Cosmic Antiproton Constraints on Effective Interaction of the Dark matter

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arXiv:1011.2310[hep-ph],JCAP01(2011)004
2011/04/04, CS2011

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:

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

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:

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

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

- Dirac DM couples to gluon field:

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

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

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:

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

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:

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

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: $\langle \sigma v \rangle > 0.91 pb$

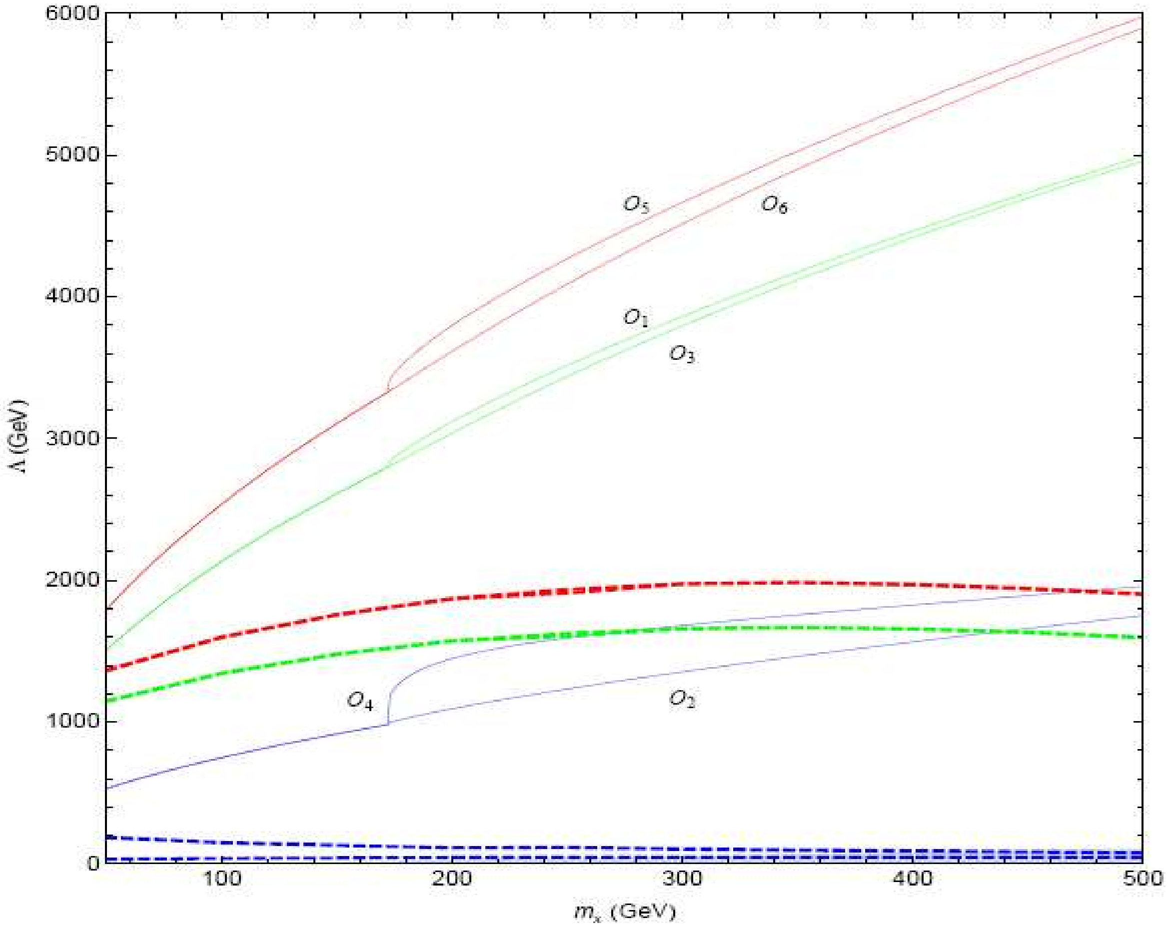
- We use the effective interaction $O_{i=1-20}$ to calculate $\langle \sigma v \rangle$ in the early universe and give **upper limit** of **cutoff** Λ_i .

