Cosmic Antiproton and Gamma-Ray Constraints on Effective Interaction of the Dark matter

Authors: Kingman Cheung, Po-Yan Tseng, Tzu-Chiang Yuan

Physics Department, NTHU
Physics Division, NCTS
Institute of Physics, Academia Sinica

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Introduction

- The present mass density of cold DM by WMAP collaboration is:

$$\Omega_{CDM} h^2 = 0.1099 \pm 0.0062 \qquad (1)$$

Ω_{CDM} is the mass density of CDM normalized by the critical density, h is the Hubble constant in units of $100km/s/Mpc$.

- If the DM was produced **thermally** in the early Universe, the DM annihilation cross section is about the order of **Weak interaction.**

$$\Omega_X h^2 \simeq \frac{0.1pb}{\langle \sigma v \rangle}, \langle \sigma v \rangle \simeq 0.91pb \qquad (2)$$

X is the DM particle, σ is the annihilation cross section, v is relative velocity, $\langle \sigma v \rangle$ is the thermal average.

- We know the gravitational nature of DM, but we know a little about its particle nature.

- In this work, we use the **effective interaction** to describe the interactions between DM and SM particles. DM exists in a hidden sector and interact with SM particle via a heavy mediator.

- For example, the interactions between a fermionic DM χ and the light quarks q (u,d,s,c,b) can be described by $\left(\bar{\chi}\Gamma\chi\right)\left(\bar{q}\Gamma' q\right)$, where $\Gamma, \Gamma' = \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \gamma^5, 1$

- There have been some works to constrain these effective interactions by present and future collider experiments, and gamma-ray experiments.

- In this work, WMAP experiment can give us the lower bound of DM annihilation cross section $\langle \sigma v \rangle$. Hence, it give us the **lower bound** of **the strength of DM effective interactions**. Otherwise, there will be too many DM in our universe.

- We also use the cosmic antiproton flux from PAMELA experiment to give us the **upper bound** of **the strength of DM effective interactions**.

Effective Interactions

- The effective interactions of Dirac fermion DM and light quarks via a (axial) vector-boson or tersor-type exchange are described by the dimension 6 operator:

$$L_{i=1-6} = O_{i=1-6} = \frac{C}{\Lambda_i^2}\left(\bar{\chi}\Gamma_1\chi\right)\left(\bar{q}\Gamma_2 q\right)$$

where $\Gamma_{1,2} = \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma^5$ with $\sigma^{\mu\nu} \equiv i\left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right)/2$, and C is coupling constant $O(1)$, Λ_i is the **cutoff scale**.

- Dirac fermion DM via (pseudo) scalar-boson-type exchange:

$$L_{i=7-10} = O_{i=7-10} = \frac{Cm_q}{\Lambda_i^3}\left(\bar{\chi}\Gamma_1\chi\right)\left(\bar{q}\Gamma_2 q\right)$$

where $\Gamma_{1,2} = 1 \quad or \quad i\gamma^5$, m_q are the light quarks mass.

- Dirac DM couples to gluon field:

$$L_{i=11-12} = O_{i=11-12} = \frac{C\alpha_s\left(2m_\chi\right)}{4\Lambda_i^3}\left(\bar{\chi}\Gamma\chi\right)G^{a\mu\nu}G^a_{\mu\nu}$$

$$L_{i=13-14} = O_{i=13-14} = \frac{C\alpha_s\left(2m_\chi\right)}{4\Lambda_i^3}\left(\bar{\chi}\Gamma\chi\right)G^{a\mu\nu}G^{*a}_{\mu\nu}$$

where $\Gamma = 1 \quad or \quad i\gamma^5$, α_s are the strong coupling constant at scale $2m_\chi$, $G^*_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}/2$.

- Complex scalar DM via vector boson exchange:

$$L_{i=15,16} = O_{i=15,16} = \frac{C}{\Lambda_i^2}\left(\chi^\dagger \overleftrightarrow{\partial_\mu}\chi\right)\left(\bar{q}\gamma^\mu\Gamma q\right)$$

where $\Gamma = 1 \quad or \quad \gamma^5$ and $\chi^\dagger \overleftrightarrow{\partial_\mu}\chi = \chi^\dagger\left(\partial_\mu\chi\right) - \left(\partial_\mu\chi^\dagger\right)\chi$.

- Complex scalar DM via scalar boson exchange:

$$L_{i=17,18} = O_{i=17,18} = \frac{Cm_q}{\Lambda_i^2}\left(\chi^\dagger\chi\right)\left(\bar{q}\Gamma q\right)$$

where $\Gamma = 1 \quad or \quad i\gamma^5$.

- Complex scalar DM couple to gluon field:

$$L_{i=19} = O_{i=19} = \frac{C\alpha_s\left(2m_\chi\right)}{4\Lambda_i^3}\left(\chi^\dagger\chi\right)G^{a\mu\nu}G^a_{\mu\nu}$$

$$L_{i=20} = O_{i=20} = \frac{iC\alpha_s\left(2m_\chi\right)}{4\Lambda_i^3}\left(\chi^\dagger\chi\right)G^{a\mu\nu}G^{*a}_{\mu\nu}$$

Annihilation Cross Sections Around the Freeze-Out

- The WMAP results give us the DM annihilation cross section $\langle \sigma v \rangle$ in the early universe is: $\langle \sigma v \rangle \simeq 0.91 pb$

- If there were some other **nonthermal** source of DM in the early universe, the constrain of WMAP is revised into: $\langle \sigma v \rangle > 0.91 pb$

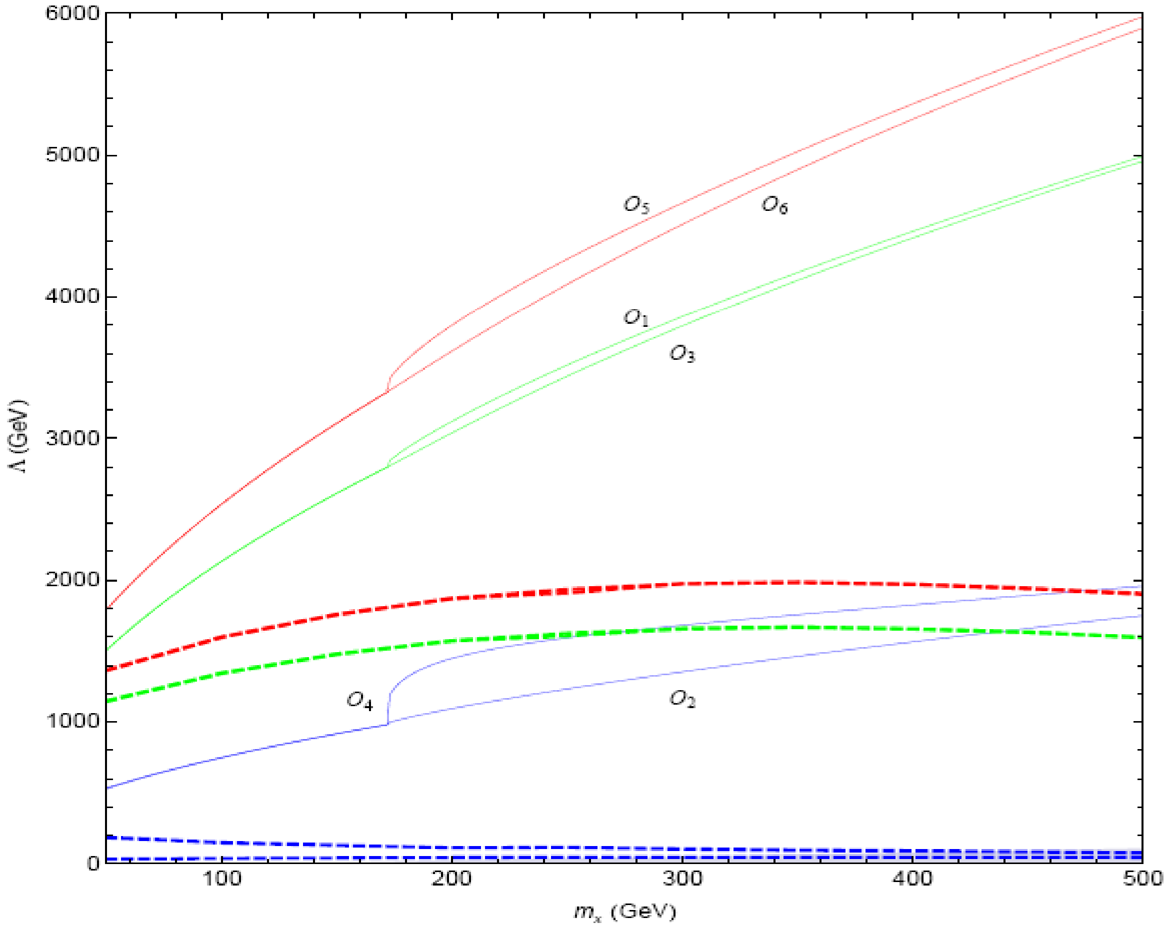
- We use the effective interaction $O_{i=1-20}$ to calculate $\langle \sigma v \rangle$ in the early universe and give **upper limit** of **cutoff** Λ_i .

