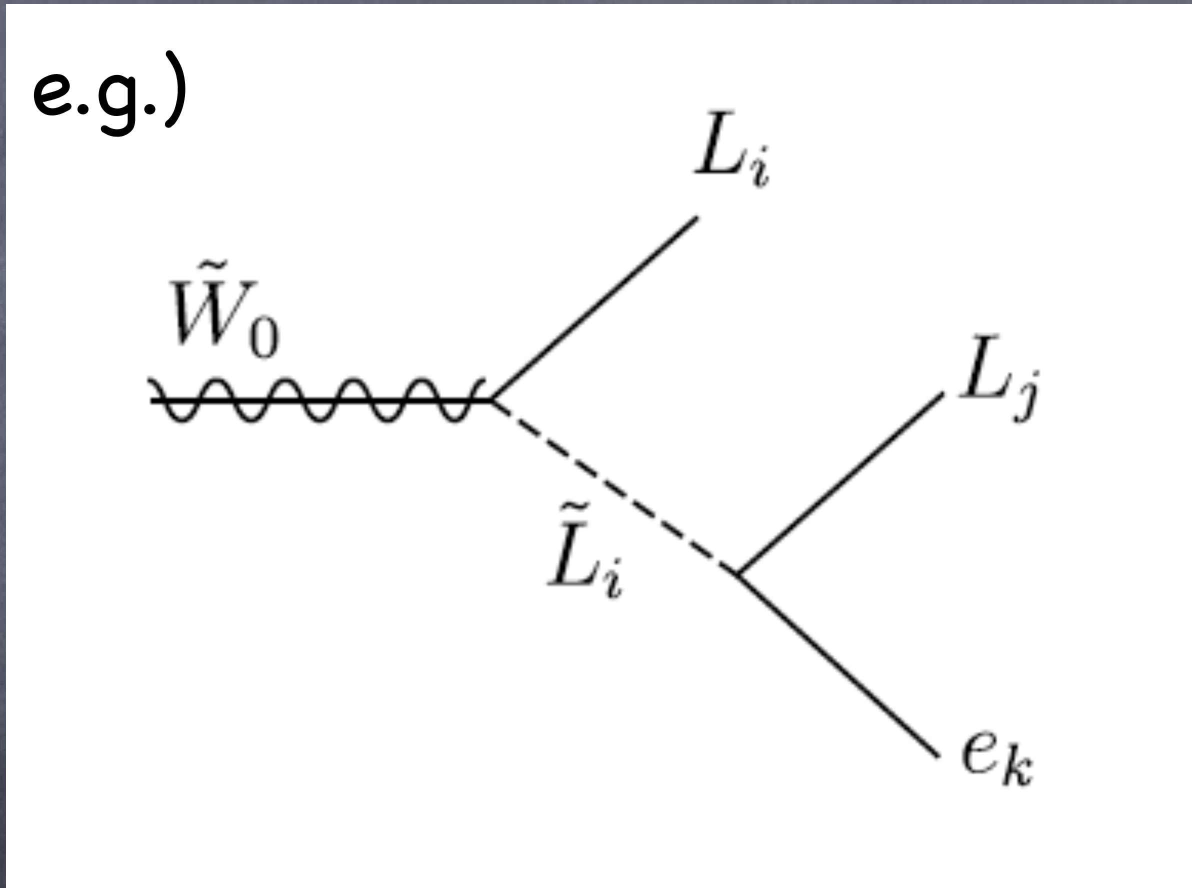
$$W = \kappa_{ijk}(C_0)^2\bar{e}_i L_j L_k,$$

