Cosmic Antiproton and Gamma Ray Constraints on Effective Interactions of Dark Matter

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Outline

- Introduction
- Direct / Indirect Detections
- Constraints on Effective Interactions from PAMELA and Fermi-LAT
- Summary

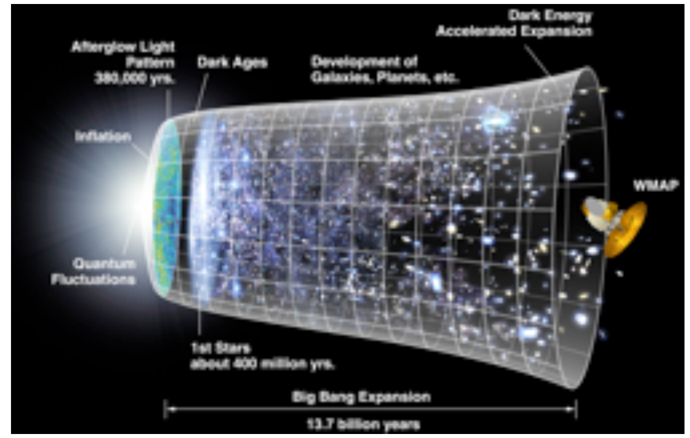
[1] Kingman Cheung, Po-Yan Tseng and TCY, JCAP 1101:004 (2011), arXiv:1011.2310

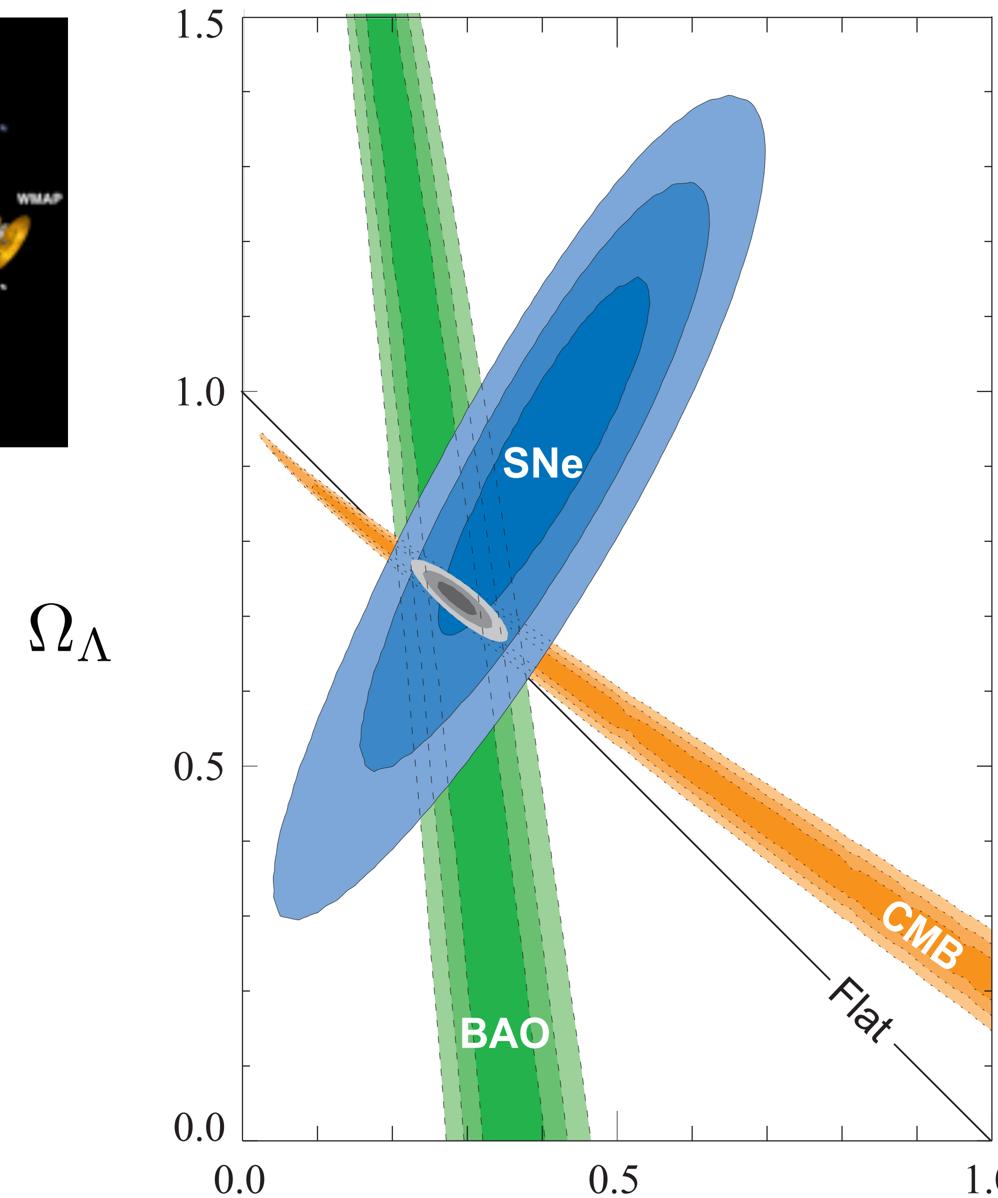
[2] Kingman Cheung, Po-Yan Tseng and TCY, JCAP 1106:023 (2011), arXiv:1104.5329

Introduction

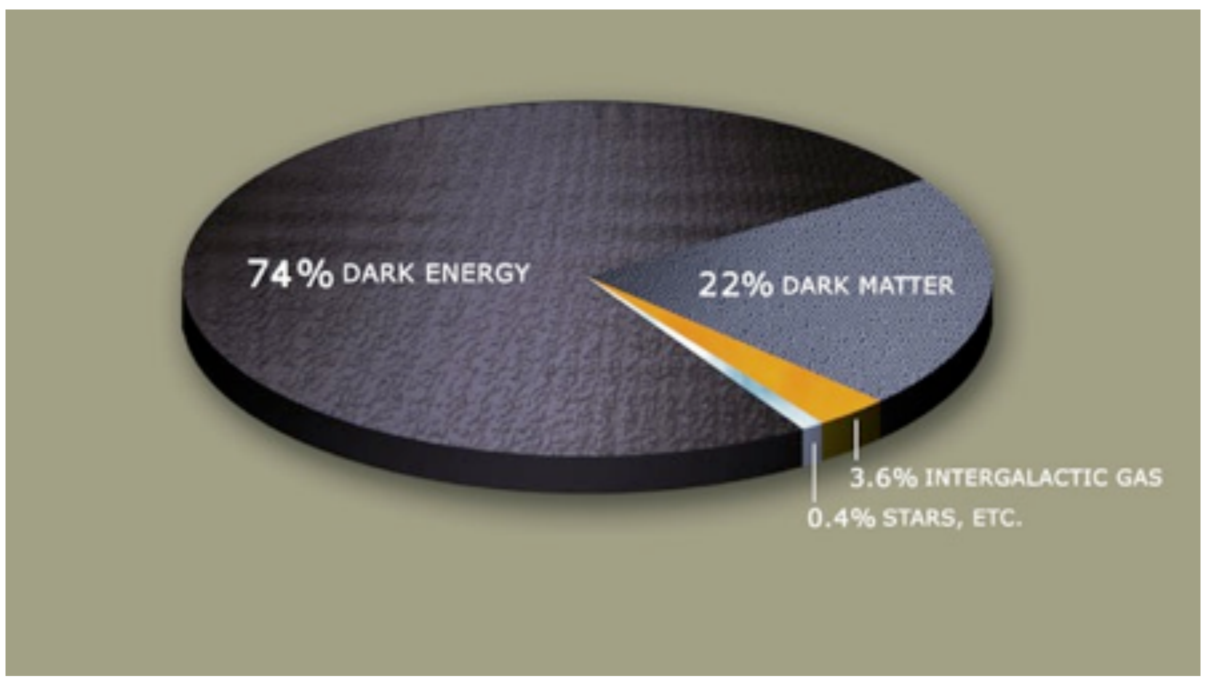
- Many evidences suggest the existence of DM
  Gravitation:
  (1) Rotation curves
  (2) WMAP relic density
  (3) Bullet Clusters
  (4) Strong and weak gravitational lensing
  (5) Structure formation
  Direct Experiment:
  (1) DAMA modulation
  (2) CoGeNT
  Indirect Experiments:
  (1) PAMELA positron excess
  (2) Fermi-LAT electron+positron spectrum

