Cosmic Antiproton Constraints on Dark Matter Effective Interaction

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Talk at Portorož 2011 -- The Role of Heavy Fermions in Fundamental Physics,
April 11 - 14 (2011), Portorož, Slovenia

Based on Kingman Cheung, Po-Yan Tseng and TCY, arXiv:1011.2310[hep-ph] JCAP01 (2011) 004

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 $(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma' q)$, where $\Gamma, \Gamma' = \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \gamma^5, 1$

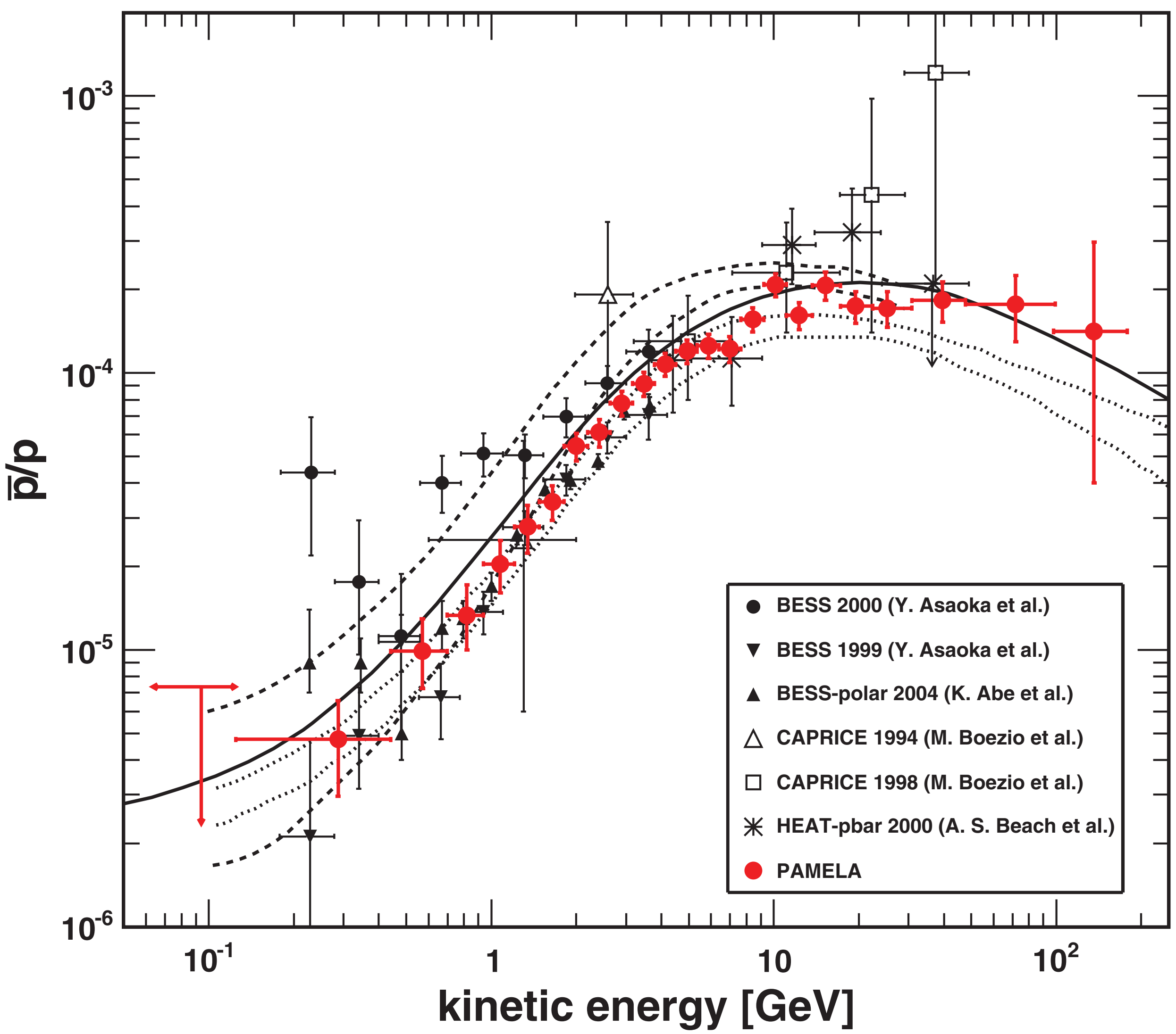
- There have been some works to constrain these effective interactions by present and future collider experiments, and gamma-ray experiments.