$$\bar{\chi}\chi \quad or \quad \chi^{\dagger}\chi \rightarrow \bar{q}q \quad or \quad gg$$

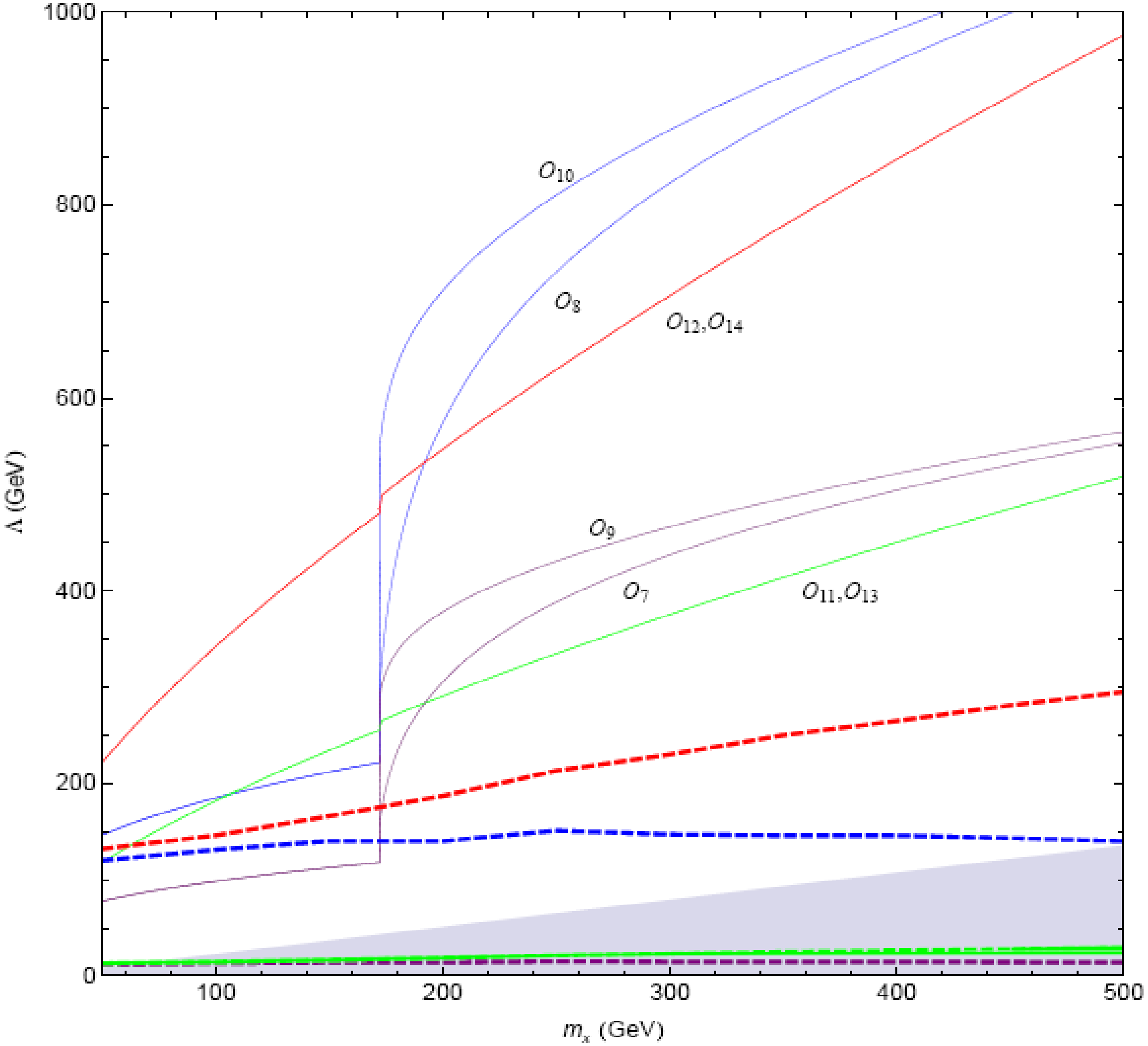
We assume DM velocity $v \approx 0.3c$ at around freeze-out time. We also included the DM annihilation into light quarks and top quark.

- In the (m_χ, Λ) plane, the solid lines are the contours with $\langle \sigma v \rangle \simeq 0.91 pb$. The regions **below** the lines are the allowed values for Λ .

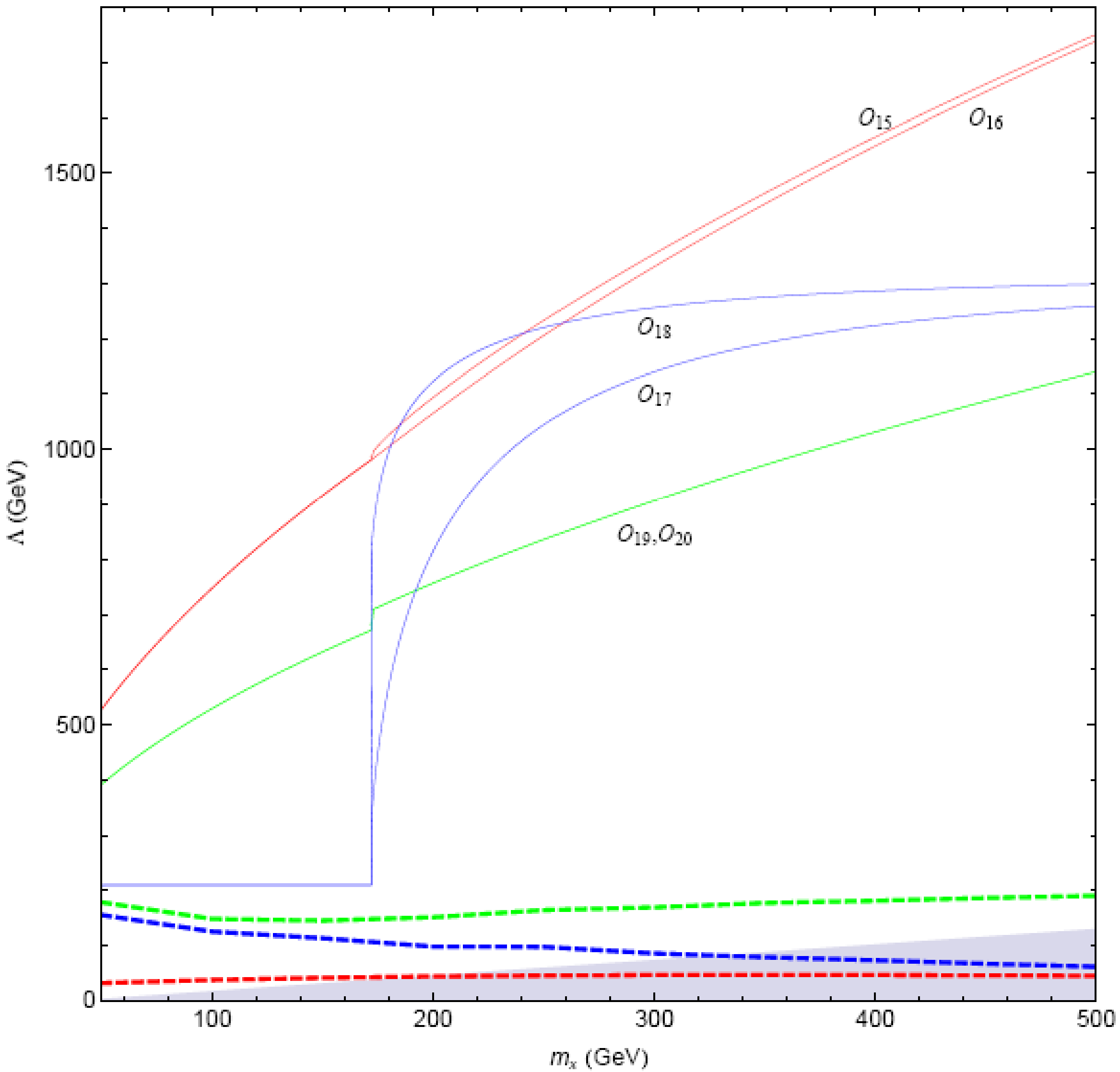
- Figure 1: operators O_{1-6} .



- Figure 2: operator O_{7-14} . The shaded area is $\Lambda < m_\chi / 2\sqrt{\pi}$ where the effective theory approach is not trustworthy.



- Figure 3: operator O_{15-20} .