2x2+1+1+1 = 7 ≡ 2 (mod 5)

w/ $\kappa \sim \mathcal{O}(1)$

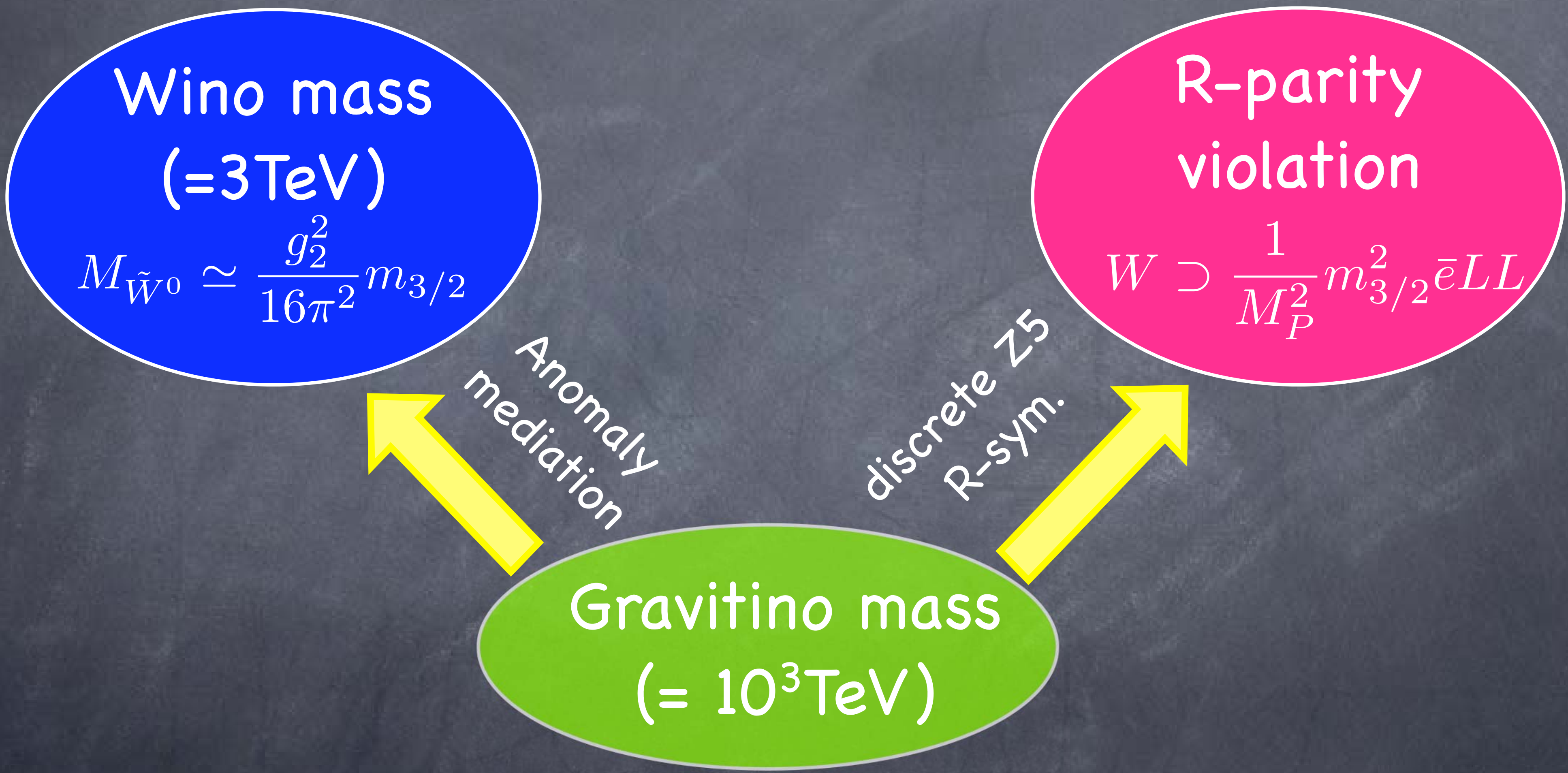
and similar terms for quark multiplets.

In our model, the Wino DM of mass 3TeV is not absolutely stable, and decays through the R-parity violating operator, eLL.



$$\Gamma \sim (10^{27}\mathrm{sec})^{-1}\,\kappa^2\left(\frac{m_{3/2}}{10^3\ \mathrm{TeV}}\right)^4\left(\frac{m_{\widetilde{W}^0}}{3\ \mathrm{TeV}}\right)^5\left(\frac{m_{\tilde{\ell}}}{5\,\mathrm{TeV}}\right)^{-4},$$

Note that both the Wino mass and the size of the R-parity violation are determined by the gravitino mass.