Standard ΛCDM Model of Cosmology





Energy Budget



$$\Omega_b h^2 = 0.02260 \pm 0.00053$$

$$\Omega_{\rm CDM} h^2 = 0.1123 \pm 0.0035$$

$$\Omega_\Lambda = 0.728^{+0.015}_{-0.016}$$

$$t_0 = 13.75 \pm 0.11 \text{ Gyr}$$

Relic Density & WIMP (cont)

On the theoretical side, one can calculate the DM relic density by the freeze-out condition:

$$\Omega_X h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v\rangle} \approx \frac{0.1\ \mathrm{pb}}{\langle \sigma_A v\rangle}$$

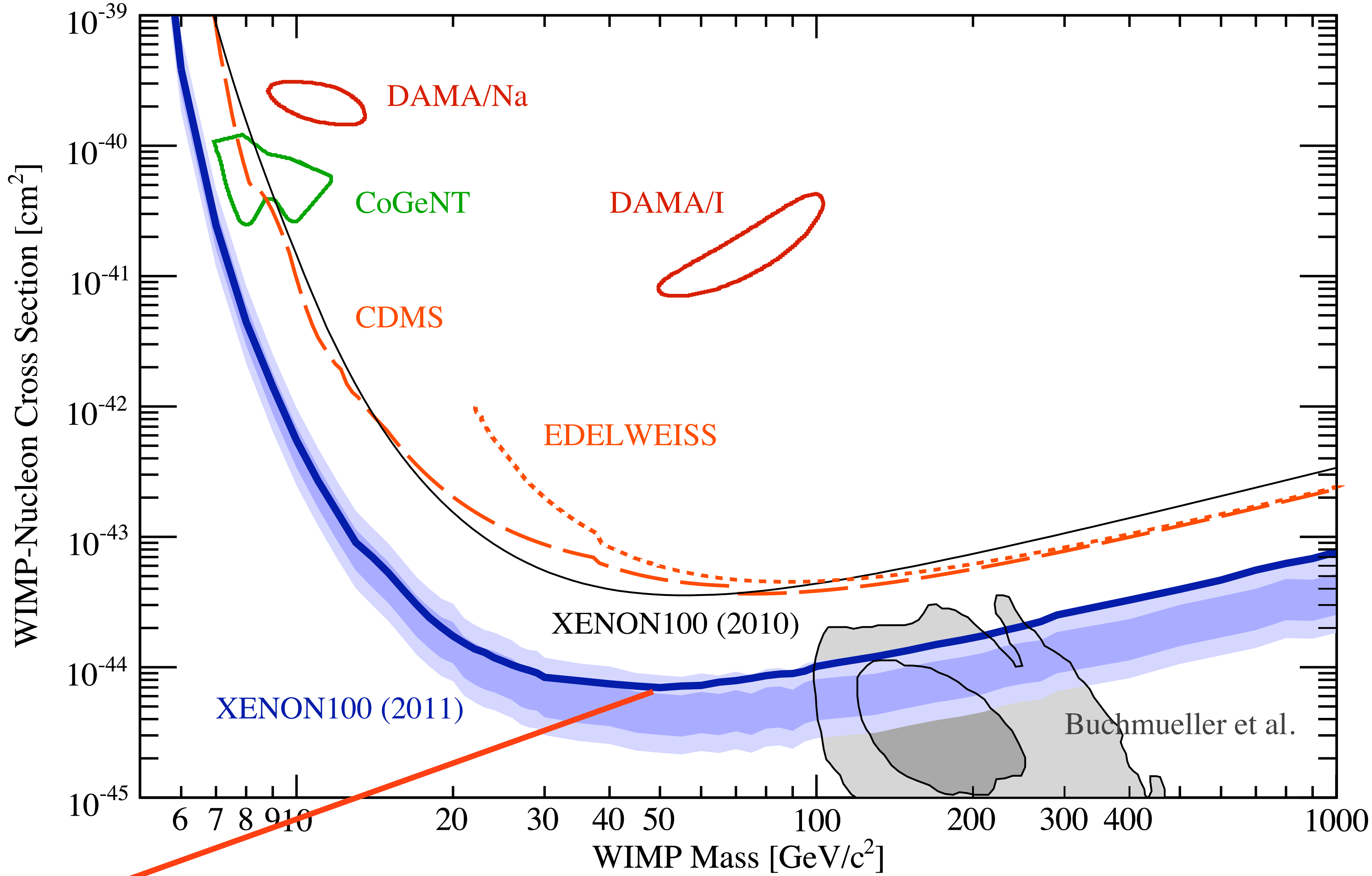
$$\Omega_{CDM}h^2(\mathrm{WMAP}) = 0.1123 \pm 0.0035$$

→ WIMP miracle

Put lower limits on $\langle \sigma_A v\rangle$ ←

Direct Detection

XENON100 Cross Sections Limits [arXiv:1104.2549]