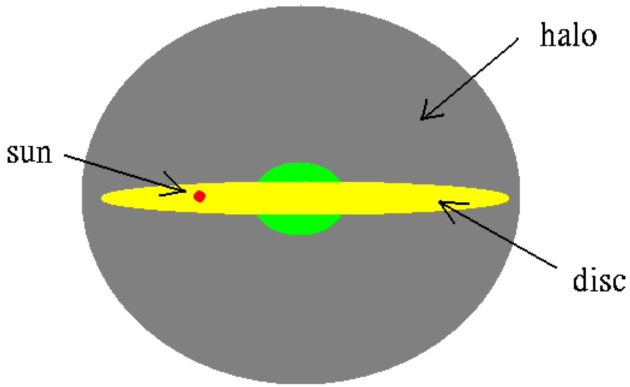


Anitproton Flux

- In the present universe, the DM in our Galaxy halo will annihilate into quarks or gluons via the effective operators $O_{i=1-20}$, and quarks and gluons will fragment into cosmic antiproton flux.

$$\bar{\chi}\chi \xrightarrow{Operator} \bar{q}q \xrightarrow{Fragment} \bar{p} + X$$

- In this calculation, we only consider the DM annihilate into light quarks (u,d,s,c,b).



- The antiprotons produced from the Galaxy halo need propagate to our earth. There are magnetic field in the Galaxy will change the energy spectra of antiproton. This phenomena is described by the **diffusion equation**:

$$\frac{\partial \psi}{\partial t} = Q(\vec{r}, p) + \vec{\nabla} \cdot \left(D_{xx} \vec{\nabla} \psi\right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} [\dot{p} \psi]$$

where $\psi = \psi(\vec{r}, p, t)$ is the density of anti-p, D_{xx} is the spatial diffusion coefficient, D_{pp} is the diffusion coefficient in momentum space, **Q** is the **source term**, $\dot{p} \equiv dp/dt$ is the momentum loss rate.

- The source term from the DM annihilation is:

$$Q_{ann} = \eta \left(\frac{\rho_{CDM}}{M_{CDM}} \right)^2 \sum \langle \sigma v \rangle_{\bar{p}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

where $\eta = 1/2 \quad (1/4)$ for (non)-identical initial state, and $T_{\bar{p}}$ is the kinetic energy of antiproton.

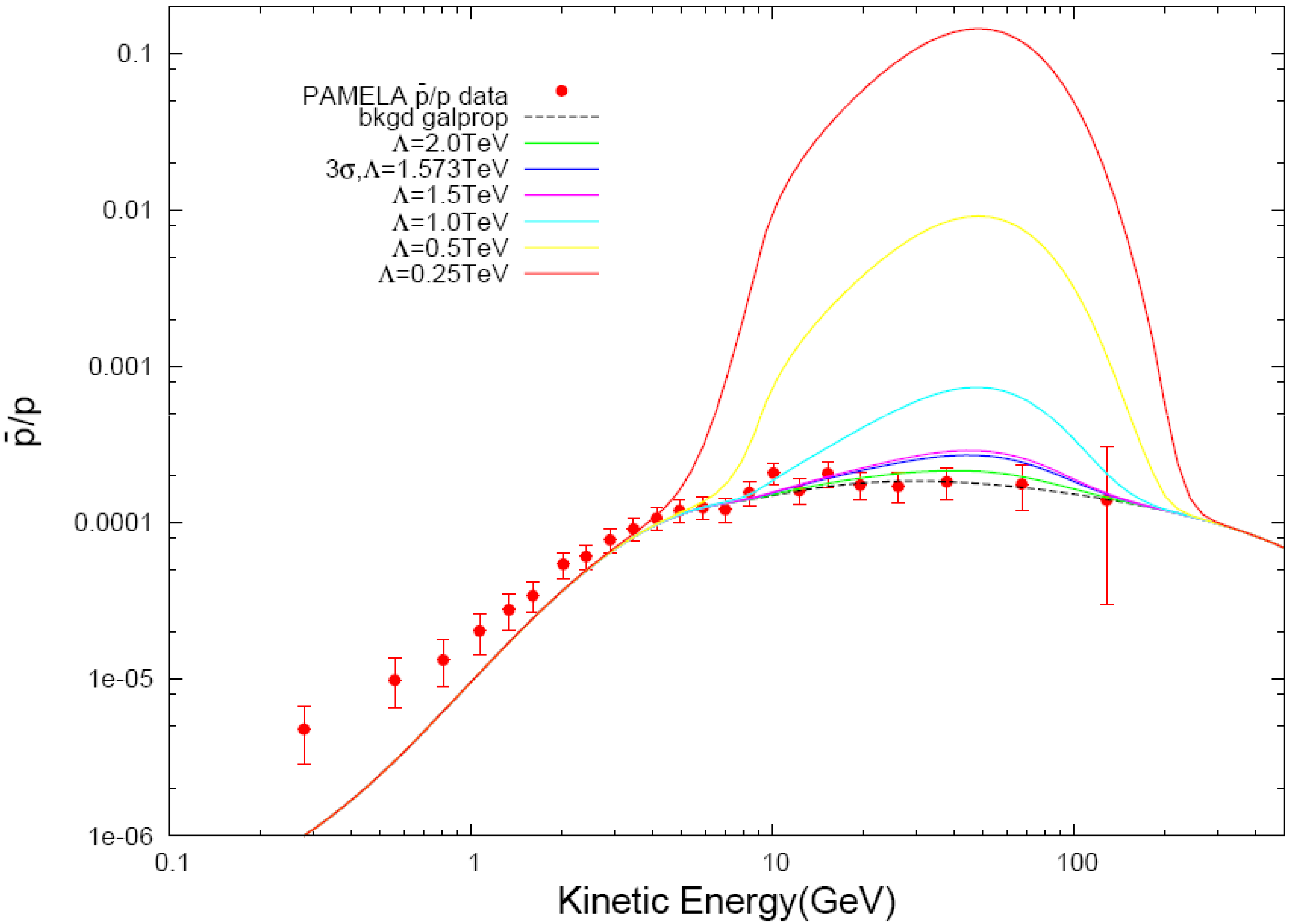
- We calculate the antiproton energy spectrum $dN_{\bar{p}} / dT_{\bar{p}}$ from DM annihilation and put the source term Q into the computer program GALPROP. GALPROP can solve the diffusion equation and output the cosmic antiproton energy spectrum in earth.

- We compare PAMELA antiproton data (data point above 4GeV) with the GALPROP output and calculate the χ^2 .

- We find the 3σ ($\chi^2 - \chi^2_{bkgd} = 9$) limit on the **cutoff** Λ_i of each effective operators $O_{i=1-20}$ for different DM mass $m_\chi = 50, 100, 200, 400 GeV$.

- The PAMELA antiproton data give the **lower limit** of **cutoff** Λ_i .

- Figure 4: operator $O_1 = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$,DM mass=200GeV.



- Using WMAP data(DM thermal relic density) and PAMELA data (antiproton flux) can give a valid range of **cutoff** Λ_i for each effective operator $O_{i=1-20}$.

- For example, Dirac DM with (axial) vector interactions $O_{1,3}$ require $1.6TeV < \Lambda_{1,3} < 3TeV \quad for \quad m_\chi = 200GeV$. The best limit is from the Dirac DM with tensor interactions $O_{5,6}$ have $1.9TeV < \Lambda_{5,6} < 3.6TeV \quad for \quad m_\chi = 200GeV$.

- $O_{2,4}$ have velocity suppression. O_{7-14} (Dirac DM with scalar-boson exchange) give weak limit because of the m_q in the coupling constant. O_{11-14} (gluonic interaction) give weak limit because of the $\alpha_s \approx 10^{-1}$ in the coupling constant. $O_{15,16}$ (complex scalar DM with vector-boson exchange) give weak limit because of the derivative bring down a factor of momentum.

- Table 3: $m_\chi = 50, 100, 200, 400 GeV$

Operators	Λ (TeV) m_χ (GeV) = 50	100	200	400
Dirac DM, Vector Boson Exchange				
$O_1 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$	1.15	1.34	1.57	1.66
$O_2 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu q)$	0.033	0.038	0.045	0.047
$O_3 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	1.15	1.34	1.57	1.66
$O_4 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	0.19	0.15	0.11	0.09
$O_5 = (\overline{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu} q)$	1.37	1.60	1.87	1.97
$O_6 = (\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{q}\sigma_{\mu\nu} q)$	1.36	1.60	1.87	1.97
Dirac DM, Scalar Boson Exchange				
$O_7 = (\overline{\chi}\chi)(\bar{q}q)$	0.012	0.013	0.014	0.015
$O_8 = (\overline{\chi}\gamma^5\chi)(\bar{q}q)$	0.12	0.13	0.14	0.15
$O_9 = (\overline{\chi}\chi)(\bar{q}\gamma^5 q)$	0.012	0.013	0.014	0.015
$O_{10} = (\overline{\chi}\gamma^5\chi)(\bar{q}\gamma^5 q)$	0.12	0.13	0.14	0.15
Dirac DM, Gluonic				
$O_{11} = (\overline{\chi}\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.013	0.015	0.019	0.027
$O_{12} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.13	0.15	0.19	0.27
$O_{13} = (\overline{\chi}\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.013	0.015	0.019	0.027
$O_{14} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.13	0.15	0.19	0.27
Complex Scalar DM, Vector Boson Exchange				
$O_{15} = (\chi^\dagger \overleftrightarrow{\partial_\mu}\chi)(\bar{q}\gamma^\mu q)$	0.033	0.038	0.045	0.047
$O_{16} = (\chi^\dagger \overleftrightarrow{\partial_\mu}\chi)(\bar{q}\gamma^\mu\gamma^5 q)$	0.033	0.038	0.045	0.047
Complex Scalar DM, Scalar Vector Boson Exchange				
$O_{17} = (\chi^\dagger\chi)(\bar{q}q)$	0.16	0.13	0.099	0.074
$O_{18} = (\chi^\dagger\chi)(\bar{q}\gamma^5 q)$	0.16	0.13	0.099	0.074
Complex Scalar DM, Gluonic				
$O_{19} = (\chi^\dagger\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.18	0.15	0.15	0.18
$O_{20} = (\chi^\dagger\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.18	0.15	0.15	0.18

Velocity Dependence in the Nonrelativistic Limit

- The current velocity of DM near the sun is about $v \simeq 300km/s \simeq 10^{-3}c$.