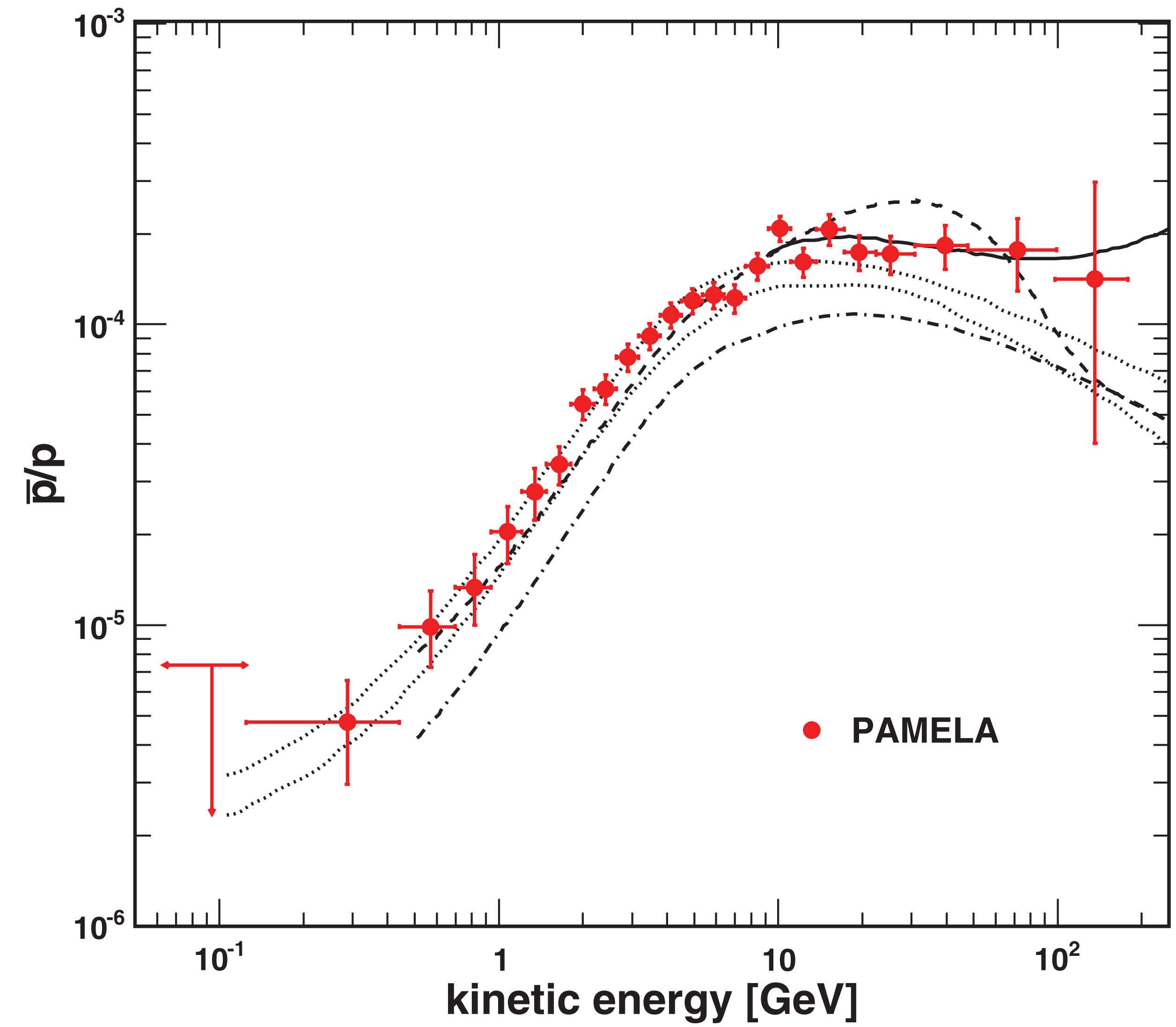
[See e.g. Cao et al, 0912.4511; Bai et al, 1005.3797; Goodman et al, 1008.1783, 1009.0008; Mack et al, 0803.0157; Fan et al, 1008.1591]

In this work

- We use relic density from WMAP to obtain a lower bound on the DM annihilation cross section. This provides us a lower bound on the strength of DM effective interaction (or upper bound on the DM scale). Otherwise, there would be too many DM in the universe.
- We use the cosmic antiproton flux from PAMELA to give us an upper bound of the strength of DM effective interaction which translate into a lower bound on the DM scale.

PAMELA $\bar{p}$ Data (2010)





Data very close to background, unlike the positron.
It can provide stringent constraints on DM physics.