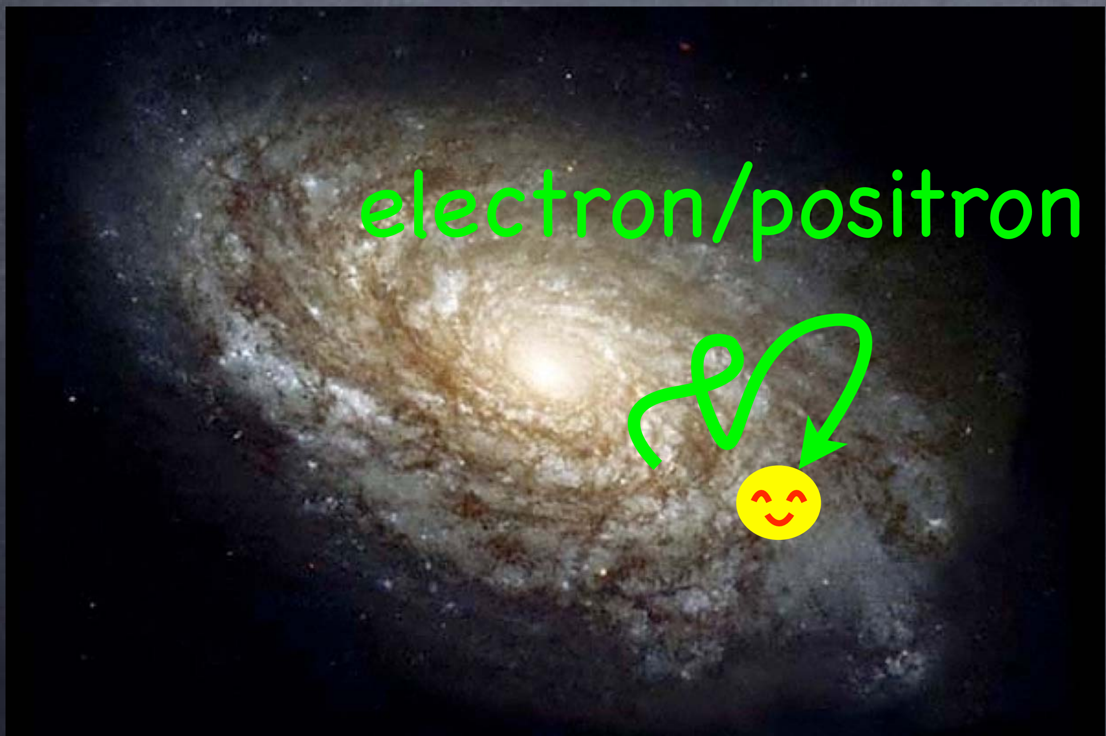
The overall scale is determined by the thermal relic abundance.

Electron + Positron flux:

Propagation through the galactic magnetic field is described by a diffusion equation

$$\frac{\partial f_e}{\partial t} = K(E)\nabla^2 f_e(E,x) + \frac{\partial}{\partial E}[b(E) f_e(E,x)] + Q(E,x)$$