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

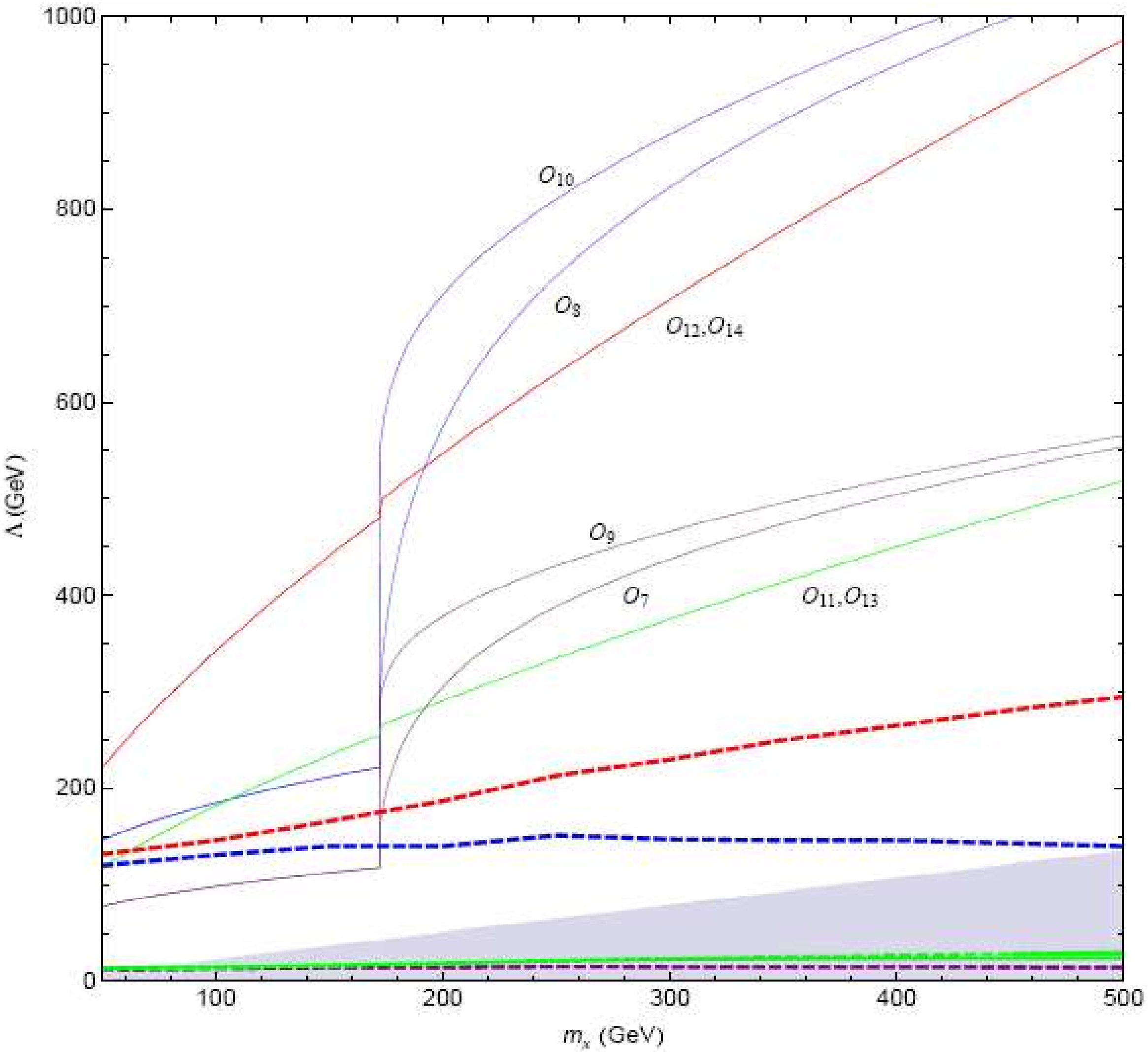
We assume DM velocity $v \approx 0.3c$ at around freeze-out time. We also included the DM annihilation into light quarks and top quark.

- 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.