Effective Interactions

- The effective interactions of Dirac fermion DM and light quarks via a (axial) vector-boson or tensor-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:

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

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

- Dirac DM couples to gluon field:

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

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

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:

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

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

- Complex scalar DM via scalar boson exchange:

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

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

Finally,

- Complex scalar DM couple to gluon field:

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

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

Except for $O_{1,3,5,6}$, all other operators are suppressed by either m_q, α_s or v_χ.

[For spin-dependent effects, see Freytsis and Ligeti, arXiv:1012.5317 (Ligeti's talk)]

[For more complete list of effective operators, see Nobile and Sannino, arXiv:1102.3116]

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

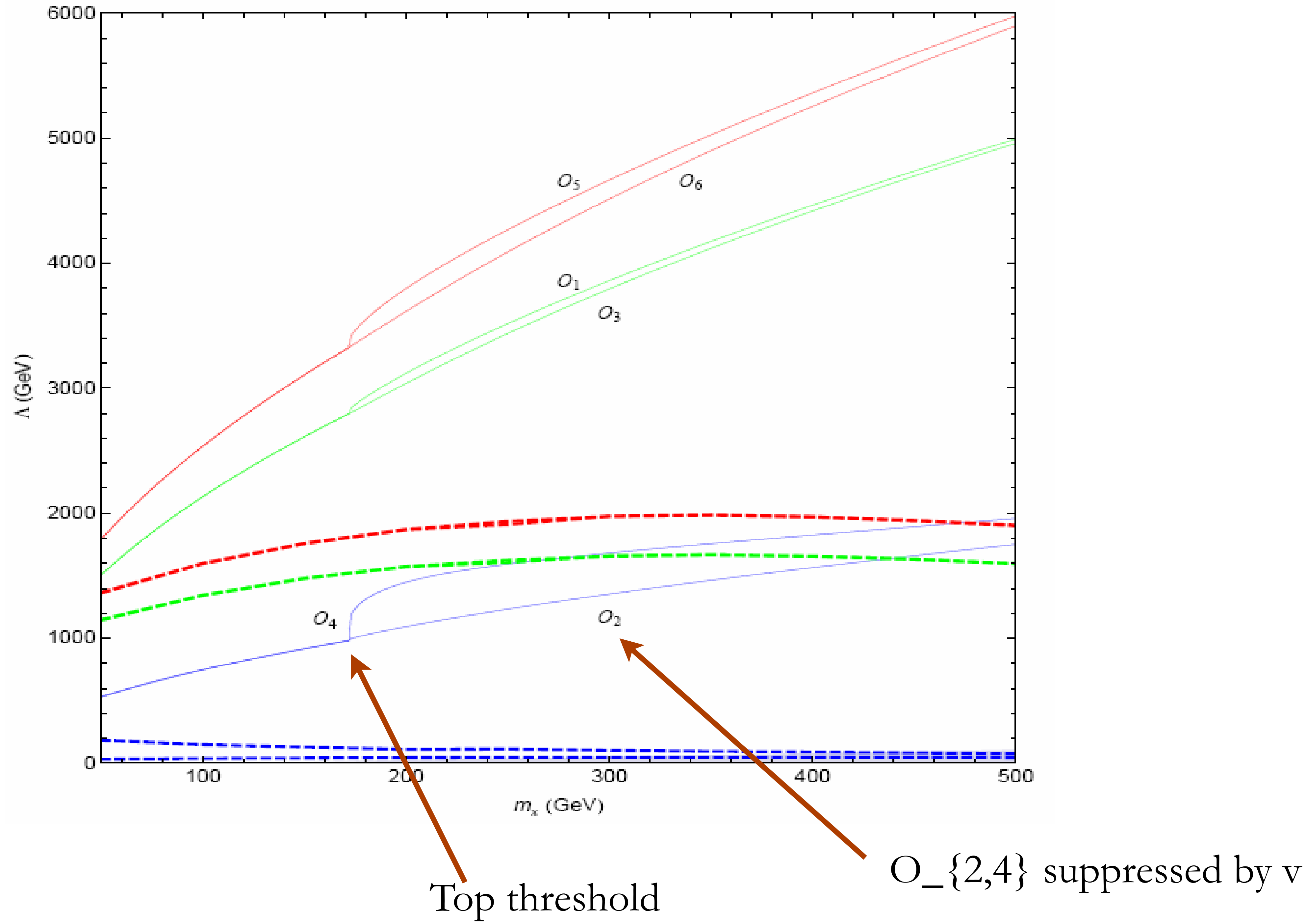
- We use the effective interaction $O_{i=1-20}$ to calculate $\langle \sigma v \rangle$ in the early universe and give **upper limit** of **cutoff** Λ_i .