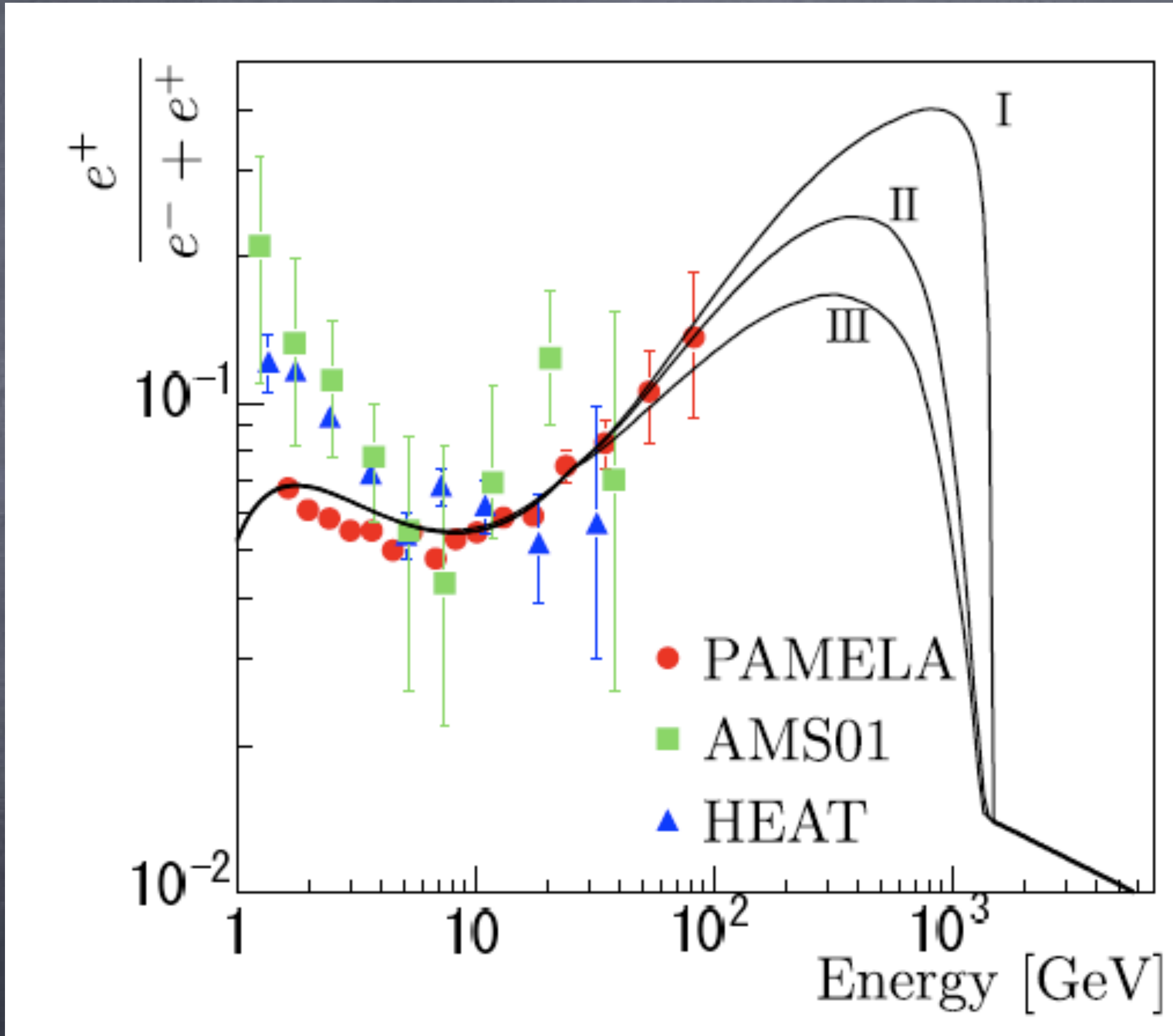
diffusion — energy loss — source



Dark Matter

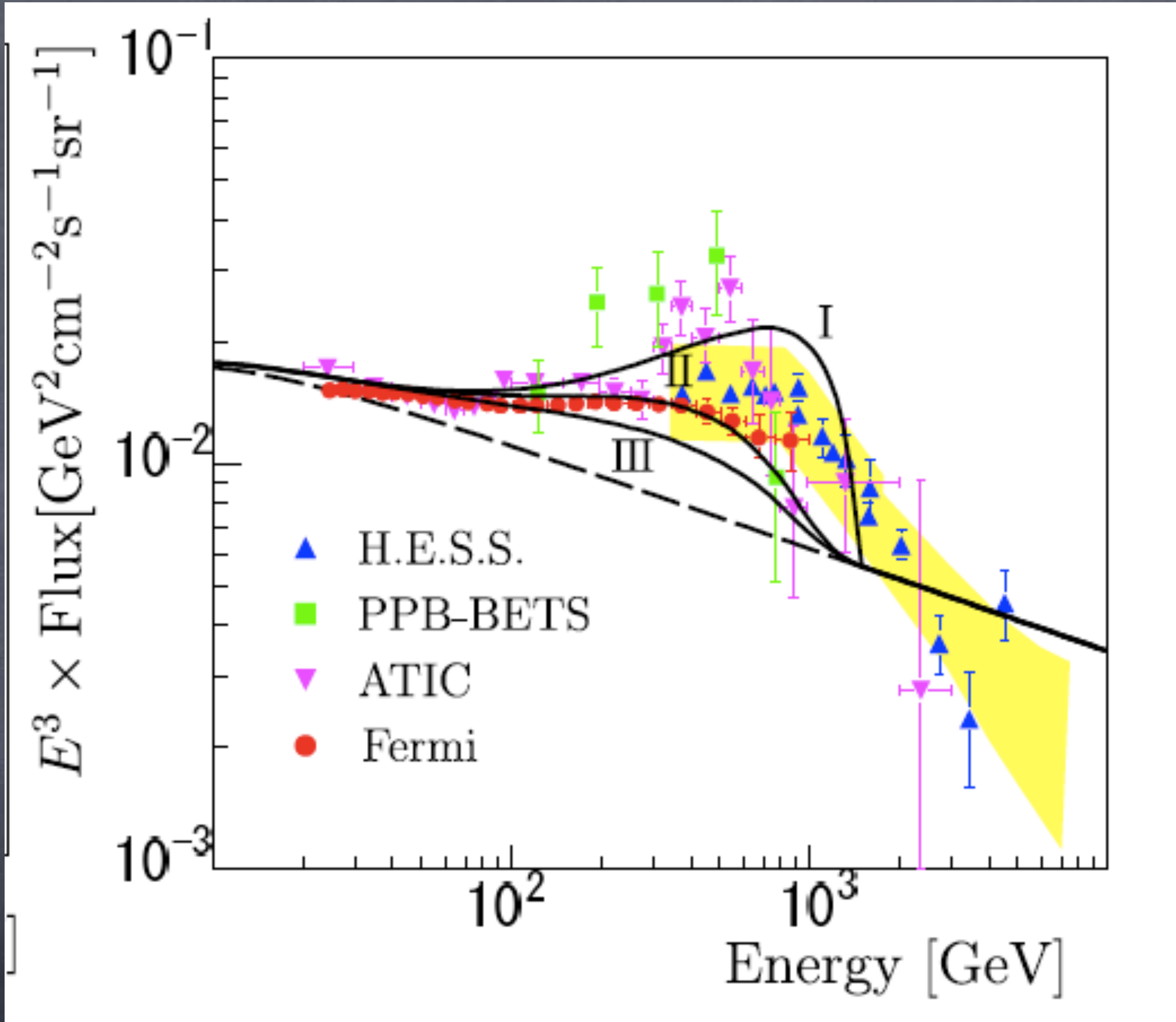
Mass & Decay rate

The Wino DM decay may account for the observed PAMELA/Fermi excesses in the CR $e^{-}+e^{+}$.

