Global Constraints on Effective Dark Matter Interactions

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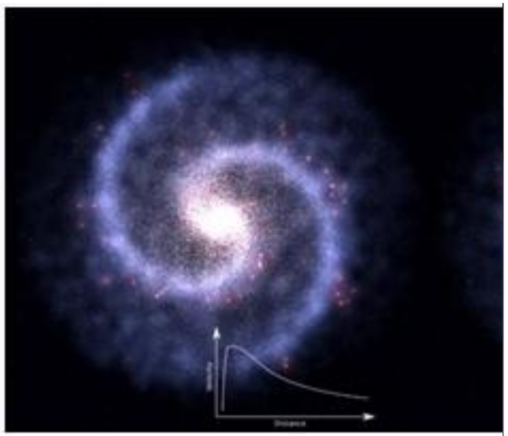
Outline

- Introduction
- Effective Dark Matter Interactions
- Experimental constraints
- Conclusions

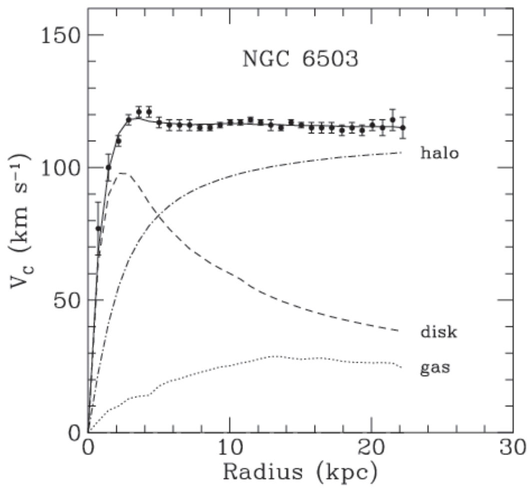
Introduction

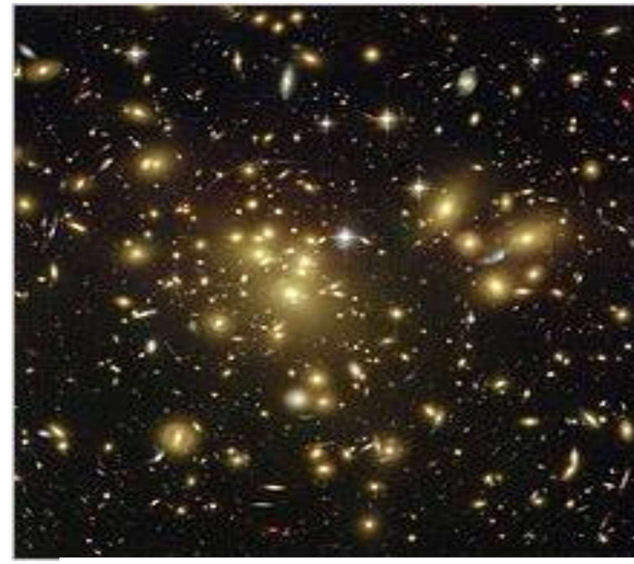
Introduction

- DM evidence from the astronomy observations.



Vera Rubin 1970
Fritz Zwicky





Hubble Telescope

Bullet Cluster

Wikipedia.org

3.