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

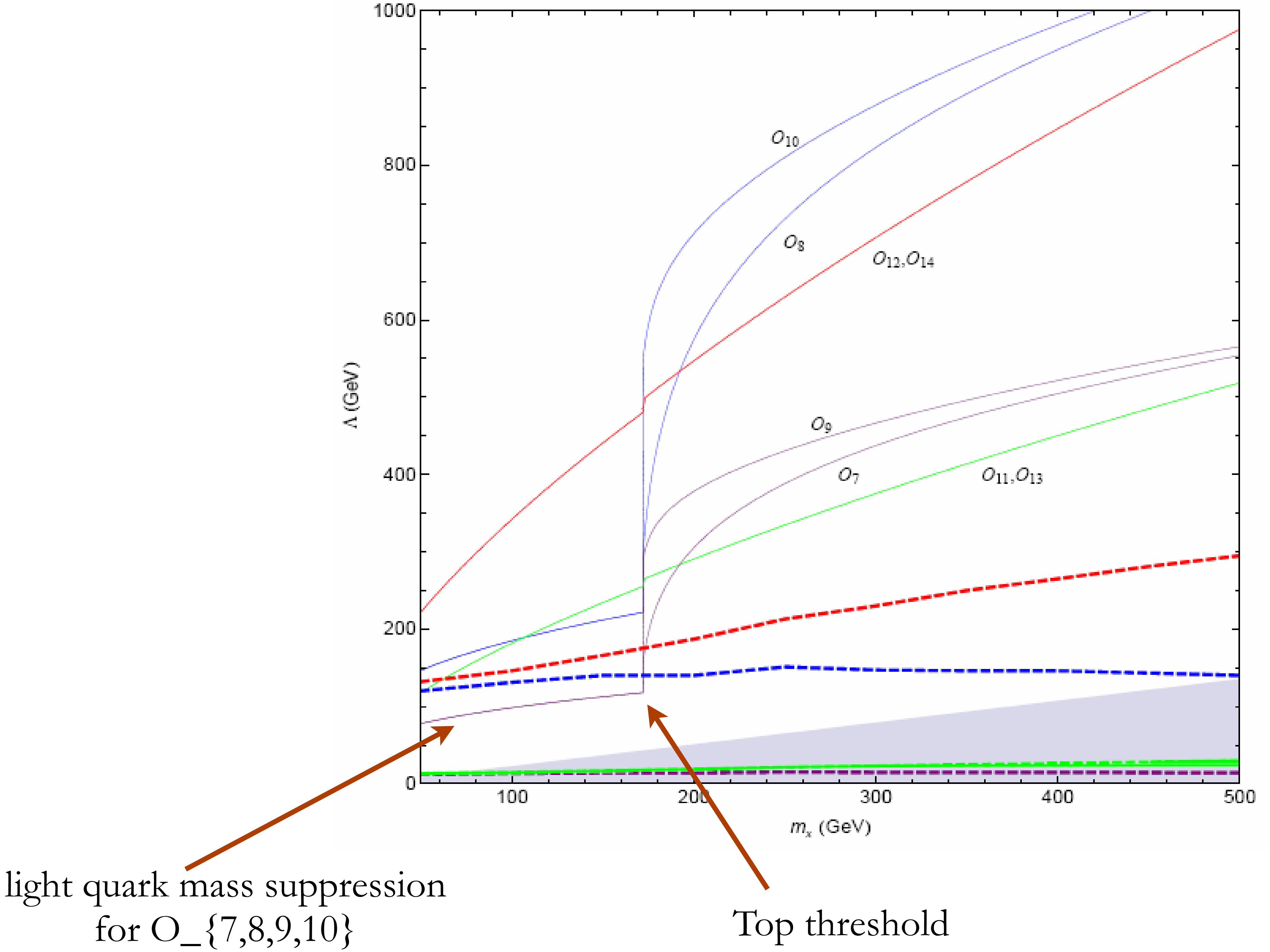
We assume DM velocity $v \approx 0.3c$ at around freeze-out time. We also included the DM annihilation into light quarks and top quark.

- 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 .