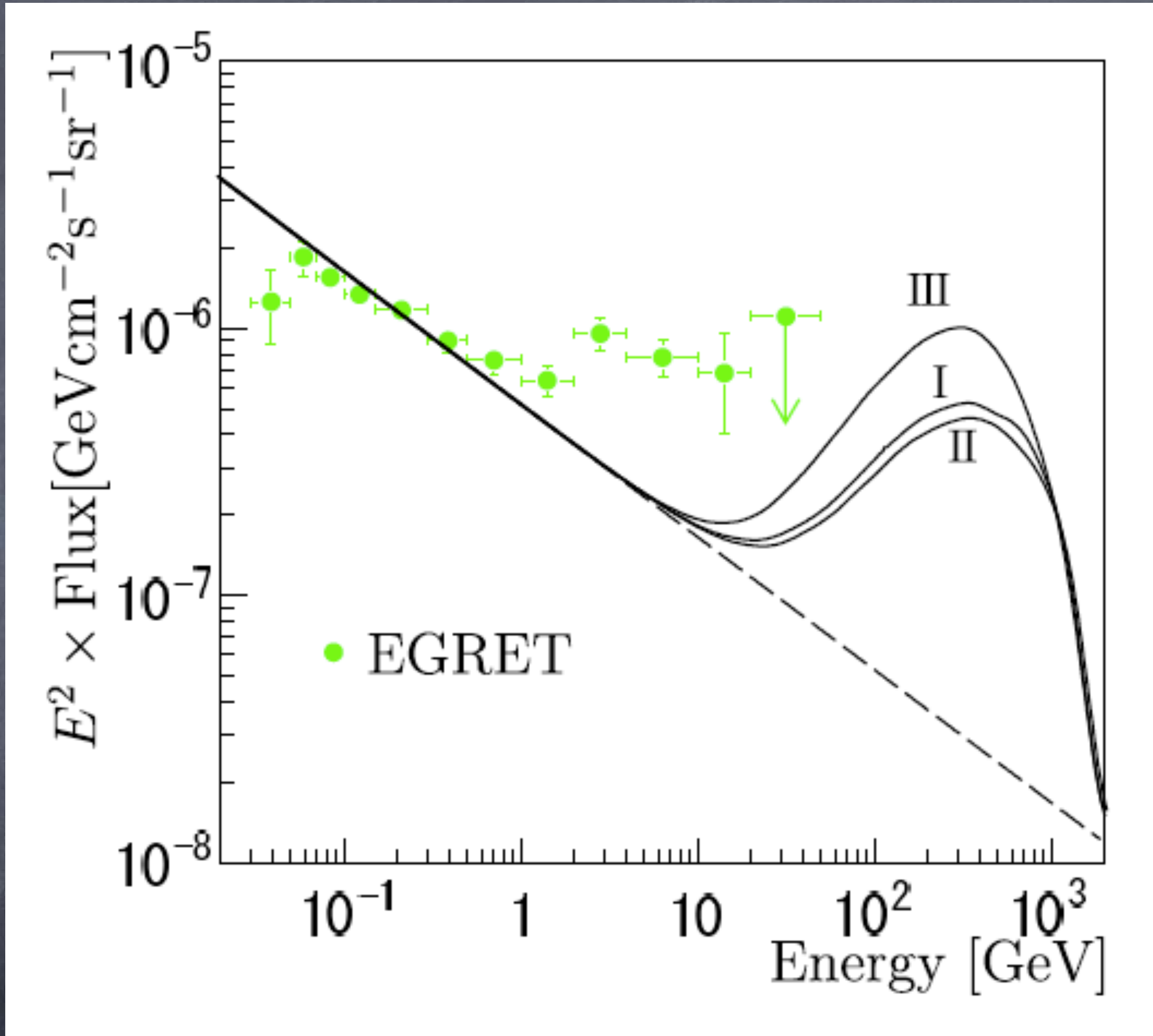


(a)