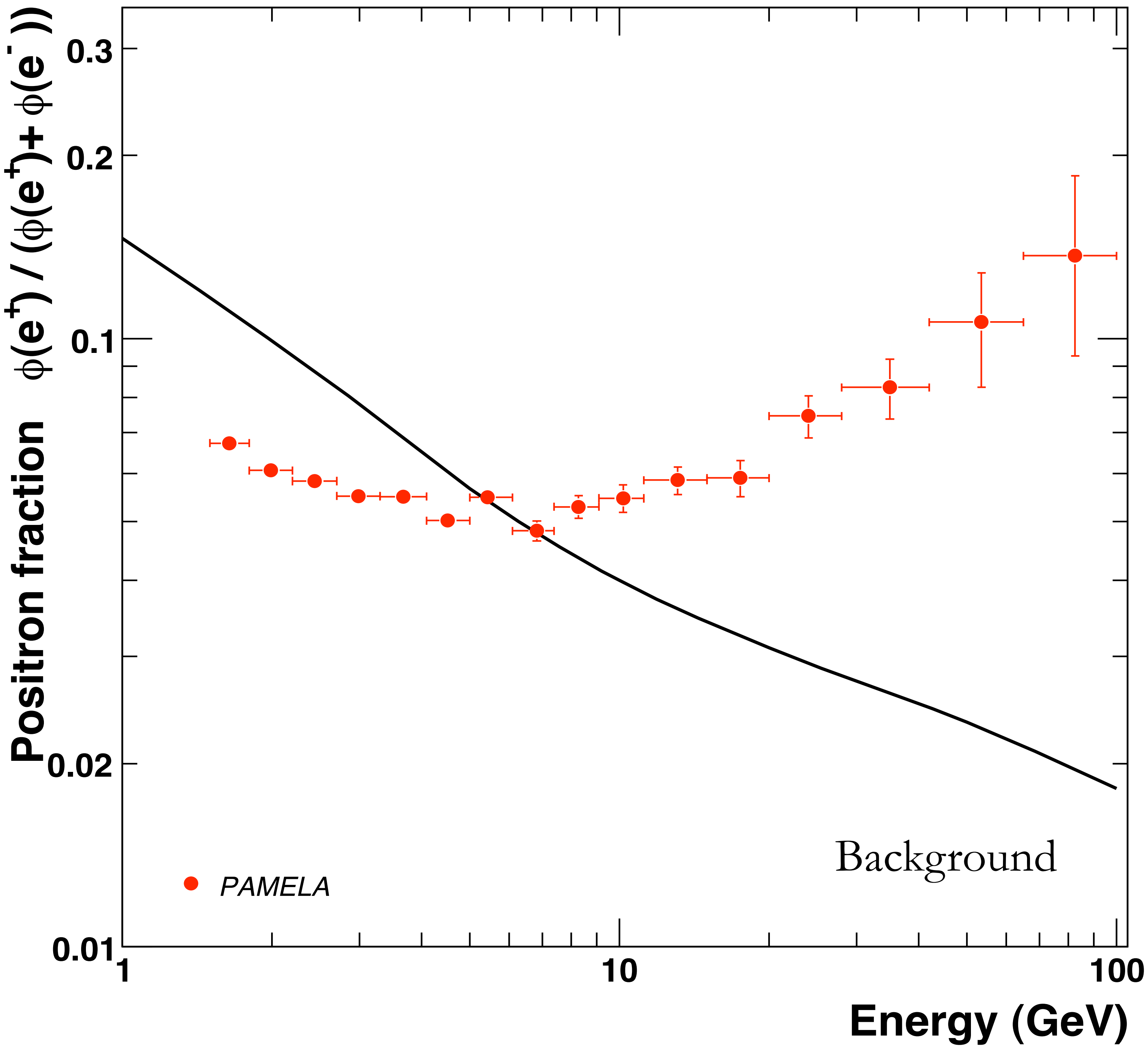


$\sigma^{\mathrm{up}} = 7.0 \times 10^{-45}\ \mathrm{cm}^2$ with $m_\chi = 50\ \mathrm{GeV}/c^2 (90\%\mathrm{CL})$

* Elastic Scattering; Isospin Conserving

Indirect Detection

PAMELA, Nature 458 (2009) 607

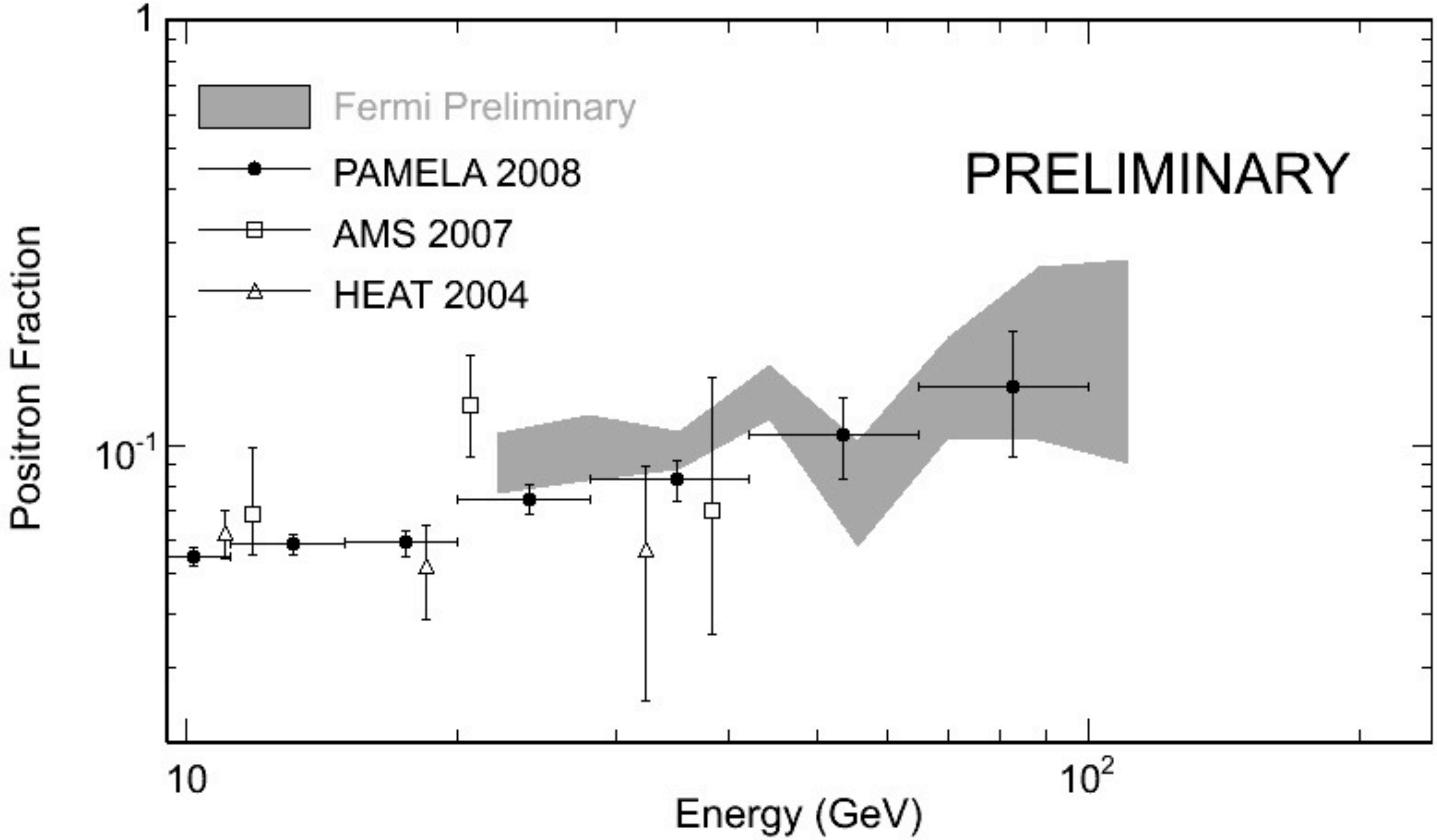


Pulsars or DM?

Positron excess in the 10-100 GeV range.
Below 10 GeV, data are affected by solar modulation.