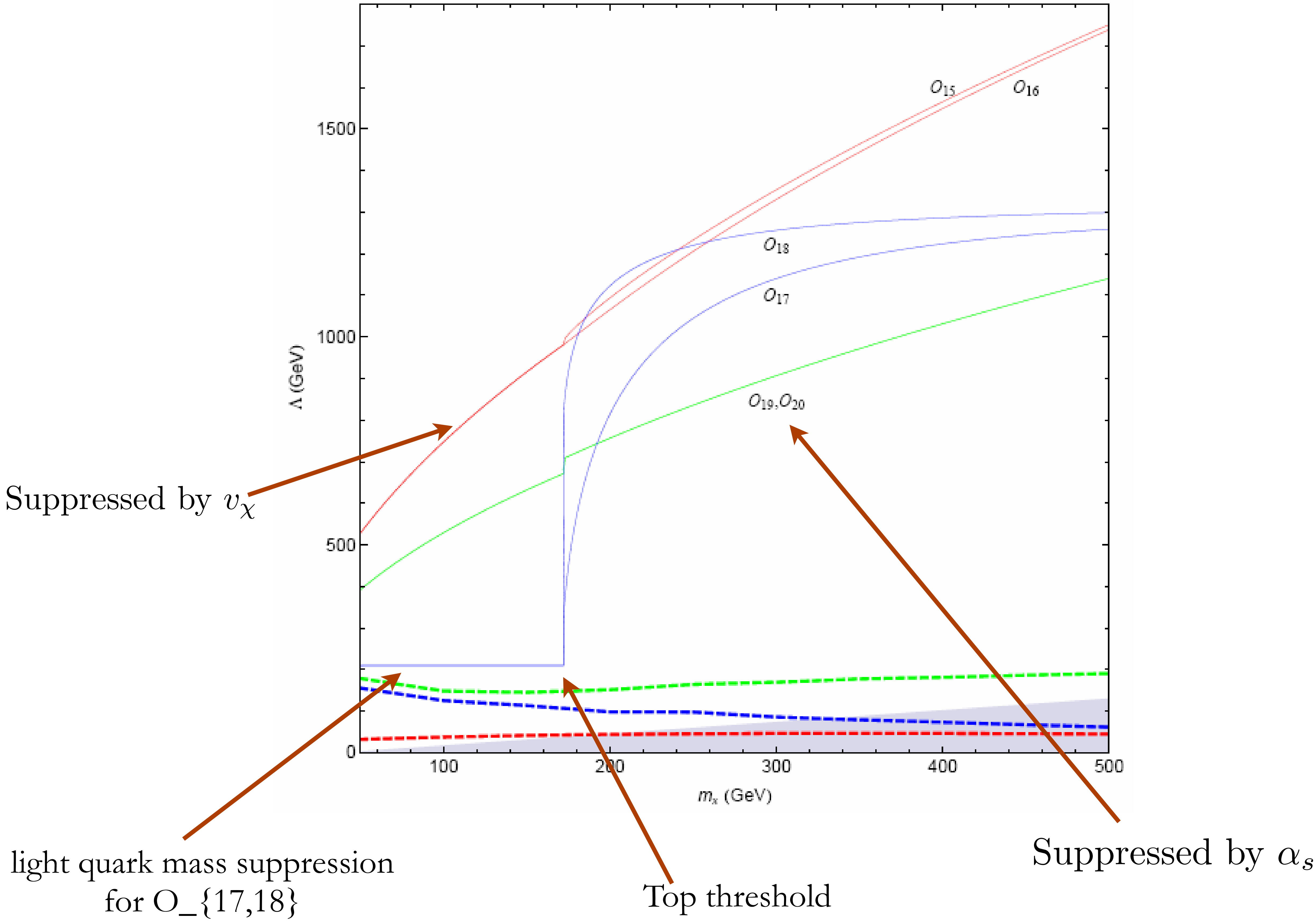
- Figure 1: operators O_{1-6} .



- 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} . Scalar DM

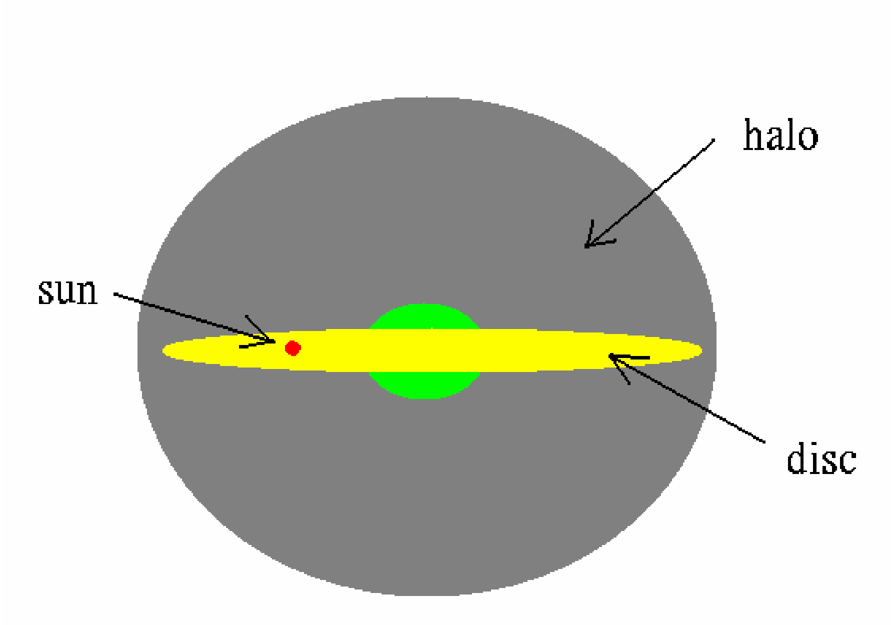


Antiproton Flux

- 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**:

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

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.