I: $e_1L_2L_3$, II: $e_2L_2L_3$, III: $e_3L_2L_3$



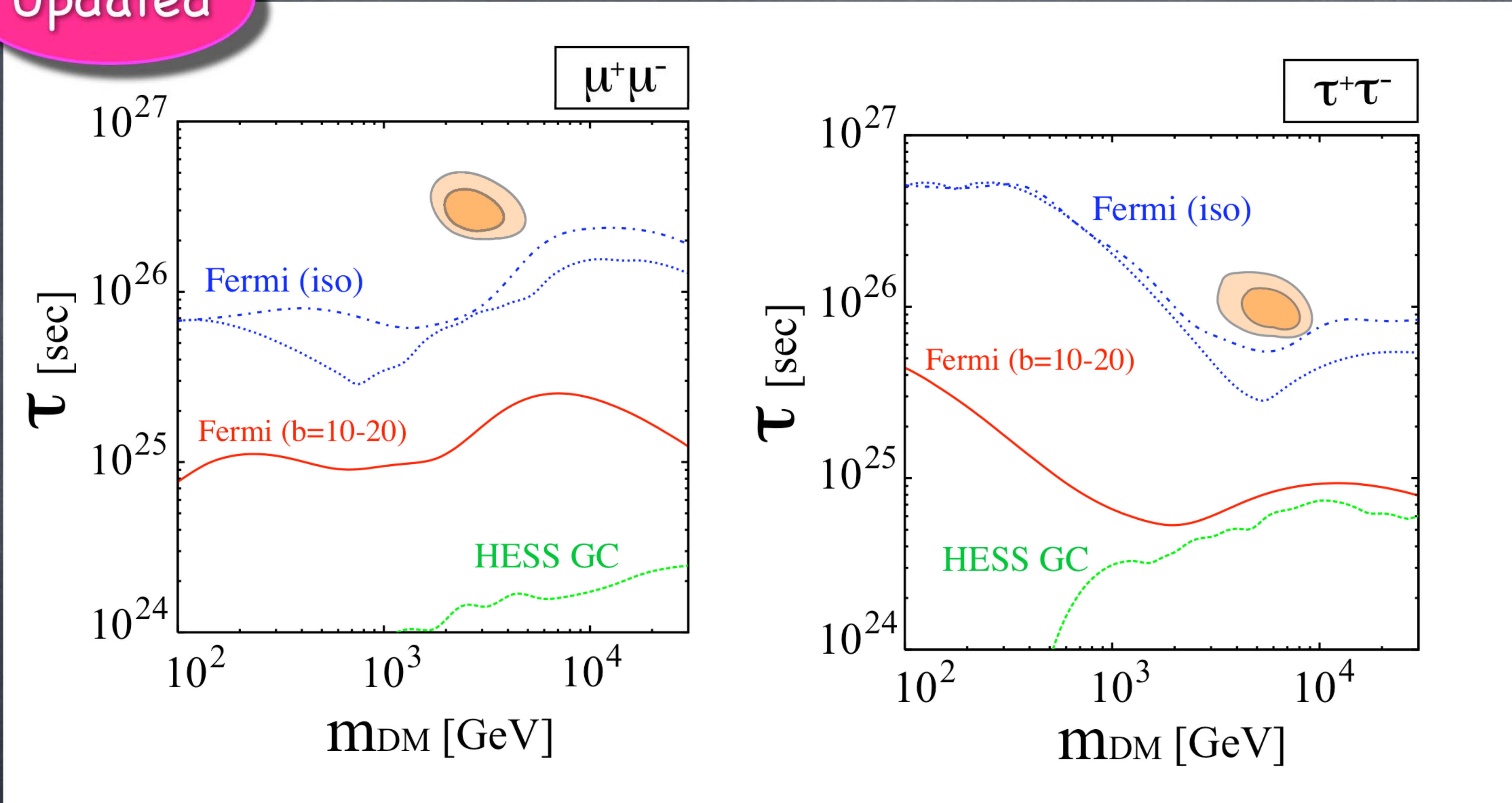
I: $e_1L_2L_3$, II: $e_2L_2L_3$, III: $e_3L_2L_3$



I: $e_1L_2L_3$, II: $e_2L_2L_3$, III: $e_3L_2L_3$

Gamma-ray constraints

Updated



Although the decay mode is slightly different from these two, it should be still allowed by the latest Fermi data.

C-R.Chen, S. Mandal, FT, arXiv:0910.2639

…yet another coincidence??