- For example, the annihilation cross section of operator O_7 (Dirac DM with a scalar boson exchange) would be suppress by the factor v^2 .

- Operator O_1 to O_6 , the relevant part of the annihilation amplitude of the Dirac DM is

$$\bar{\psi}(p_2)\Gamma\psi(p_1)$$

,where $\Gamma = \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma^5$.

- In the nonrelativistic limit, the Dirac spinor of DM and antiparticle are:

$$\psi = \xi \begin{pmatrix} 1 \\ \varepsilon \end{pmatrix} \quad , \quad \overline{\psi} = \eta^{\dagger} \left(\varepsilon, \quad 1 \right) \gamma^{0}$$

,where $\varepsilon = O(v/c)$.

- In Dirac representation, the gamma matrices are given by

$$\gamma^{0} = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \gamma^{i} = \begin{pmatrix} 0 & \sigma_{i} \\ -\sigma_{i} & 0 \end{pmatrix}, \quad \gamma^{5} = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

, where $\sigma_{i} \left(i = 1, 2, 3 \right)$ are Pauli matrices.

- In nonrelativistic limit, the space-like and time-like part of $\overline{\psi} \gamma^{\mu} \psi$ are

$$\overline{\psi} \gamma^{0} \psi \simeq 2 \varepsilon \eta^{+} \xi$$

$$\overline{\psi} \gamma^{i} \psi \simeq \left(1 + \varepsilon^{2} \right) \eta^{+} \sigma_{i} \xi$$

The **time-like** part is **suppressed** by v/c , but the space-like part are not.

- In nonrelativistic limit, the space-like and time-like part of $\overline{\psi}\gamma^{\mu}\gamma^{5}\psi$ are

$$\overline{\psi}\gamma^{0}\gamma^{5}\psi \simeq \left(1+\varepsilon^{2}\right)\eta^{+}\xi$$

$$\overline{\psi}\gamma^{i}\gamma^{5}\psi \simeq 2\varepsilon\eta^{+}\sigma_{i}\xi$$

,where **space-like** part are **suppressed** by v/c .

- In the calculation of annihilation cross section $\overline{\chi}\chi \rightarrow \overline{q}q$, we can consider the space-like and time-like parts of $\overline{\psi}\Gamma\psi$ separately, when it is squared, traced, and contracted with the trace of the light quark leg $\overline{q}\gamma^{\mu}q \quad or \quad \overline{q}\gamma^{\mu}\gamma^{5}q$.

- After being squared and traced, the **time-like** part of $\overline{q}\gamma^{\mu}q \quad or \quad \overline{q}\gamma^{\mu}\gamma^{5}q$ gives a value close to **zero**, and the **space-like** part of it gives a value of order m_{χ}^{2}.

- Therefore, $\bar{\psi}\gamma^{\mu}\psi$ multiplied to $\bar{q}\gamma^{\mu}q \quad or \quad \bar{q}\gamma^{\mu}\gamma^{5}q$ will **not** be **suppressed**, while $\bar{\psi}\gamma^{\mu}\gamma^{5}\psi$ multiplied to $\bar{q}\gamma^{\mu}q \quad or \quad \bar{q}\gamma^{\mu}\gamma^{5}q$ will be **suppressed**.

- Hence, the limits on O_1 and O_3 are stronger than those on O_2 and O_4. The O_5 and O_6 have unsuppressed components in $\mu\nu = 0i$.

- In nonrelativistic limit, the DM part of operators O_7 to O_{14} are

$$\bar{\psi}\psi \sim \varepsilon\eta^{+}\xi$$
$$\bar{\psi}\gamma^{5}\psi \sim \eta^{+}\xi$$

- Therefore, the limits on O_8 and O_{10} are stronger than those on O_7 and O_9 . The limits on O_{12} and O_{14} are stronger than those on O_{11} and O_{13} .

- In O_{15} to O_{20}, only $O_{15,16}$ are suppressed by v/c, others are not. Because there is the differential operator $\overleftrightarrow{\partial}_\mu$ in $O_{15,16}$, and this will bring down a vertex factor p_μ.

$$p_0 \sim m_\chi$$

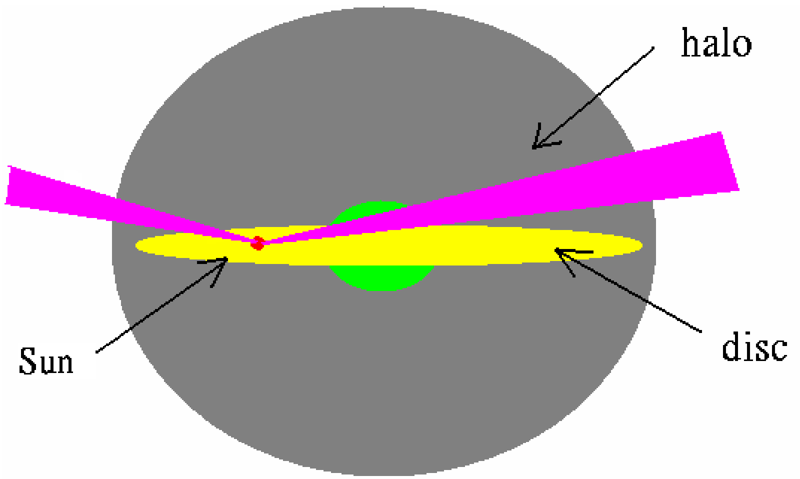
$$p_i \sim v/c$$

- Therefore in $O_{15,16}$, when $\chi^\dagger \overleftrightarrow{\partial}_\mu \chi$ multiplied to the quark leg $\bar{q}\gamma^\mu q \quad or \quad \bar{q}\gamma^\mu \gamma^5 q$, they will be suppressed by v/c.

Fermi-LAT Gamma-Ray Data

- We use the Gamma-ray spectrum data from the mid-latitude area of our galaxy skymap ($10^0 \leq |b| \leq 20^0, 0^0 \leq l \leq 360^0$). We have clearly understanding with the material and point sources. We can calculate the Gamma ray background more accurately.

- There are more DM accumulate in the Galaxy Center. However, Galaxy Center may has supermassive black hole, and some unknown source.



Background

- The Background Gamma ray mainly comes from the interaction between high energy cosmic ray particle with the interstellar medium and radiation field of charged particle.

1. π^0 decay: The high energy cosmic ray (proton) collide with the nucleons of the interstellar medium. Then, the π^0 are produced and most of π^0 will decay into two photons.

2. Inverse Compton (IC) : The high energy $e^{\pm}$ collide with the photons of interstellar medium or CMB photons.

3. Bremsstrahlung: The high energy $e^{\pm}$ are deflected by the Coulomb field of the interstellar medium.

4. Extragalactic background (EGB) : It is expected to be **isotropic**. The sources of EGB come from unresolved point sources, diffuse emission of large scale structure formation, etc. Because there are large uncertainty in the EGB, it is determined lastly among the other components of Gamma-ray background.

The Fermi-LAT measured the Gamma-ray and fitted the EGB by

$$E^2 \frac{d\Phi}{dE} = A\left(\frac{E}{0.281GeV}\right)^{\delta}$$

,where $\gamma = |\delta - 2| = 2.41 \pm 0.05$ is power-law index
and $A = \left(0.95^{+0.18}_{-0.17}\right) \times 10^{-6} \quad GeV \quad cm^{-2} s^{-1} sr^{-1}$

- We use Galprop (web version), which is a computer program and can calculate the cosmic ray flux, to do the theoretical estimation of the background Gamma-ray flux. Galprop can give the estimations of background 1, 2, and 3.

- Background 1 (π^0 decay) are mostly determined by the cosmic ray proton flux.

- Background 2 (IC) and 3 (bremss) are mostly determined by cosmic ray electron flux.

- Because **Fermi-LAT** and **AMS** experiments already measured the flux of cosmic electron and proton. Then, the Gamma-ray flux background of π^0decay, IC, and bremss are almost determined.