Introduction

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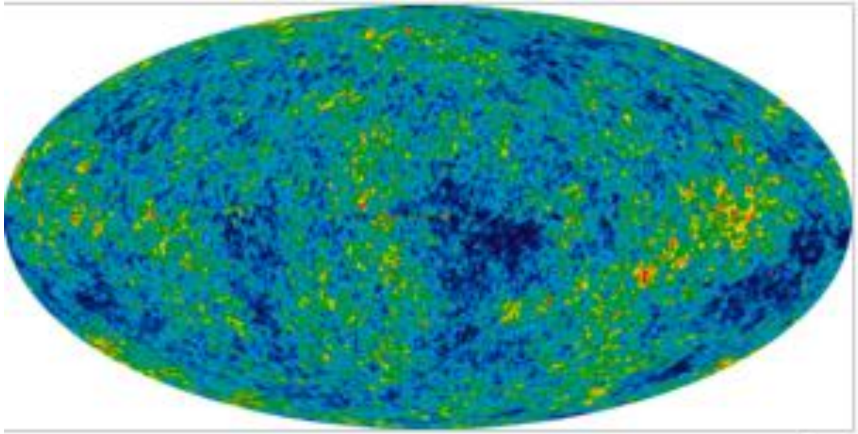
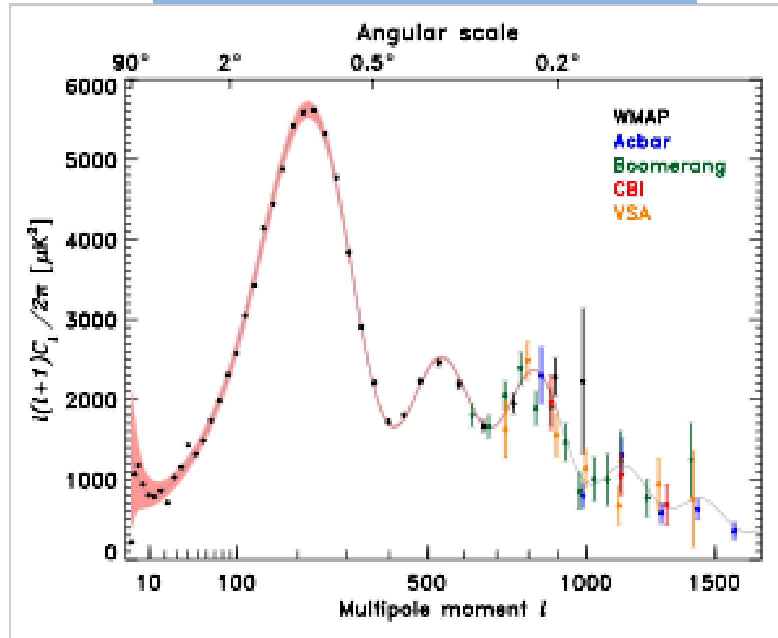


WMAP image of the CMB temperature anisotropy.

Wikipedia.org



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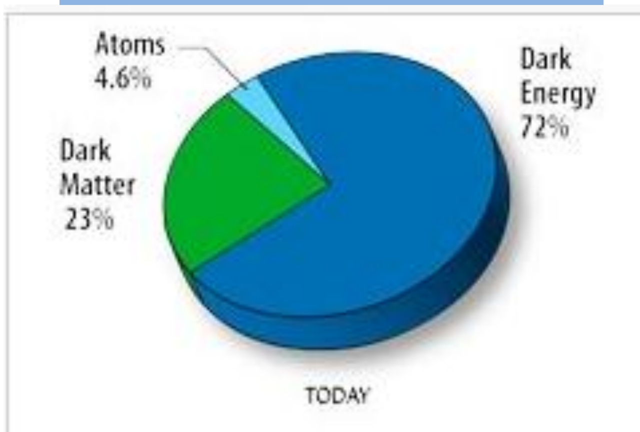


- In darkon model, there is a real-scalar boson D and couple to SM particle via Higgs boson H

$$\mathcal{L}_D = -\frac{\lambda_D}{4} D^4 - \frac{m_D^2}{2} D^2 - \lambda D^2 H^\dagger H \ .$$

- The amplitude of $DD \to f\bar{f}$

$$\mathcal{L} = \frac{g m_f}{2 m_W} \bar{f} f \, \frac{1}{(2 m_D)^2 - m_h^2} \, \lambda v D^2 \ .$$

- In the limit $m_H \gg m_D$

$$\mathcal{L} = C \frac{m_f}{\Lambda^2} \, (\bar{f} f) D^2$$

dim 5 effective, contact interaction.

- Another example, $Z-Z'$ portal model. The fermionic DM χ interact with SM particle via heavy Z' mixing with Z.

$$\mathcal{L} = \bar{\chi}\gamma^{\mu}(g_v^{\chi} - g_a^{\chi}\gamma^5)\chi\, Z_{\mu} + \bar{f}\gamma^{\mu}(g_v^{f} - g_a^{f}\gamma^5) f\, Z_{\mu}$$

- The amplitude of $\chi\bar{\chi} \to f\bar{f}$ in the limit $m_Z \gg m_{\chi}$

$$\mathcal{L} \sim \frac{g_v^{\chi} g_v^{f}}{m_Z^2}\,(\bar{\chi}\gamma^{\mu}\chi)\,(\bar{f}\gamma_{\mu}f) + \frac{g_v^{\chi} g_a^{f}}{m_Z^2}\,(\bar{\chi}\gamma^{\mu}\chi)\,(\bar{f}\gamma_{\mu}\gamma^5 f)$$
$$+\frac{g_a^{\chi} g_v^{f}}{m_Z^2}\,(\bar{\chi}\gamma^{\mu}\gamma^5\chi)\,(\bar{f}\gamma_{\mu}f) + \frac{g_a^{\chi} g_a^{f}}{m_Z^2}\,(\bar{\chi}\gamma^{\mu}\gamma^5\chi)\,(\bar{f}\gamma_{\mu}\gamma^5 f)$$