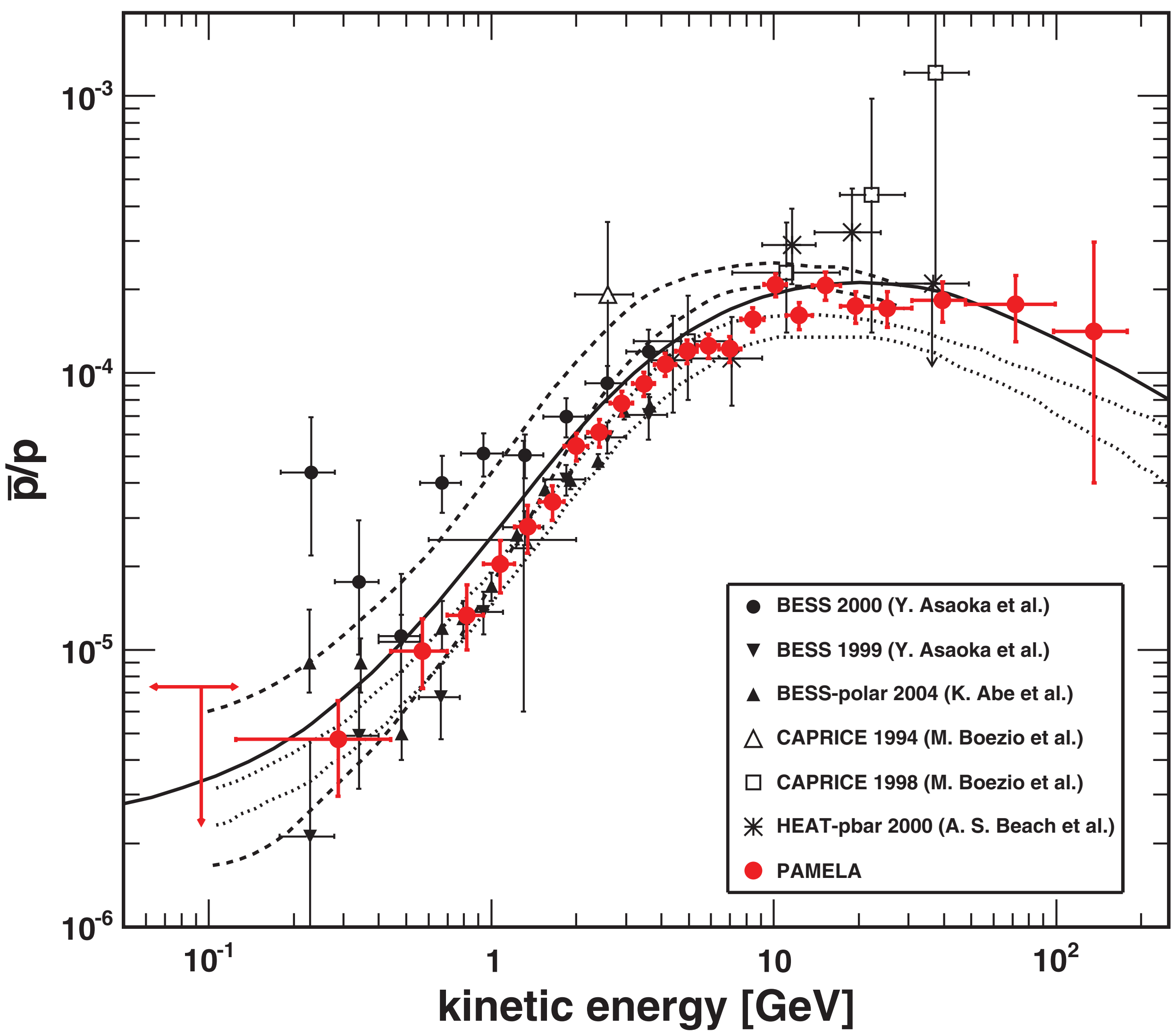
Indirect Detection (Cont.)

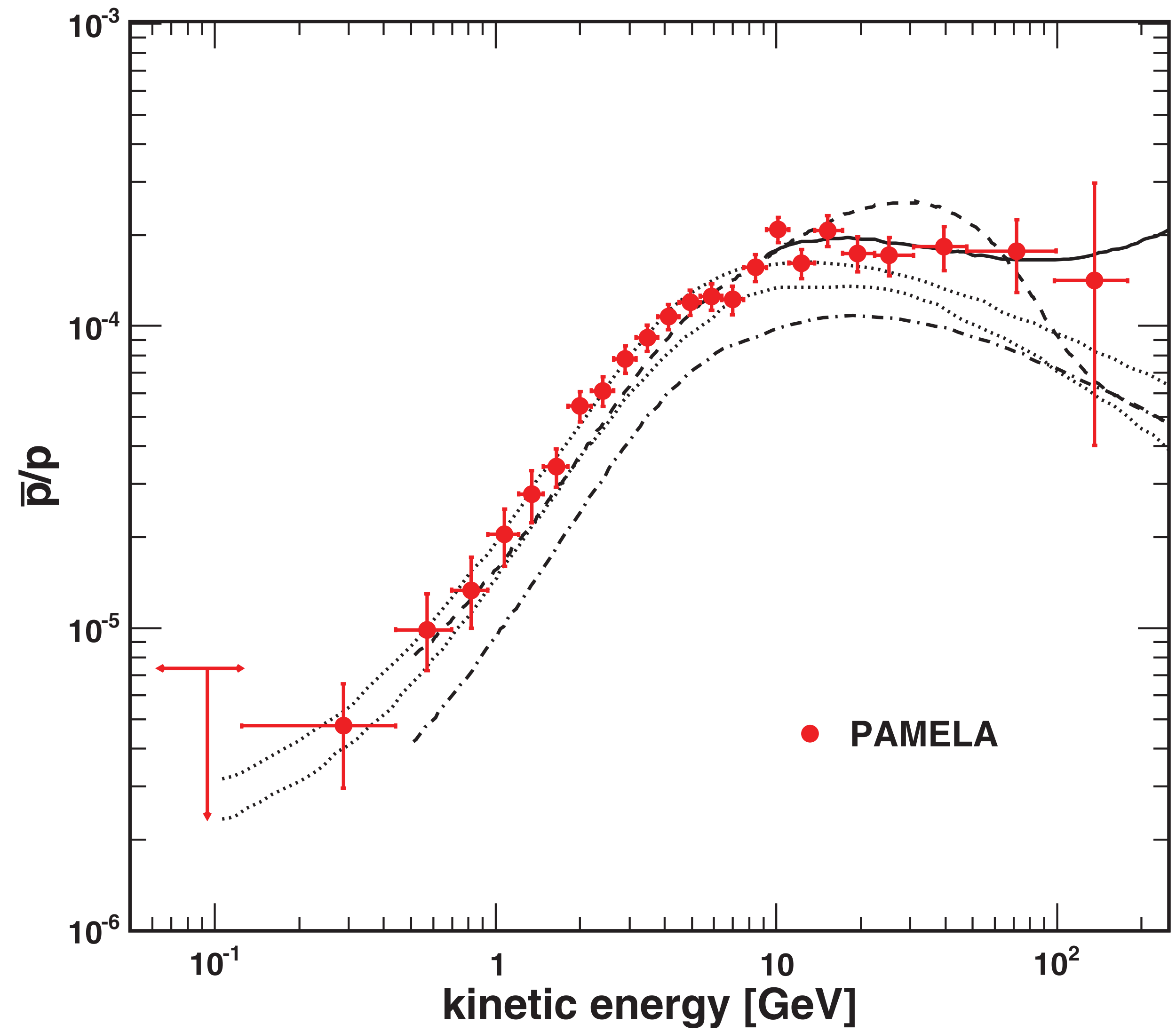
- Fermi-LAT recently confirmed the PAMELA result, using the Earth B- field



Indirect Detection (Cont.)

PAMELA $\bar{p}$ Data (2010) PRL 105 (2010) 121101





Data very close to background.

It can provide stringent constraints on DM physics.

$$\chi\bar{\chi} \to q\bar{q} \text{ or } gg \to \bar{p} + X$$

Constraints on Effective Interactions

- Origin of DM
(1) MACHOS
(2) massive neutrinos
(3) axions
(4) WIMP
(5) etc

- WIMP Models are favored by relic density constraint of WMAP
(1) MSSM with R-parity (LSP)
(2) UED with KK parity (LKP)
(3) Little Higgs models with T-parity (LTP)
(4) Darkon (Scalar Phantoms) model (Silveira & Zee, 1985)
(5) Inert doublet model (IDM) [See P. Osland's talk]
(6) etc

- Our approach (adopted by many other groups as well):
(1) effective interaction of WIMP DM with SM particles
(2) assumption: the connector sector must be heavy and integrated out
(3) DM can be scalar or fermionic; vector DM not considered
(4) Twist 2 and higher operators are ignored

Λ : Effective scale

Dirac DM

SUSY / SD

SUSY / SI

Scalar DM

Darkon

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

Suppressed by m_q^2 and v^2

Suppressed by α_s^2 and v^2

Suppressed by v^2

Suppressed by m_q^2

Enhanced by m_t^2

Suppressed by α_s^2

Table 1. The list of effective interactions between the dark matter and the light degrees of freedom (quark or gluon). We have suppressed the color index on the quark and gluon fields. These operators have also been analyzed in refs. [3, 5, 8, 13].