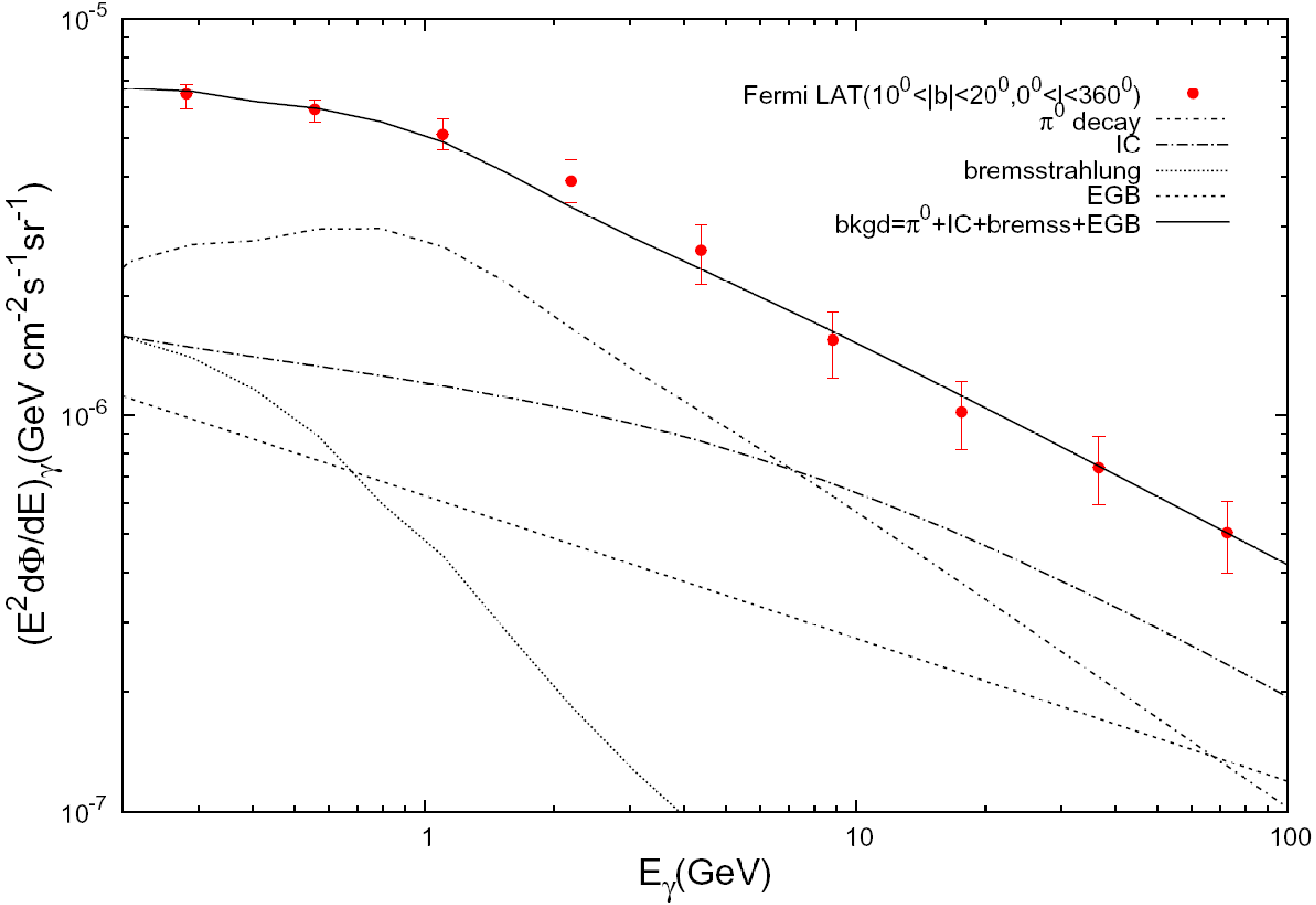
- We added background EGB into background from Galprop and fitted the Fermi-LAT mid-latitude data. Then, we obtained the flux of EGB is

$$E^2 \frac{d\Phi}{dE} = \left(0.99 \times 10^{-6}\right)\left(\frac{E}{0.281 GeV}\right)^{-0.36} \qquad GeV \quad cm^{-2} s^{-1} sr^{-1}$$

  , where the power-law index is $\gamma = 2.36$. The $\chi^2 = 2.435$ for 7 d.o.f in our fitting. It is close to the EGB from Fermi-LAT paper.

- We can see that the theoretical spectrum fits with the Fermi-LAT data very well.

- Gamma-ray flux bkgd:



Dark Matter Annihilation

- Via these effective operators, the DM in the galaxy halo will annihilate with each other and produce photons by the process:

$$\chi\bar{\chi} \to q\bar{q} \quad or \quad gg \to \pi^0 + X \to 2\gamma + X$$

, where $q = u, d, c, s, b$.

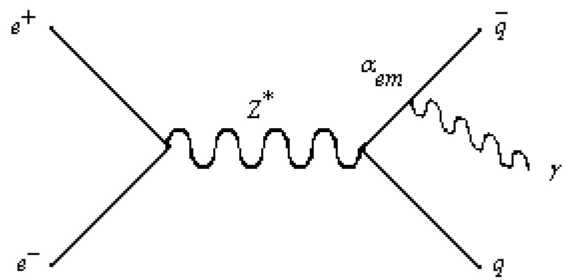
- DM and anti-DM annihilate into quark and anti-quark (or gluon pair), then quark and anti-quark will fragment into many π^0 . About 99% of π^0 will further decays into 2γ .

- We used two methods to obtain the photon energy spectrum dN/dE_γ of the DM annihilation process.

1. Using the process $e^+e^- \rightarrow Z^* \rightarrow q\bar{q}$ in Pythia to simulate the process

$$\chi\bar{\chi} \rightarrow q\bar{q} \rightarrow \pi^0 + X \rightarrow 2\gamma + X$$

Using the process $e^+e^- \rightarrow Z^* \rightarrow q\bar{q}$ with the initial radiation turned off in Pythia. The e^+e^- annihilate into a Z boson, and the Z boson go into quark and anti-quark. The center mass energy of e^+e^- is $2m_\chi$. Then, we extracted the energy spectrum of the final state photon. Most photons come from decay of π^0 , which is produced by the fragmentation of quark and anti-quark. Very small photons come from bremsstralung of the quark leg.



2. Considering the process: $\chi\bar{\chi} \rightarrow q\bar{q}$

   Using the fragmentation function code (B.A.Kniehl,G.Kramer,B.Potter) of $q, \bar{q}, g$ into π^0, then we have energy spectrum of π^0 in the process:

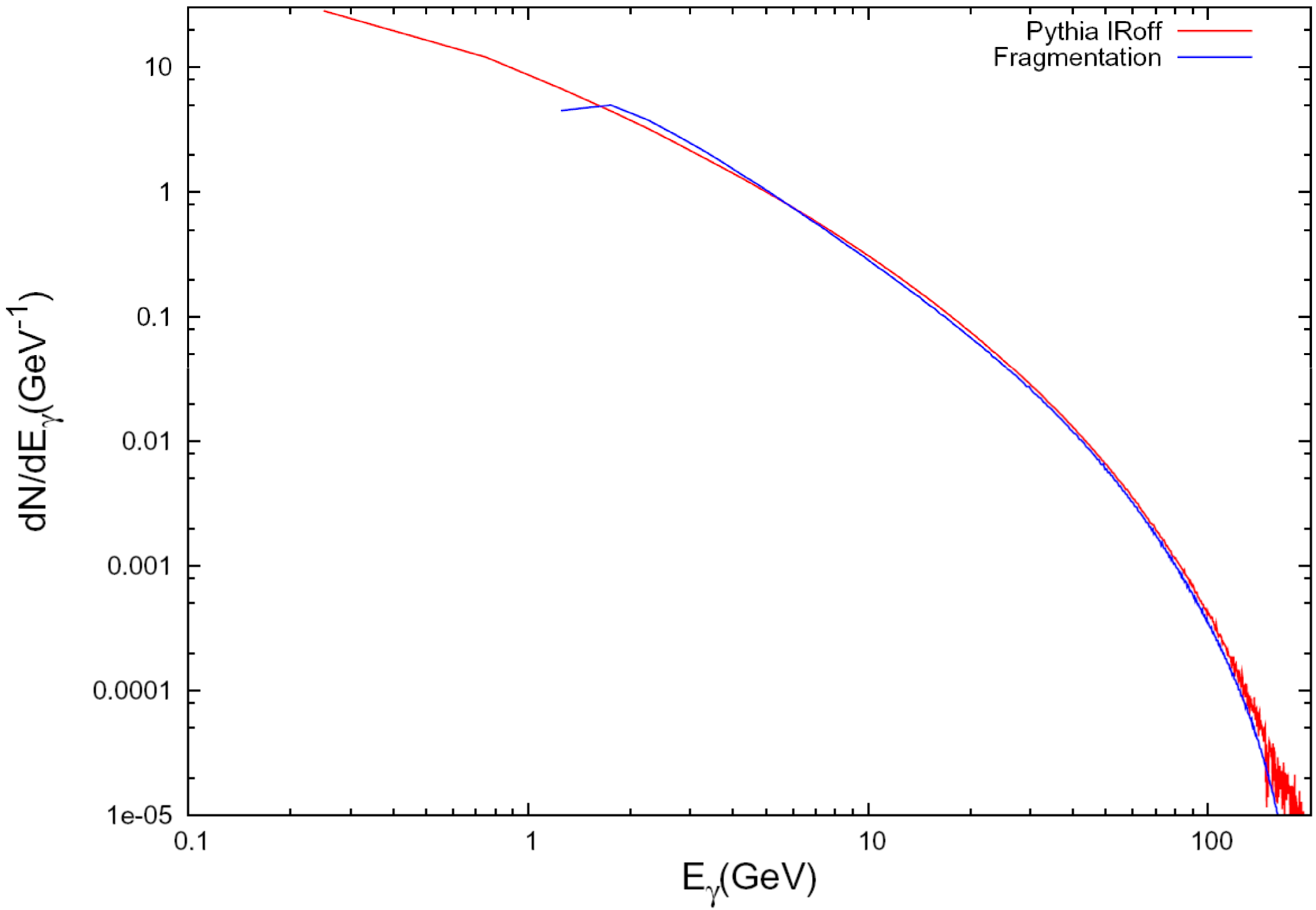
   $$\chi\bar{\chi} \rightarrow q\bar{q}. \quad or \quad gg \rightarrow \pi^0 + X$$