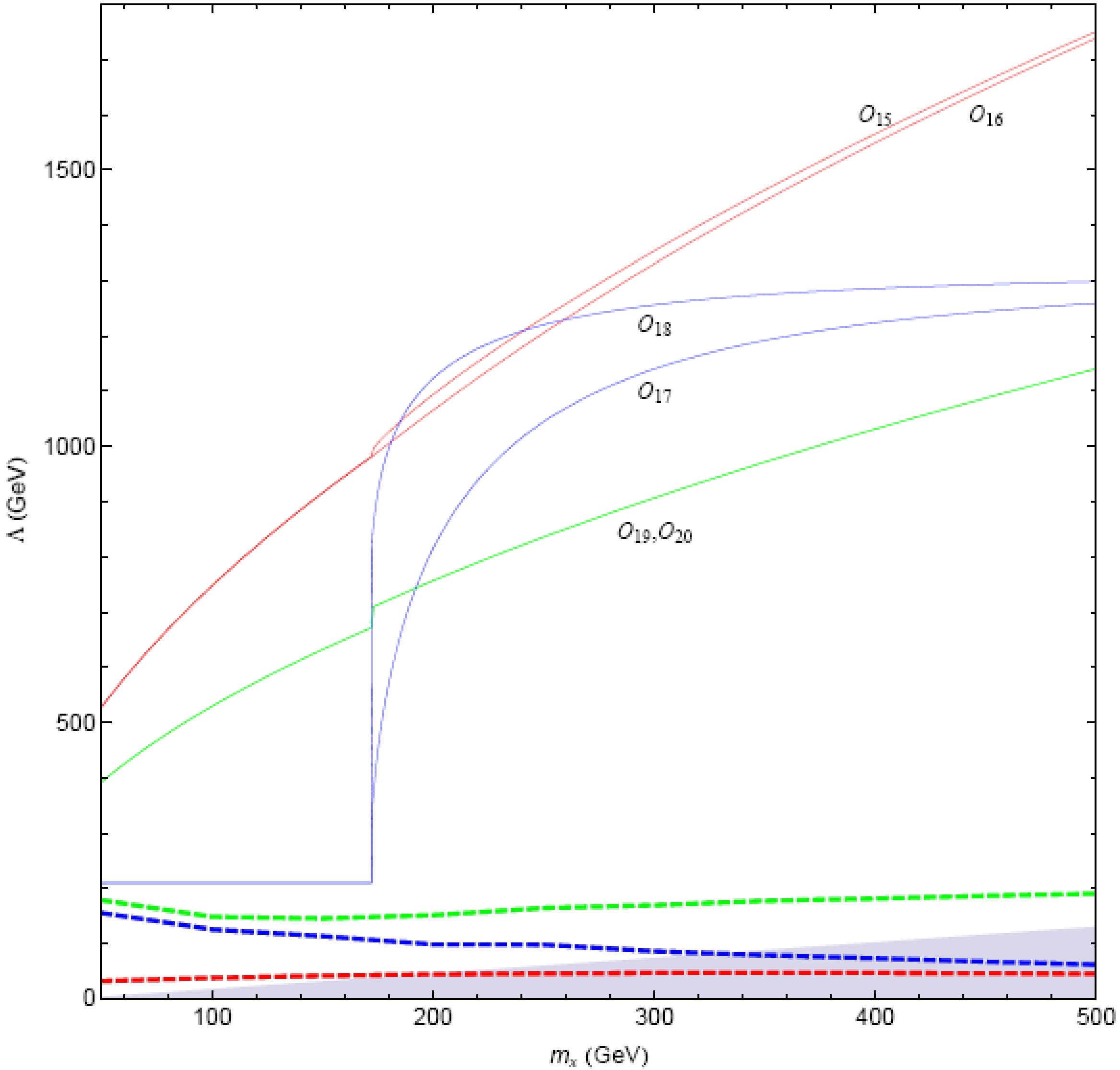
- Figure 1: operators O_{1-6}.



- 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} .

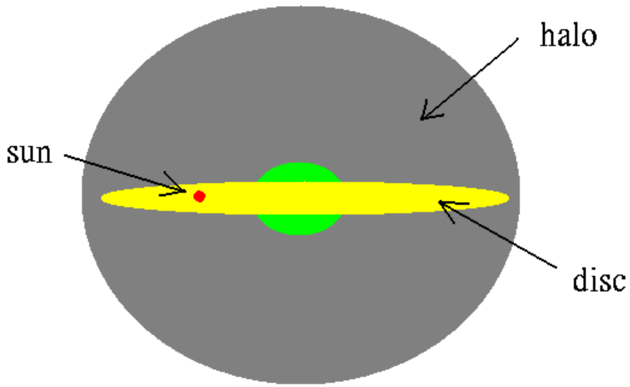


Anitproton Flux

- 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**:

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

where $\psi = \psi\left(\vec{r}, p, t\right)$ 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.