Constraints on Λ

$$\chi\bar{\chi} \to q\bar{q} \text{ or } gg \to \bar{p} + X \qquad (q = u, d, s, c, b)$$

- WMAP relic density can provide an upper limit on Λ
- PAMELA anti-proton spectrum can provide a lower limit on Λ
- Fragmentation functions are taken from Ablino et al [NPB 725 (2005) 181 - 206]; obtained by fitting all relevant data from e+ e- annihilation experiments
- Use GALPROP [Moskalenko & Strong] to include propagation effect for anti-proton from galaxy to earth
- Source term for diffusion

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

Antiproton fraction spectrum from O_1

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm bkgd}$ $\chi^2_{\rm bkgb}\ (\geq 4\ \mathrm{GeV}) = 5.0$ for 13 d.o.f.

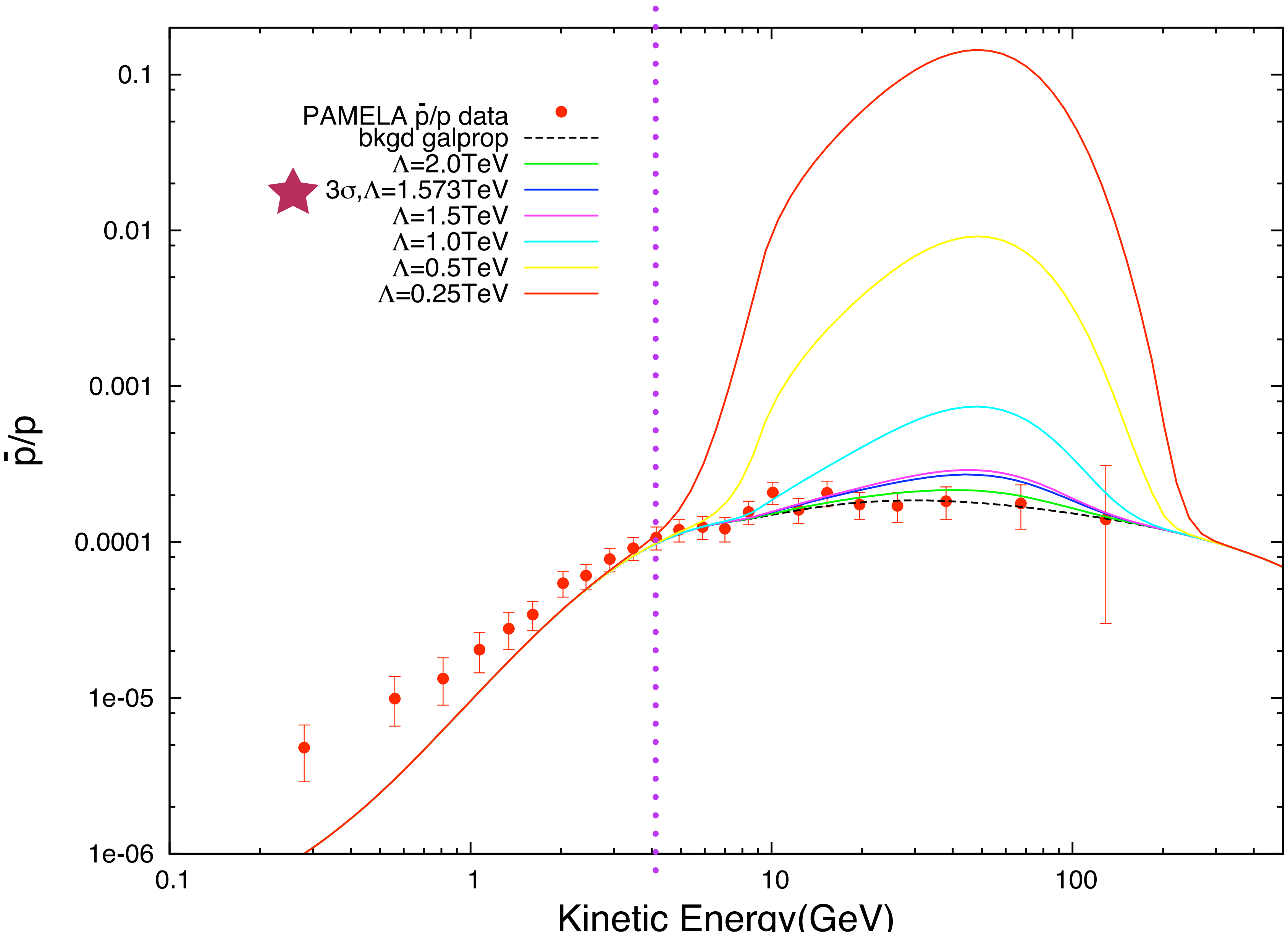


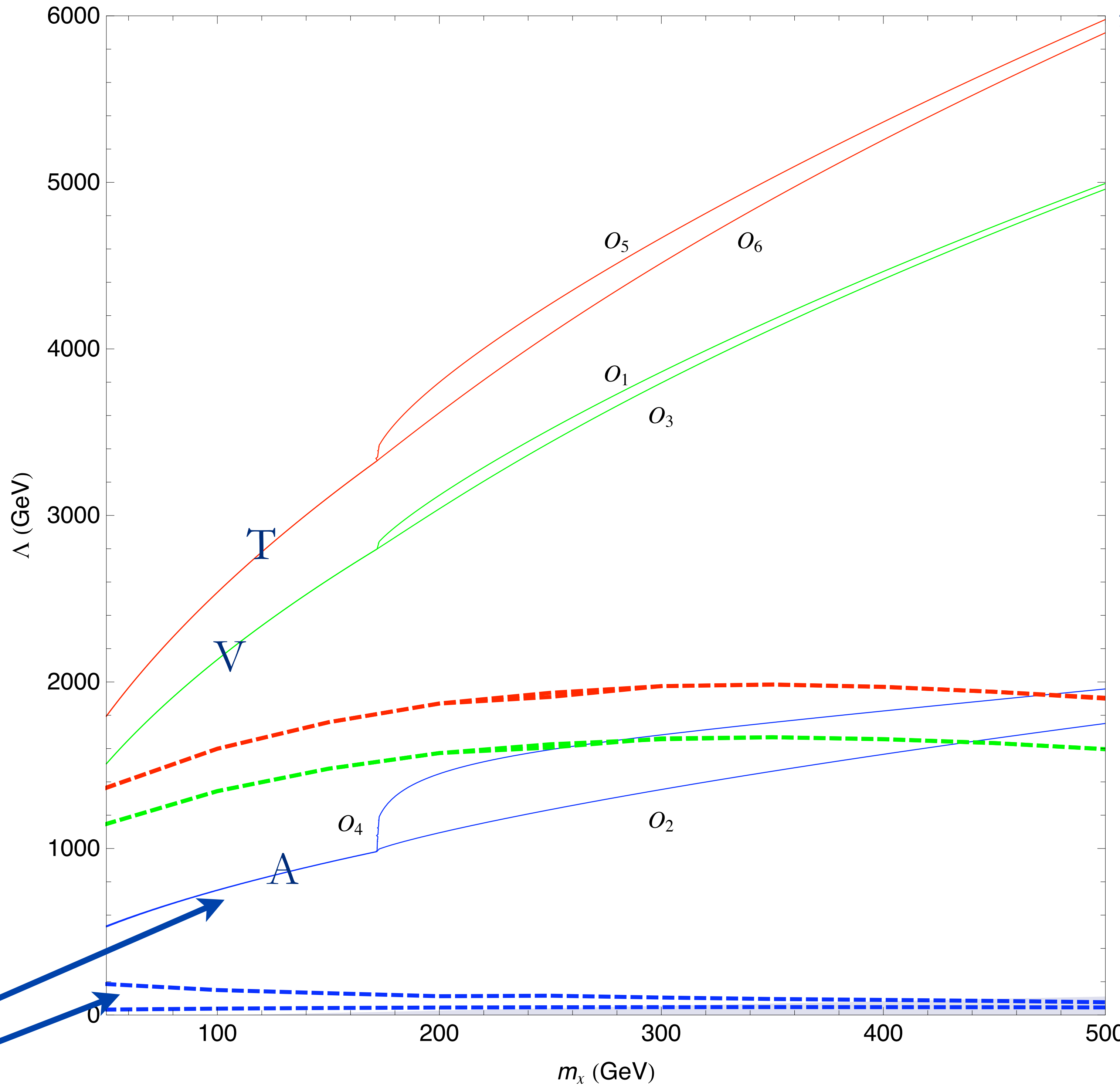
Figure 4. Antiproton fraction spectrum predicted for the operator $O_1 = \frac{1}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$ for a few values of Λ. The mass of the dark matter is chosen to be 200 GeV here. The data points are from PAMELA [12].