   Boosting the γ energy spectrum $dN/dE_\gamma\left(\pi^0 \rightarrow \gamma\gamma\right)$ into π^0 frame and convolute $dN/dE_\gamma\left(\pi^0 \rightarrow \gamma\gamma\right)$ with π^0 spectrum. We can have dN/dE_γ in this process

   $$\chi\bar{\chi} \rightarrow q\bar{q} \quad or \quad gg \rightarrow \pi^0 + X \rightarrow 2\gamma + X$$

- The photon energy spectra dN/dE_γ from the above two methods are consensus with each other.

- DM mass=200GeV. Photon energy spectrum from Pythia and Fragmentation code.



- With the effective operators (O_{11} to O_{14} and O_{19}, O_{20}) that DM will annihilate into gluon pair, we used the 2nd method to extract the photon energy spectrum .

- The cosmic Gamma-ray flux can be calculate via this equation:

$$\Phi = \frac{\langle \sigma v \rangle}{2} \frac{dN}{dE_\gamma} \frac{1}{4\pi m_\chi^2} \int_{line\ of\ sight} ds \quad \rho^2(s,\psi)$$

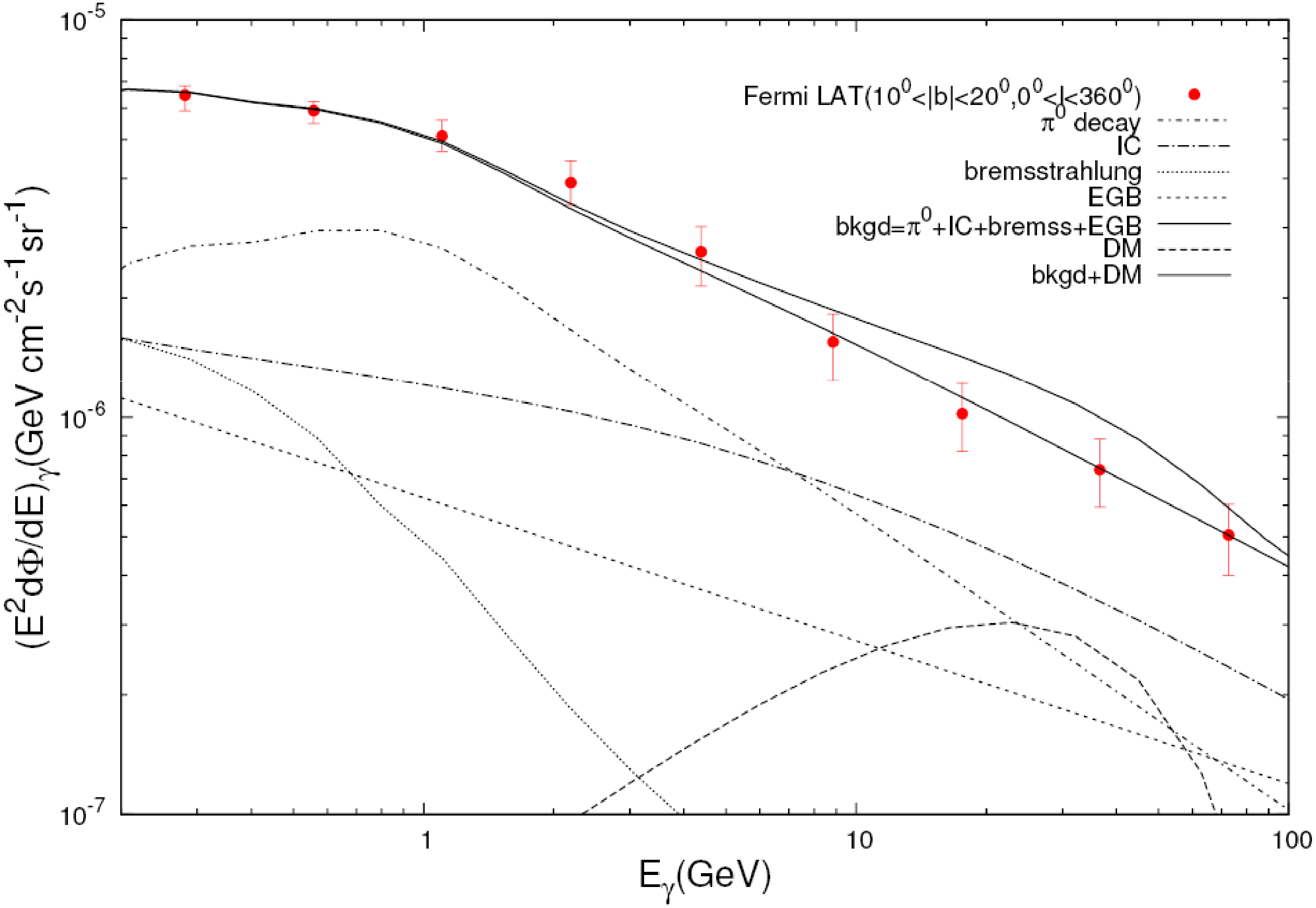
, where ρ/m_χ is the DM number density, $\langle \sigma v \rangle$ is the annihilation cross section, and dN/dE_γ is the photon energy spectrum per annihilation. S is the parameter along the line of sight, and ψ is the angle from the direction of the Galaxy Center.

The factor 2 in the denominator comes from the particle and anit-particle annihilation.

- Adding the Gamma-ray contribution of DM annihilation into the background from Galprop and fitted EGB. We compared the theoretical Gamma-ray flux with Fermi-LAT data and calculate the χ^2.

- We choose 3σ deviation ($\Delta\chi^2 \equiv \chi^2 - \chi^2_{bkgd} = 9$) from the Fermi-LAT data and give the **lower limit** of the cutoff Λ_i as well as the **upper limit** of DM annihilation cross section $\langle \sigma v \rangle$ for each operators.

- Figure 1. For O_1 , and $m_\chi = 200GeV$. Cutoff $\Lambda = 1.5TeV$. The pick of spectrum from DM annihilation is about $0.1m_\chi$.



Constraints from Fermi-LAT

- The **lower limit** of cutoff $\Lambda \simeq O(1)TeV$ for the unsuppressed operators (O_1, O_3, O_5, O_6) for $m_\chi = 50-500GeV$, and the **lower limit** of cutoff $\Lambda \simeq O(0.01-0.1)TeV$ for the suppressed operators by small velocity, light quark mass, or strong coupling constant.

- Table 2.**Lower limit** of cutoff Λ_i from **Fermi-LAT Gamma-ray**

Operators	Λ (TeV)			
	m_χ (GeV) = 50	100	200	500
Dirac DM, (axial) vector/tensor exchange				
$O_1 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$	0.87	1.15	1.46	1.94
$O_2 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu q)$	0.025	0.033	0.042	0.055
$O_3 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	0.87	1.15	1.46	1.94
$O_4 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	0.13	0.12	0.11	0.10
$O_5 = (\overline{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu} q)$	1.04	1.36	1.74	2.31
$O_6 = (\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{q}\sigma_{\mu\nu} q)$	1.04	1.36	1.74	2.31
Dirac DM, (pseudo) scalar exchange				
$O_7 = (\overline{\chi}\chi)(\bar{q}q)$	0.009	0.011	0.014	0.017
$O_8 = (\overline{\chi}\gamma^5\chi)(\bar{q}q)$	0.094	0.11	0.14	0.17
$O_9 = (\overline{\chi}\chi)(\bar{q}\gamma^5 q)$	0.009	0.011	0.014	0.017
$O_{10} = (\overline{\chi}\gamma^5\chi)(\bar{q}\gamma^5 q)$	0.094	0.11	0.14	0.17