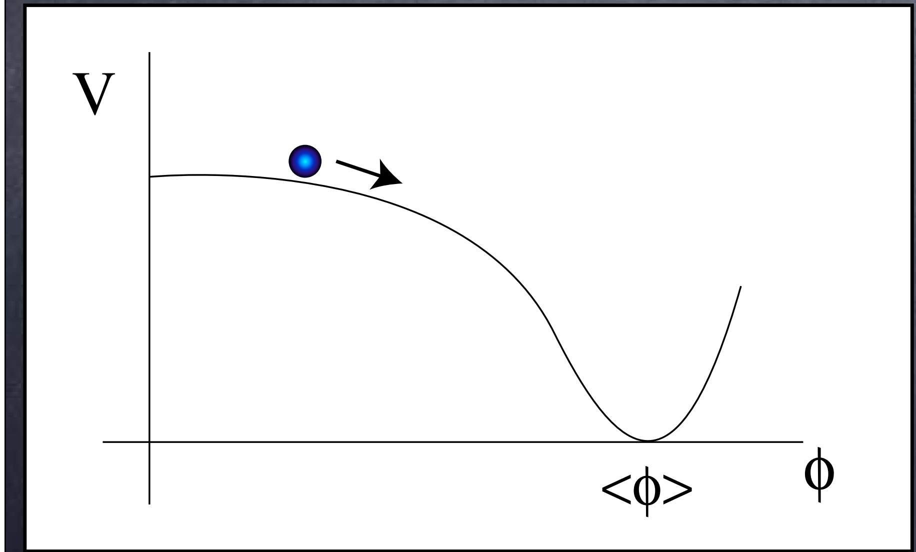
New inflation model with Z_5 R-symmetry

Izawa and Yanagida ,`97

$$K(\phi, \phi^\dagger) = |\phi|^2 + \frac{k}{4}|\phi|^4,$$
$$W(\phi) = v^2\phi - \frac{g}{6}\phi^6.$$

$$R[\phi] = 2 \;\; R[\phi^6] = 12 \equiv 2 \pmod 5$$

Consistent with the discrete Z_5 R-symmetry.



$$V(\varphi) \simeq v^4 - \frac{k}{2}v^4\varphi^2 - \frac{g}{2^{\frac{5}{2}-1}}v^2\varphi^5 + \frac{g^2}{2^5}\varphi^{10}$$

Inflaton acquires non-vanishing VEV:

$$\langle\phi\rangle \simeq (v^2/g)^{1/5}$$

The gravitino mass is related to the inflaton parameters!

$$m_{3/2} = W(\phi_0) \simeq \frac{5v^2}{6}\left(\frac{v^2}{g}\right)^{\frac{1}{5}}$$

$$\sim \boxed{\mathcal{O}(10^6)\,\mathrm{GeV}}$$ for $g = \mathcal{O}(1)$

The WMAP normalization δ = 10^{-5}
is imposed.

Conclusions

It is likely that the PAMEA and Fermi found an excess in the CR positrons/electrons.

If so, we need to modify the conventional model of CR electron/positron. The possible sources are 1) pulsars; 2) SNR; or 3) Dark Matter.

In the case of DM, other observational channels, especially gamma-ray, could refute/support the scenario.

We have proposed a model based on the discrete Z_5 R symmetry in which R-parity is broken by the constant term in W (= gravitino mass).

The thermal relic Wino DM of mass 3TeV can explain the observed PAMELA/Fermi anomalies in this framework.

The new inflation model based on Z_5 R symmetry can give rise to the gravitino mass of 10^3TeV.

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Focus week on ``Indirect DM search"

7-11 Dec. 2009 at IPMU

Invited speakers include:

- Marco Casolino (INFN, University of Rome Tor Vergata)
- Paolo Gondolo (University of Utah)
- Kouichi Hirotani (National Tsing Hua University)
- Masahiro Hoshino (University of Tokyo)
- Dan Hooper (FNAL)
- Alejandro Ibarra (Technische Universitat Munchen)
- Tesla Jeltema (UCO/Lick Observatories)
- Philipp Mertsch (Oxford)
- Igor Moskalenko (Stanford University)*
- Stefano Profumo (UCSC)
- Surjeet Rajendran (MIT)
- Pasquale Serpico (CERN)
- Shoji Torii (Waseda University)
- Carsten Rott (Ohio State University)

Organizers:

Dan Hooper

Stefano Profumo

Fuminobu Takahashi