Spectrum less than 4 GeV varies significantly with DM halo profiles in GALPROP

Upper and lower limits for Λ of fermionic DM operators

O_1 - O_6

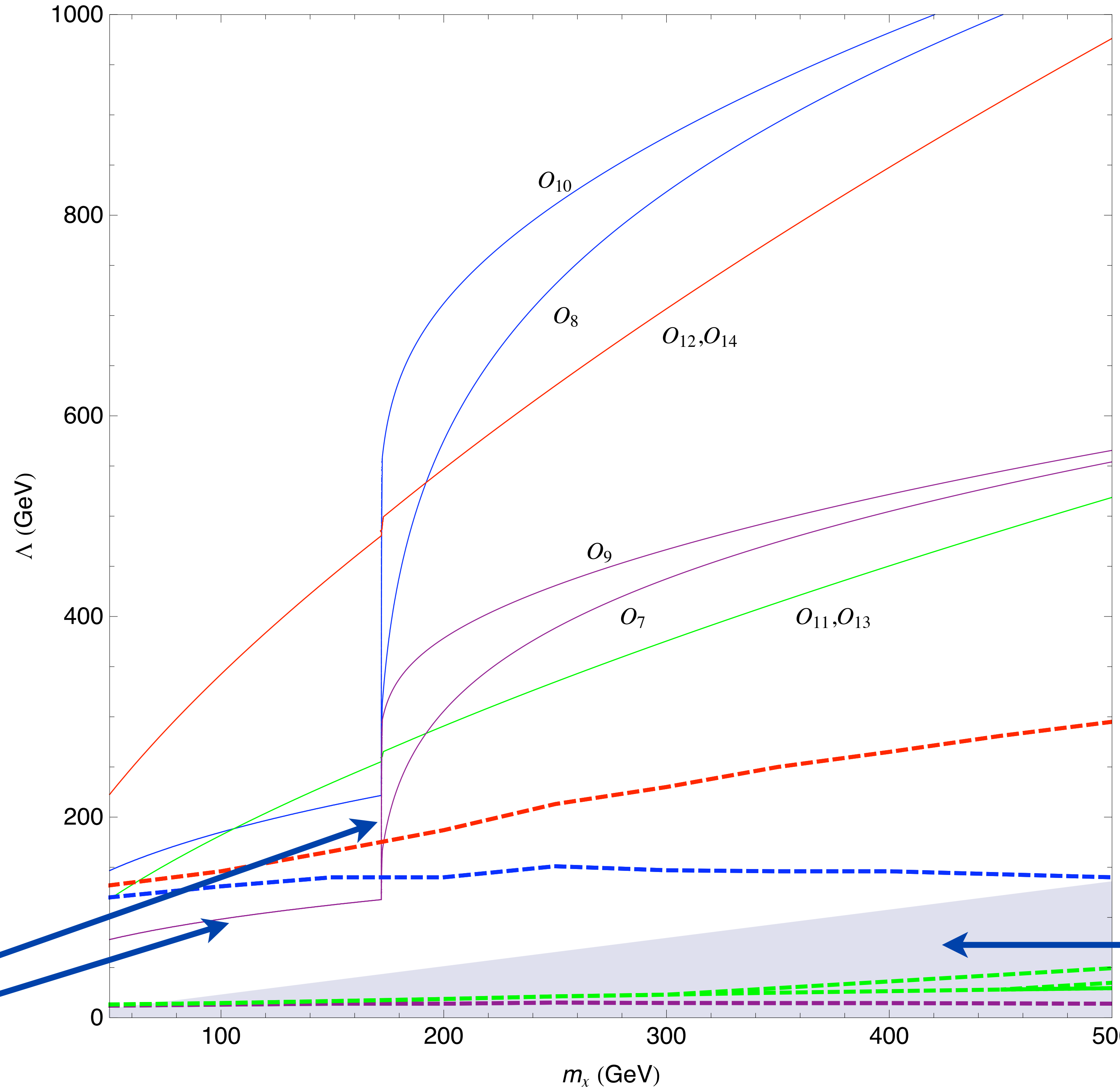
* One operator at a time
* Ignore possible interference among operators