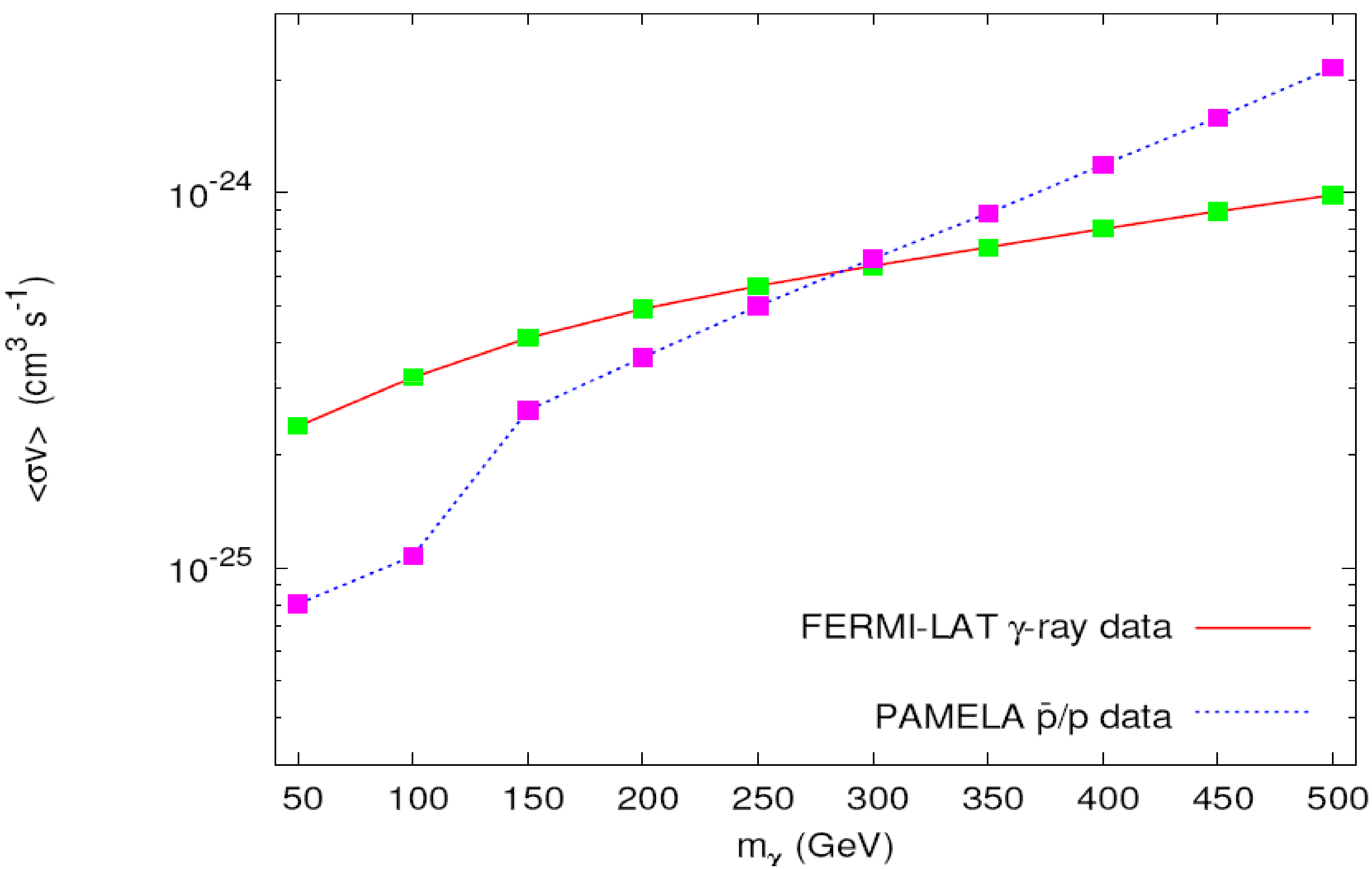
Dirac DM, gluonic				
$O_{11} = (\overline{\chi}\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.011	0.013	0.017	0.024
$O_{12} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.11	0.13	0.17	0.24
$O_{13} = (\overline{\chi}\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.011	0.013	0.017	0.024
$O_{14} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.11	0.13	0.17	0.24
Complex Scalar DM, (axial) vector exchange				
$O_{15} = (\chi^\dagger \overleftrightarrow{\partial_\mu} \chi)\, (\bar{q}\gamma^\mu q)$	0.025	0.033	0.042	0.055
$O_{16} = (\chi^\dagger \overleftrightarrow{\partial_\mu} \chi)\, (\bar{q}\gamma^\mu\gamma^5 q)$	0.025	0.033	0.042	0.055
Complex Scalar DM, (pseudo) scalar exchange				
$O_{17} = (\chi^\dagger\chi)\, (\bar{q}q)$	0.11	0.10	0.095	0.083
$O_{18} = (\chi^\dagger\chi)\, (\bar{q}\gamma^5 q)$	0.11	0.10	0.095	0.083
Complex Scalar DM, gluonic				
$O_{19} = (\chi^\dagger\chi)\, G_{\mu\nu}G^{\mu\nu}$	0.13	0.13	0.13	0.14
$O_{20} = (\chi^\dagger\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	0.13	0.13	0.13	0.14

Antiproton and Gamma-ray Flux Comparison

- Once we have the **lower limit** of cutoff Λ for each DM mass, we can calculate the **upper limit** of $\langle \sigma v \rangle \left(\chi \overline{\chi} \to q \overline{q} \right)$ DM annihilation cross section as a function of DM mass m_χ.

- The **upper limit** of $\langle \sigma v \rangle \left(\chi \overline{\chi} \to q \overline{q} \right)$ are approximately independent of the operators with quark and anti-quark final state. These operators produce similar shape of the Gamma-ray spectra from DM annihilation.

- Figure 4.



10^{-24}
10^{-25}
$<\sigma v>$ $(cm^3 s^{-1})$
FERMI-LAT γ-ray data
PAMELA $\bar{p}/p$ data
50
100
150
200
250
300
350
400
450
500
m_χ (GeV)

- In figure 4, the x-axis is at the value of $\langle \sigma v \rangle \simeq 0.91 pb \simeq 3 \times 10^{-26} cm^3 s^{-1}$ which gives the correct DM relic density, if DM was produced thermally in the early universe.

- The two curves in figure 4 are the **upper limit** of the DM annihilation cross section $\langle \sigma v \rangle (\chi \bar{\chi} \to q \bar{q})$ in the present universe. These two curves are obtained from the **Fermi-LAT Gamma-ray** data and **PAMELA antiproton** data, respectively.

- For lighter DM mass (50-300GeV), PAMELA antiproton data can give more severe constraints on effective operators. For heaver DM mass (300-500GeV), Fermi-LAT Gamma-ray data gives stronger constraints than PAMELA data.

Direct Detection Experiments Constraint

- **CDMS** and **XENON100** give strong constraints on the DM spin-independent (SI) cross section.
  The **upper limit** from CDMS is: $\sigma_{\chi N}^{SI} \simeq 3.8\times 10^{-44} cm^2 \quad at \quad m_\chi = 70 GeV$
  The **upper limit** from XENON100 is:
  $\sigma_{\chi N}^{SI} \simeq 0.7\times 10^{-44} cm^2 \quad at \quad m_\chi = 50 GeV$

- For **Dirac DM** operators, only operators O_1 and O_7 (**Dirac DM** with **vector** or **scalar boson** exchange) will give the DM spin-independent cross section.

- For operator $O_7 = m_q\left(\bar{\chi}\chi\right)\left(\bar{q}q\right)/\Lambda_7^3$, the SI cross section is:

$$\sigma_{\chi N}^{SI} = \frac{\mu_{\chi N}^2}{\pi}\left|G_s^N\right|^2$$

, where $\mu_{\chi N}$ is the reduced mass of the DM and nucleon, and

$$G_s^N = \sum_q \left\langle N\left|\bar{q}q\right|N\right\rangle\left(\frac{m_q}{\Lambda^3}\right), \quad \left\langle N\left|\bar{q}q\right|N\right\rangle = \frac{m_N}{m_q}\times\begin{cases} f_{Tq}^N : light \quad quarks \\ \frac{2}{27} f_{Tg}^N : heavy \quad quarks \end{cases}$$

Using the values of f_{Tq}^N and f_{Tg}^N in the DarkSUSY and taking average between the neutron and proton for $\sigma_{\chi N}^{SI}$. We have

$$\sigma_{\chi N}^{SI} \simeq \frac{m_N^4}{\pi\Lambda_7^6}\left(0.3769\right)^2$$

Using the limit $\sigma_{\chi N}^{SI} < 10^{-44} cm^2$ for $m_\chi \sim 50-200 GeV$, we have

$$\Lambda_7 > 330 GeV$$

This limit for cutoff Λ_7 is better than that from **Gamma-ray** constraints ($\Lambda_7 \simeq O\left(10\right) GeV$).