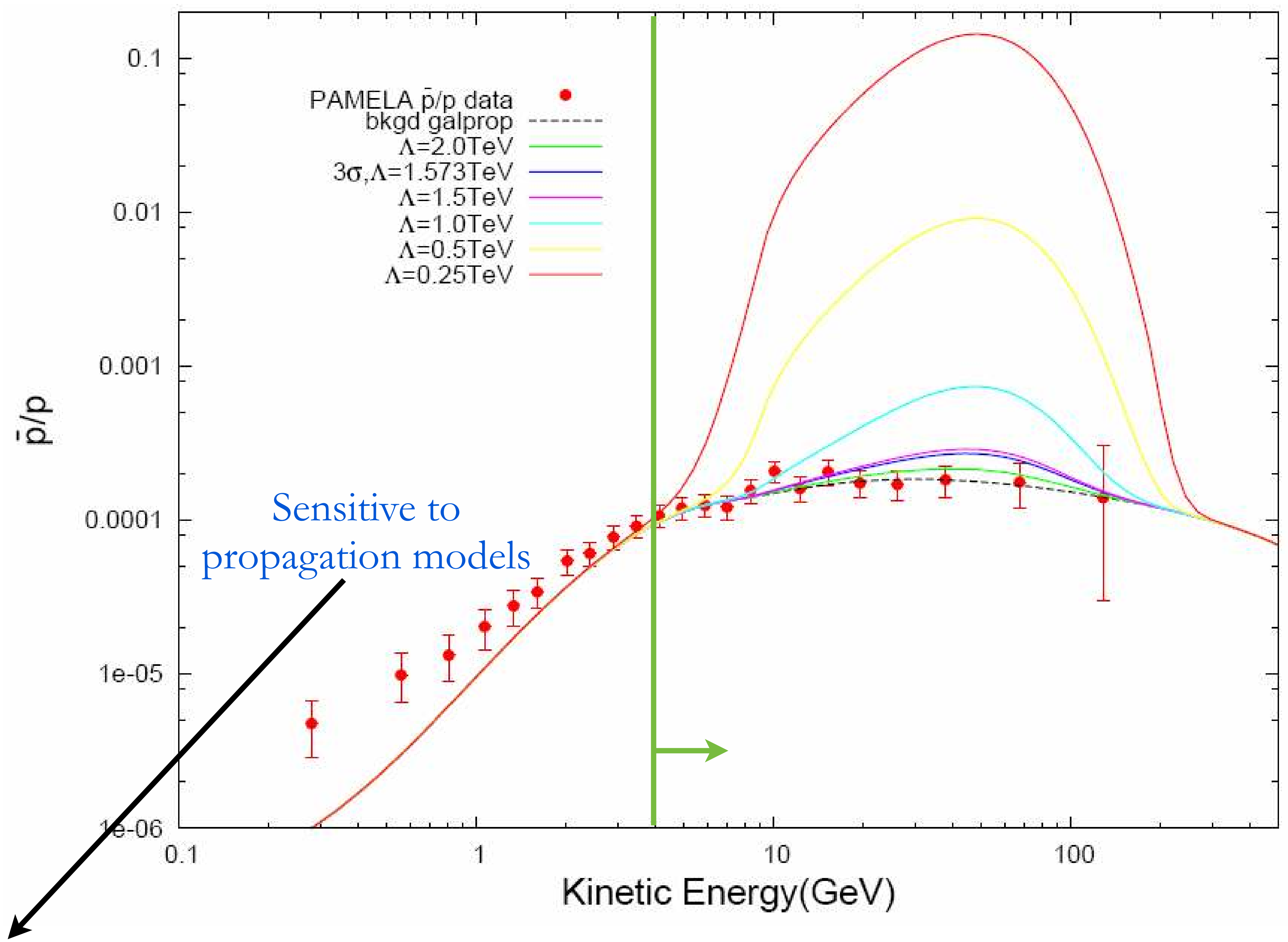
- We calculate the antiproton energy spectrum $dN_{\bar{p}} / dT_{\bar{p}}$ from DM annihilation and put the source term Q into the computer program GALPROP. GALPROP can solve the diffusion equation and output the cosmic antiproton energy spectrum in earth.