Suppressed by v^2

$$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm bkgd} = 9\ (3\sigma)$$

Upper and lower limits for Λ of fermionic DM operators O_7 - O_{14}



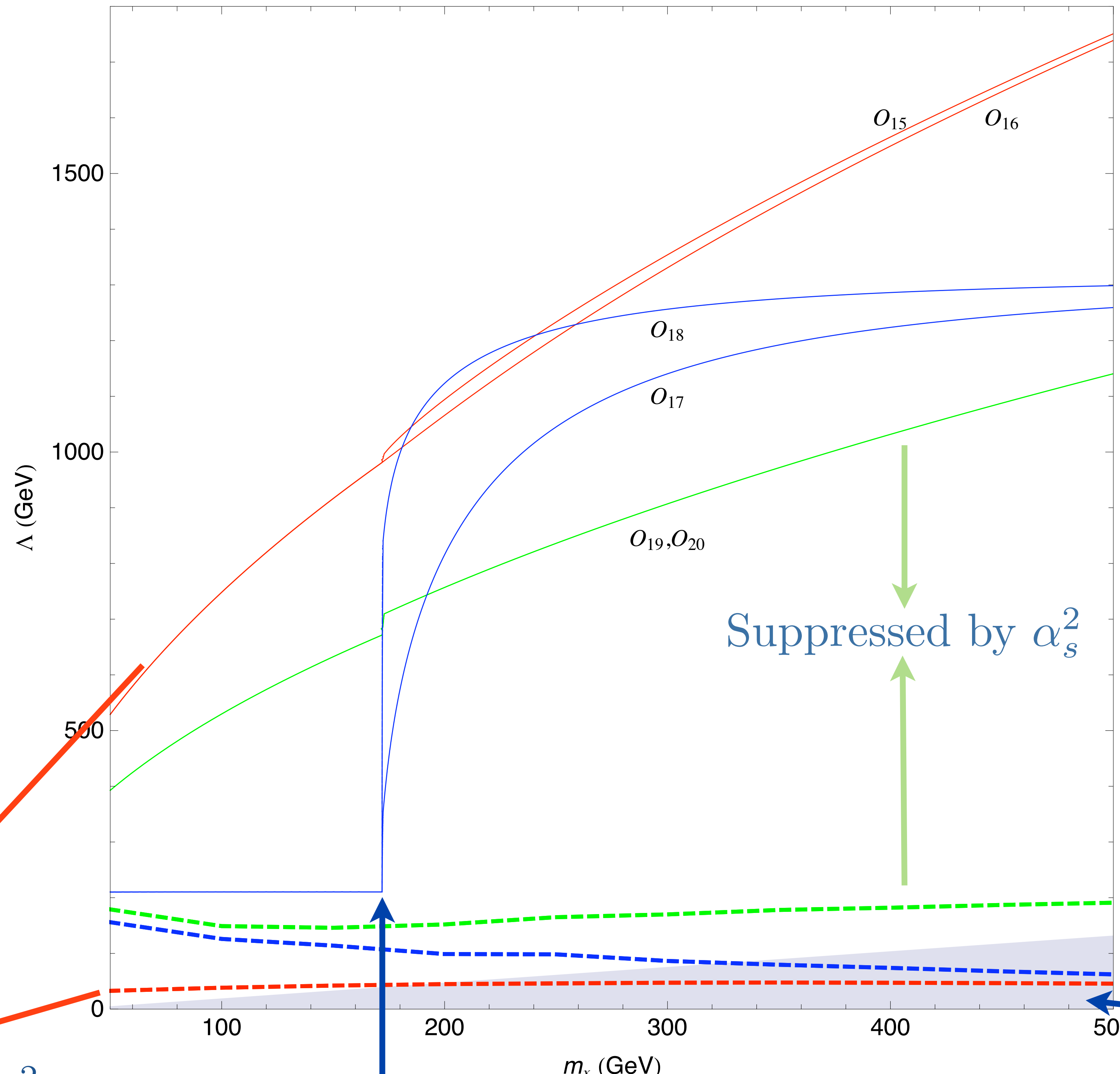
Suppressed by v^2

$\Lambda \leq m_\chi / 2\sqrt{\pi}$

EFT and/or PT breaks down!

Upper and lower limits for Λ of scalar DM operators

O_{15} - O_{20}



Suppressed by α_s^2

Suppressed by v^2

top/anti-top threshold

$\Lambda \leq m_\chi/2\sqrt{\pi}$

EFT and/or PT breaks down!

$3\ \sigma$ lower limits for effective scale Λ of each operator

$\chi^2_{\rm bkgb}\ (\geq 4\ \mathrm{GeV}) = 5.0$ for 13 d.o.f.

Dirac DM

Scalar DM

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 $\chi^2(\mathrm{bkdg}) = 5.0$.

Scalar DM has weaker limits!

Background Diffuse γ Rays

- Primary source for $E > 1$ GeV: annihilation of CR particles with intermedium atom (X).

$$p + X \to \pi^0 \to 2\gamma$$
$$He + X \to \pi^0 \to 2\gamma$$

- Secondary source: Interaction of charged particles with external medium or radiation fields (such as IC scattering, Bremsstrahlung, Synchrotron radiation, etc)

IC: $$e^{\pm} + \gamma_{\mathrm{CMB}} \to \gamma + e^{\pm}$$

Background Diffuse γ Rays (cont.)

- EGB (Extragalactic diffuse γ rays)
  (a) fainter; first detected at 1975 by SAS-2, later confirmed by EGRET data at 1998
  (b) isotropic sky distribution
  (c) origins are most uncertain; believed to be superposition of many contributions from
    (1) unresolved extragalactic sources (AGN, starburst galaxies, γ-ray bursts, ..)
    (2) truly diffuse emission processes (large-scale structure formation, interaction of ultra high energy CRs with relic photons, etc)

Background Diffuse γ Rays (cont.)

- EGB (Extragalactic diffuse γ rays) (cont.)
  (d) Fermi-LAT recent measurement [PRL 104, 101101 (2010)] of diffuse γ-ray at mid-latitude region and fitted this EGB as

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

$$A = (0.95^{+0.18}_{-0.17}) \times 10^{-6}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

$$\gamma = 2.41 \pm 0.05 = |\delta - 2|$$

- Our fitted EGB

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

- Numerical code (GALPROP) was used to calculate the diffuse galactic background from primary and secondary sources