- For operator $O_1 = \left(\bar{\chi}\gamma^{\mu}\chi\right)\left(\bar{q}\gamma_{\mu}q\right)/\Lambda_1^2$, the SI cross section is:

$$\sigma_{\chi N}^{SI} = \frac{\mu_{\chi N}^2}{256\pi}\left|b_N\right|^2$$

, where $b_N \simeq \frac{3}{2}\left(\alpha_u^V + \alpha_d^V\right)$, and $\alpha_{u,d}^V = 1/\Lambda_1^2$ are the coefficients in front of the operator O_1 . We have

$$\sigma_{\chi N}^{SI} \simeq \frac{9}{256\pi}\frac{m_N^2}{\Lambda_1^4}$$

Using the limit $\sigma_{\chi N}^{SI} < 10^{-44}\,cm^2$, we obtain

$$\Lambda_1 > 4.4TeV$$

It is about 2-3 times larger than the limit of cutoff Λ_1 from **Gamma-ray** constraints ($\Lambda_1 \simeq O(1)TeV$).

Discussion and Conclusions

- We use the effective interaction approach to study the interactions between DM and light quarks.

- Using WMAP data (CDM relic density) give the **upper limit** of **cutoff** and PAMELA antiproton data (Fermi-LAT Gamma-ray data) give the **lower limit** of **cutoff**, we can have the valid regions for each cutoff Λ_i.

- The **lower limit** of **cutoff** is about 1-2 TeV, for the unsuppressed operators. It is about 0.01-0.1 TeV, for the suppressed operators.

- Only the operators O_1 (vector exchange) and O_7 (scalar exchange) for the **Dirac DM** contribute to the spin-independent cross section. **CDMS** and **XENON100** give very strong constraints for these two operators.

- These constrains for effective operators of DM and SM light quarks give useful information for collider searches and direct detection.

Thank You !

- Table 1:

Operator	Coefficient
Dirac DM, Vector Boson Exchange	
$O_1 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$
$O_2 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$
$O_3 = (\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
$O_4 = (\overline{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
$O_5 = (\overline{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$
$O_6 = (\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$
Dirac DM, Scalar Boson Exchange	
$O_7 = (\overline{\chi}\chi)(\bar{q}q)$	$\frac{Cm_q}{\Lambda^3}$
$O_8 = (\overline{\chi}\gamma^5\chi)(\bar{q}q)$	$\frac{iCm_q}{\Lambda^3}$
$O_9 = (\overline{\chi}\chi)(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^3}$
$O_{10} = (\overline{\chi}\gamma^5\chi)(\bar{q}\gamma^5 q)$	$\frac{Cm_q}{\Lambda^3}$

Dirac DM, Gluonic	
$O_{11} = (\overline{\chi}\chi)\, G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$
$O_{12} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}G^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$
$O_{13} = (\overline{\chi}\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$
$O_{14} = (\overline{\chi}\gamma^5\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$
Complex Scalar DM, Vector Boson Exchange	
$O_{15} = (\chi^\dagger \overleftrightarrow{\partial_\mu} \chi)(\bar{q}\gamma^\mu q)$	$\frac{C}{\Lambda^2}$
$O_{16} = (\chi^\dagger \overleftrightarrow{\partial_\mu} \chi)(\bar{q}\gamma^\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$
Complex Scalar DM, Scalar Vector Boson Exchange	
$O_{17} = (\chi^\dagger\chi)(\bar{q}q)$	$\frac{Cm_q}{\Lambda^2}$
$O_{18} = (\chi^\dagger\chi)(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^2}$
Complex Scalar DM, Gluonic	
$O_{19} = (\chi^\dagger\chi)\, G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^2}$
$O_{20} = (\chi^\dagger\chi)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^2}$

Parameter (unit)	Value
Minimum galactocentric radius r_{min} (kpc)	00.0
Maximum galactocentric radius r_{max} (kpc)	25.0
Minimum height z_{min} (kpc)	−04.0
Maximum height z_{max} (kpc)	+04.0
ISRF factors for IC calculation: optical, FIR, CMB $ISRF_{factors}$	1.9, 1.9, 1.9
Gamma-ray Intensity Skymap Longitude minimum $long_{min}$ (degrees)	0.0
Gamma-ray Intensity Skymap Longitude maximum $long_{max}$ (degrees)	360.0
Gamma-ray Intensity Skymap Latitude minimum lat_{min} (degrees)	+10.0
Gamma-ray Intensity Skymap Latitude maximum lat_{max} (degrees)	+20.0
Binsize in Longitude for Gamma-ray Intensity Skymaps d_{long} (degrees)	0.50
Binsize in Latitude for Gamma-ray Intensity Skymaps d_{lat} (degrees)	0.50
Diffusion Coefficient Normalization D_{0xx} (10^{28} cm^{2}s^{-1})	6.1
Diffusion Coefficient Index Below Break Rigidity D_{g1}	0.33
Diffusion Coefficient Index Above Break Rigidity D_{g2}	0.33
Diffusion Coefficient Break Rigidity $D_{rigid\,br}$ (10^3 MV)	4.0
Alfven Speed v_A (km s^{-1})	30
Nuclear Break Rigidity $nuc_{rigid\,br}$ (10^3 MV)	10.0
Nucleus Injection Index Below Break Rigidity nuc_{g1}	2.00
Nucleus Injection Index Above Break Rigidity nuc_{g2}	2.43
Proton Flux Normalization (10^{-9} cm^{-2} sr^{-1} s^{-1} MeV^{-1})	4.90
Proton Kinetic Energy for Normalization (10^5 MeV)	1.00
Electron Break Rigidity0 $electron_{rigid\,br0}$ (10^4 MV)	3.0
Electron Break Rigidity $electron_{rigid\,br}$ (10^9 MV)	1.0
Electron Injection Index Below Break Rigidity0 $electron_{g0}$	2.20
Electron Injection Index Above Break Rigidity0 and Below Break Rigidity $electron_{g1}$	2.54
Electron Injection Index Above Break Rigidity $electron_{g2}$	2.5
Electron Flux Normalization (10^{-10} cm^{-2} sr^{-1} s^{-1} MeV^{-1})	4.0
Electron Kinetic Energy for Normalization (10^4 MeV)	3.45

Operator	Coefficient	Velocity Scaling in $\langle \sigma v \rangle$
Dirac DM, (axial) vector/tensor exchange		
$O_1 = (\overline{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$	m_χ^2
$O_2 = (\overline{\chi}\gamma^\mu\gamma^5\chi)\,(\bar{q}\gamma_\mu q)$	$\frac{C}{\Lambda^2}$	$m_\chi^2 v^2$
$O_3 = (\overline{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$	m_χ^2
$O_4 = (\overline{\chi}\gamma^\mu\gamma^5\chi)\,(\bar{q}\gamma_\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$	$m_\chi^2 v^2$
$O_5 = (\overline{\chi}\sigma^{\mu\nu}\chi)\,(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$	m_χ^2
$O_6 = (\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi)\,(\bar{q}\sigma_{\mu\nu} q)$	$\frac{C}{\Lambda^2}$	m_χ^2
Dirac DM, (pseudo) scalar exchange		
$O_7 = (\overline{\chi}\chi)\,(\bar{q}q)$	$\frac{Cm_q}{\Lambda^3}$	$m_q^2 m_\chi^2 v^2$
$O_8 = (\overline{\chi}\gamma^5\chi)\,(\bar{q}q)$	$\frac{iCm_q}{\Lambda^3}$	$m_q^2 m_\chi^2$
$O_9 = (\overline{\chi}\chi)\,(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^3}$	$m_q^2 m_\chi^2 v^2$
$O_{10} = (\overline{\chi}\gamma^5\chi)\,(\bar{q}\gamma^5 q)$	$\frac{Cm_q}{\Lambda^3}$	$m_q^2 m_\chi^2$
Dirac DM, gluonic		
$O_{11} = (\overline{\chi}\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$	$m_\chi^4 v^2$
$O_{12} = (\overline{\chi}\gamma^5\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$	m_χ^4
$O_{13} = (\overline{\chi}\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^3}$	$m_\chi^4 v^2$
$O_{14} = (\overline{\chi}\gamma^5\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^3}$	m_χ^4
Complex Scalar DM, (axial) vector exchange		
$O_{15} = (\chi^\dagger \overleftrightarrow{\partial_\mu}\chi)\,(\bar{q}\gamma^\mu q)$	$\frac{C}{\Lambda^2}$	$m_\chi^2 v^2$
$O_{16} = (\chi^\dagger \overleftrightarrow{\partial_\mu}\chi)\,(\bar{q}\gamma^\mu\gamma^5 q)$	$\frac{C}{\Lambda^2}$	$m_\chi^2 v^2$
Complex Scalar DM, (pseudo) scalar exchange		
$O_{17} = (\chi^\dagger\chi)\,(\bar{q}q)$	$\frac{Cm_q}{\Lambda^2}$	m_q^2
$O_{18} = (\chi^\dagger\chi)\,(\bar{q}\gamma^5 q)$	$\frac{iCm_q}{\Lambda^2}$	m_q^2
Complex Scalar DM, gluonic		
$O_{19} = (\chi^\dagger\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^2}$	m_χ^2
$O_{20} = (\chi^\dagger\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^2}$	m_χ^2