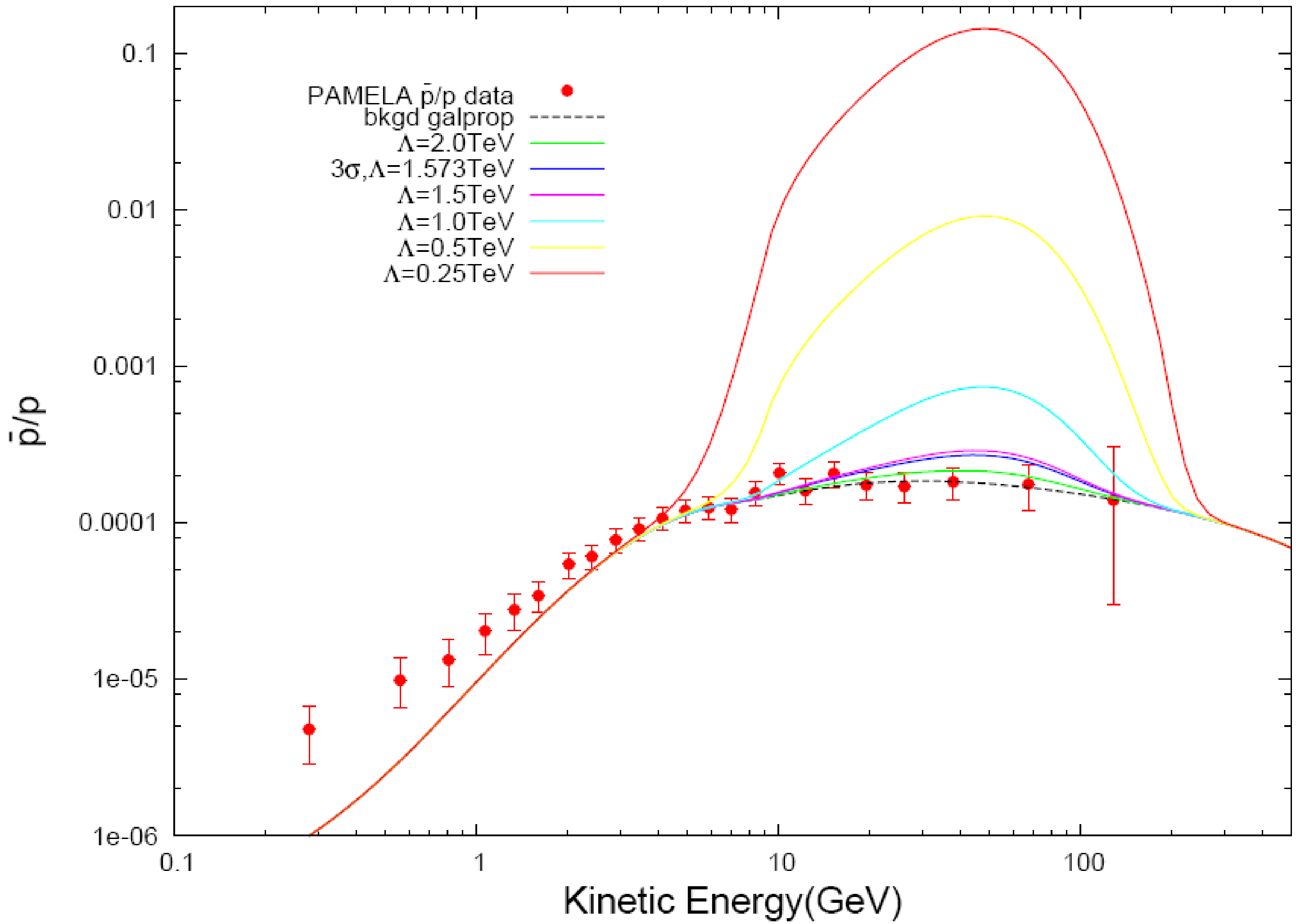
- We calculate the antiproton energy spectrum $dN_{\bar{p}} \big/ dT_{\bar{p}}$ from DM annihilation and put the source term Q into the computer program GALPROP. GALPROP can solve the diffusion equation and output the cosmic antiproton energy spectrum in earth.

- 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 $O_1 = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma^{\mu}\chi\right)\left(\bar{q}\gamma_{\mu}q\right)$,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

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

,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 $\bar{\psi}\gamma^{\mu}\gamma^{5}\psi$ are

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

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

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

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

- After being squared and traced, the **time-like** part of $\bar{q}\gamma^{\mu}q \quad or \quad \bar{q}\gamma^{\mu}\gamma^{5}q$ 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.

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 give the **lower limit** of **cutoff**, we can have the valid regions for each cutoff Λ_i,e.g.

$$1.6TeV < \Lambda_1 < 3TeV \quad for \quad m_\chi = 200GeV$$

- 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	
$O_{19} = (\chi^\dagger\chi)\,G_{\mu\nu}G^{\mu\nu}$	$\frac{C\alpha_s}{4\Lambda^2}$
$O_{20} = (\chi^\dagger\chi)\,G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{iC\alpha_s}{4\Lambda^2}$