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

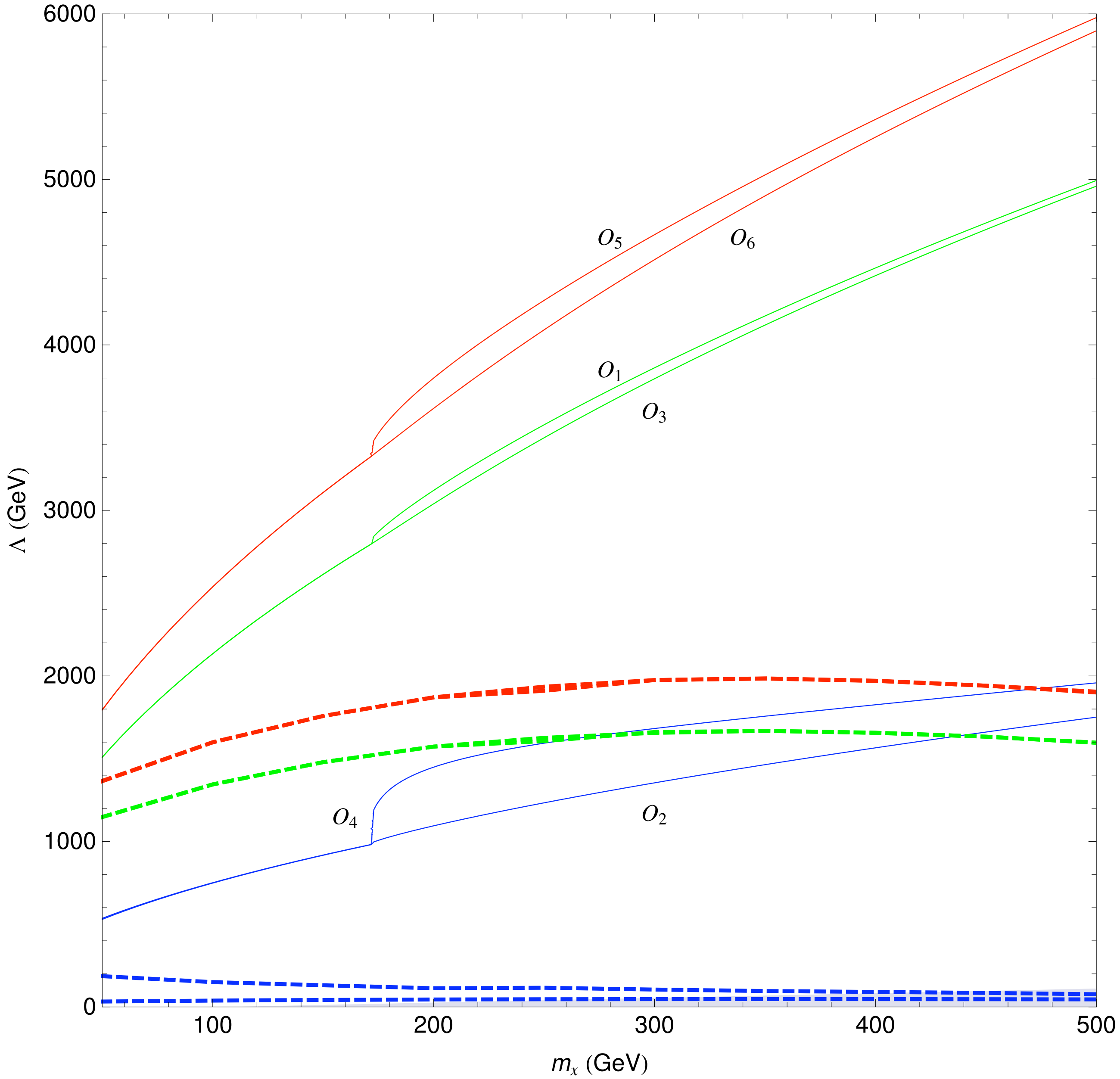


See Low, Keung and Shaughnessy, PRD82, 115019 (2010)