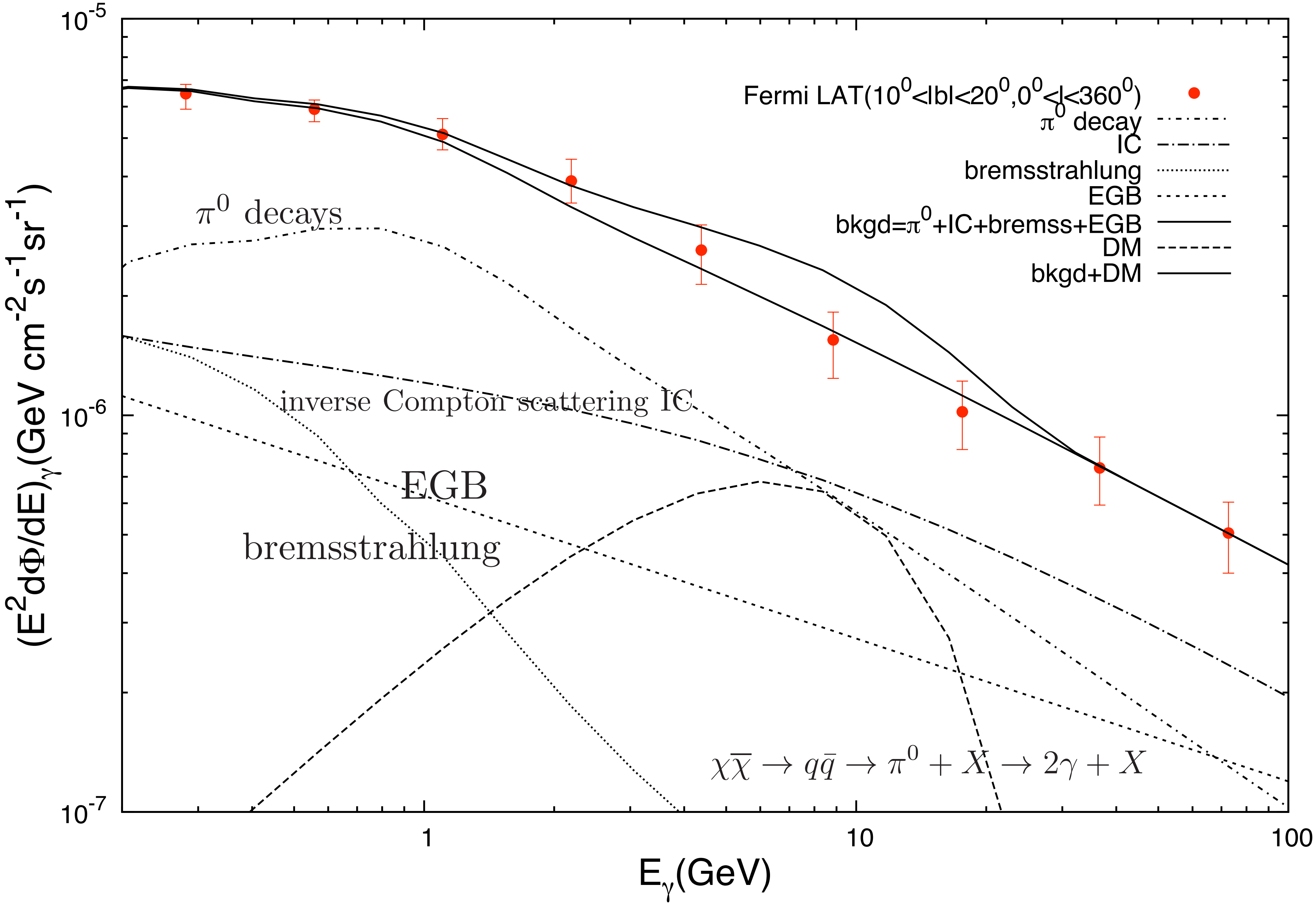
DM Annihilates into γ Rays

$$\chi\bar{\chi} \to q\bar{q}\ ,\ gg \to \pi^0 + X \to 2\gamma + X \qquad (q = u, d, s, c, b)$$

- DM can annihilate into quark, antiquark and gluon
- quark, antiquark, gluon can all fragment into neutral pion, which decays into photons and contribute to diffuse γ rays
- Again, fragmentation functions are taken from Ablino et al [NPB 725 (2005) 181 - 206]; obtained by fitting all relevant data from e+ e- annihilation experiments; public code
- Propagation effects for photons are expected to be small within our galaxy (< 25 kpc)

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

The photon spectrum $E^2(d\Phi/dE_\gamma)$ versus the photon energy



$m_\chi = 50$ GeV; O_1 with $\Lambda = 0.87$ TeV (3σ)

3 σ lower limits for effective scale Λ of each operator

Dirac DM

Scalar DM

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

Table 3. The 3σ lower limits on the effective sale Λ of each operator listed in table 1. We take the coefficient $C = 1$ with m_χ = 50, 100, 200 and 500 GeV.

Scalar DM has weaker limits!

Comparisons Between Anti-proton and Gamma Ray Constraints on 3σ Upper Limits on <σ*v*>

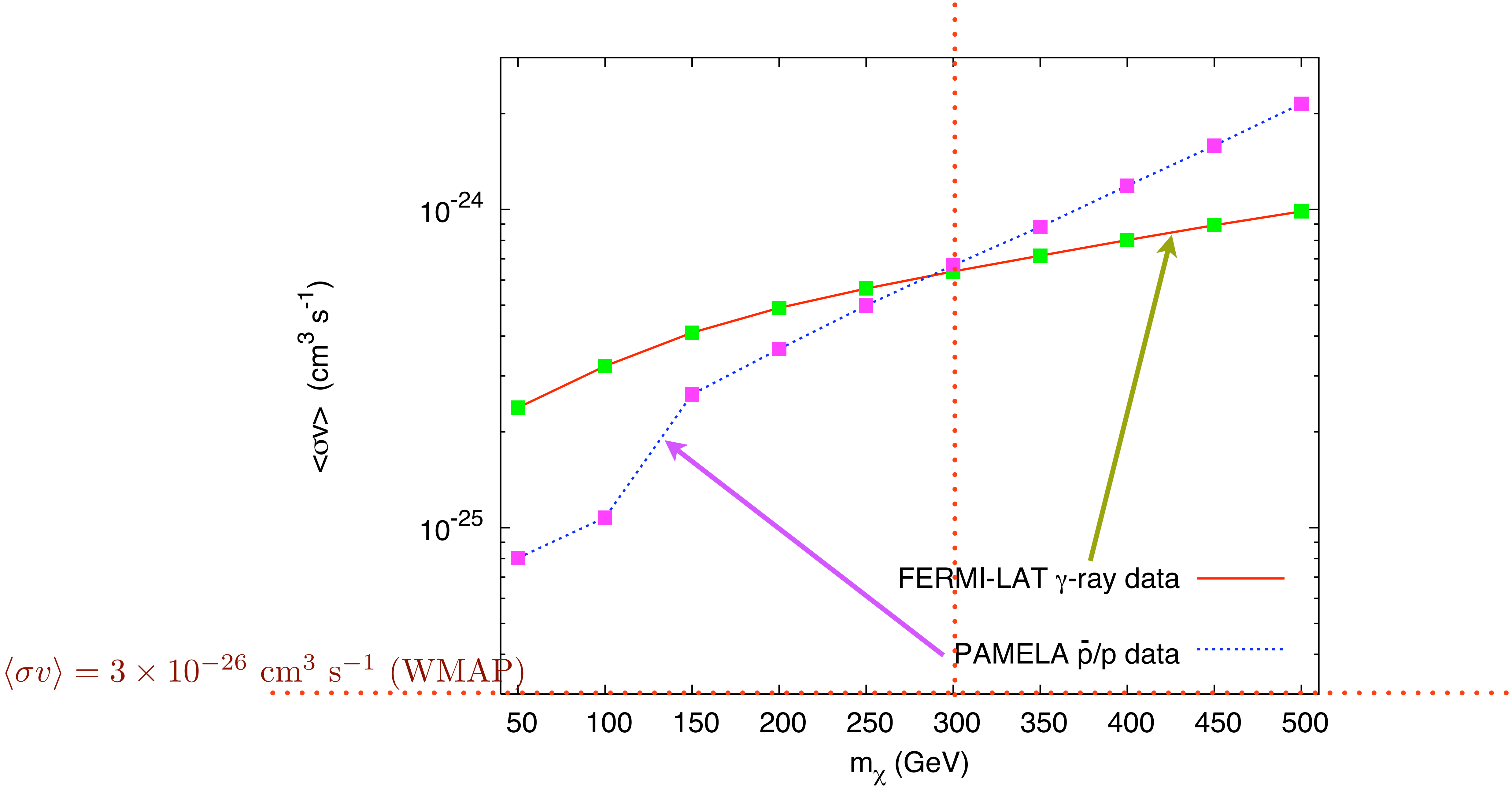


Figure 4. The 3σ upper limits on the annihilation cross section $\sigma v(\chi\bar{\chi} \to q\bar{q})$ versus the DM mass due to the Fermi-LAT photon-flux data ($10^\circ < |b| < 20^\circ$, $0^\circ < l < 360^\circ$) and due to the PAMELA antiproton-flux data [13]. The limits are approximately independent of the operators. The annihilation cross sections above the curves are ruled out. The x-axis is at the value $3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ which is the required annihilation cross section to give the correct thermal relic density.

Summary

- PAMELA anti-proton spectrum and Fermi-LAT diffuse gamma-ray spectrum at mid-latitude are used to constrain the effective interaction strengths; complementary to each other depend on DM mass
- 3σ lower limit on the effective scale Λ is deduced, while WMAP relic density can provide an upper limit for Λ
- Best limits for vector $O_{\{1,3\}}$ and tensor operators $O_{\{5,6\}}$ with $\Lambda \sim 1$ -- 2 TeV. Other operators are suppressed with weaker limits
- These limits are comparable to gamma-ray line search and to limits obtained from collider searches on DM [works by Tait et al]
- However, direct limits from XENON100 are $\Lambda_1 > 4.4$ TeV from O_1 and $\Lambda_7 > 330$ GeV from O_7 which are more stringent
- In general, due to suppression factors, limits from scalar DM are weaker than fermionic DM from these indirect detections

Dziękuję bardzo