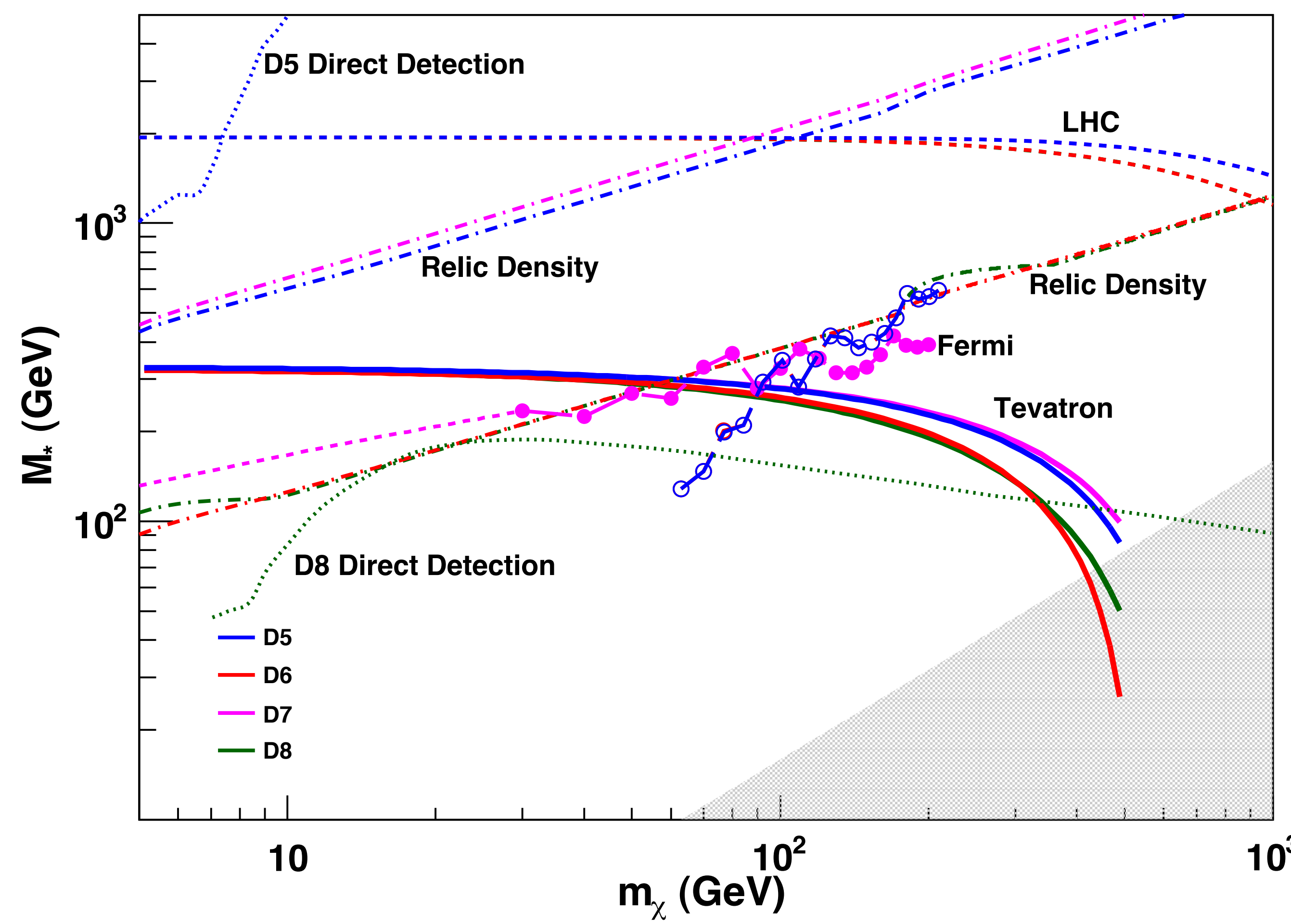
Operators	Λ (TeV)			
	m_χ (GeV) = 50	100	200	400
Dirac DM, Vector Boson Exchange				
$O_1 = (\overline{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu q)$	1.15	1.34	1.57	1.66
$O_2 = (\overline{\chi}\gamma^\mu\gamma^5\chi)\,(\bar{q}\gamma_\mu q)$	0.033	0.038	0.045	0.047
$O_3 = (\overline{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu\gamma^5 q)$	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

Table 3. The 3σ lower limits on the operators listed in table 1. We take the coefficient $C = 1$ with $m_\chi = 50$, 100, 200 and 400 GeV. We have used the PAMELA data points above the kinetic energy $T = 4$ GeV in our analysis, because of the large uncertainty of the theoretical background at low energy. The $\chi^2(\text{bkdg}) = 5.0$.

Comparison with Fermi-LAT Gamma Ray Line Limits



[Goodman et al, NPB 844 (2011) 55, arXiv:1009.0008]



$$O_{1,3} : 1.1 - 1.7 \text{ TeV}$$

$$D_{5,7} : 0.1 - 0.5 \text{ TeV}$$

Discussions and Conclusions

- 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.

- These constraints for effective operators of DM and light quarks and gluons may give useful information for collider searches and direct detections.

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