Effective Dark Matter Interactions

Effective Interactions

- Fermionic DM χ interaction with pair of Fermion f via vector, axial-vector, and tensor exchange.

$$O_1 = \sum_f \frac{C_1^f}{\Lambda_1^2} (\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f) ,$$

$$O_2 = \sum_f \frac{C_2^f}{\Lambda_2^2} (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu f) ,$$

$$O_3 = \sum_f \frac{C_3^f}{\Lambda_3^2} (\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu\gamma^5 f) ,$$

$$O_4 = \sum_f \frac{C_4^f}{\Lambda_4^2} (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu\gamma^5 f) ,$$

$$O_5 = \sum_f \frac{C_5^f}{\Lambda_5^2} (\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{f}\sigma_{\mu\nu} f) ,$$

$$O_6 = \sum_f \frac{C_6^f}{\Lambda_6^2} (\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{f}\sigma_{\mu\nu} f) ,$$

- For Majorana DM, operator O1, O3, O5, and O6 are zero.

Effective Interactions

- Fermionic DM χ via (pseudo-)scalar exchange.

$$O_7 = \sum_f \frac{C_7^f m_f}{\Lambda_7^3} (\bar{\chi}\chi)(\bar{f}f) ,$$

$$O_8 = \sum_f \frac{iC_8^f m_f}{\Lambda_8^3} (\bar{\chi}\gamma^5\chi)(\bar{f}f) ,$$

$$O_9 = \sum_f \frac{iC_9^f m_f}{\Lambda_9^3} (\bar{\chi}\chi)(\bar{f}\gamma^5 f) ,$$

$$O_{10} = \sum_f \frac{C_{10}^f m_f}{\Lambda_{10}^3} (\bar{\chi}\gamma^5\chi)(\bar{f}\gamma^5 f) .$$

- The fermion mass m_f dependent is included in the coupling.

Effective Interactions

- Fermionic DM χ could also couple to gluon fields.

$$O_{11} = \frac{C_{11}}{\Lambda_{11}^3}(\bar{\chi}\chi)\left(-\frac{\alpha_s}{12\pi}G^{\mu\nu}G_{\mu\nu}\right),$$
$$O_{12} = \frac{iC_{12}}{\Lambda_{12}^3}(\bar{\chi}\gamma^5\chi)\left(-\frac{\alpha_s}{12\pi}G^{\mu\nu}G_{\mu\nu}\right),$$
$$O_{13} = \frac{C_{13}}{\Lambda_{13}^3}(\bar{\chi}\chi)\left(\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}\right),$$
$$O_{14} = \frac{iC_{14}}{\Lambda_{14}^3}(\bar{\chi}\gamma^5\chi)\left(\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}\right).$$

- The $\alpha_s(2m_\chi)$ is the strong coupling constant, because operators may from one-loop at scale $2m_\chi$

Effective Interactions

- Finally are the operators for complex scalar DM.

$$O_{15} = \sum_f \frac{iC_{15}^f}{\Lambda_{15}^2} \left(\chi^\dagger \overleftrightarrow{\partial_\mu} \chi\right) \left(\bar{f}\gamma^\mu f\right) ,$$

$$O_{16} = \sum_f \frac{iC_{16}^f}{\Lambda_{16}^2} \left(\chi^\dagger \overleftrightarrow{\partial_\mu} \chi\right) \left(\bar{f}\gamma^\mu \gamma^5 f\right) ,$$

$$O_{17} = \sum_f \frac{C_{17}^f m_f}{\Lambda_{17}^2} \left(\chi^\dagger \chi\right) \left(\bar{f} f\right) ,$$

$$O_{18} = \sum_f \frac{iC_{18}^f m_f}{\Lambda_{18}^2} \left(\chi^\dagger \chi\right) \left(\bar{f}\gamma^5 f\right) ,$$

$$O_{19} = \frac{C_{19}}{\Lambda_{19}^2} \left(\chi^\dagger \chi\right) \left(-\frac{\alpha_s}{12\pi} G^{\mu\nu} G_{\mu\nu}\right) ,$$

$$O_{20} = \frac{C_{20}}{\Lambda_{20}^2} \left(\chi^\dagger \chi\right) \left(\frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu}\right) .$$

- For real scalar DM, O15 and O16 are zero.

Effective Interactions

Operator	NR Limit (Direct Detection)	SI	SD	Dirac/Complex	Majorana/Real	NR Limit $\langle\sigma^{\text{anni}}v\rangle$ (Relic Density)
O_1	Yes	Yes	No	Yes	No	$\frac{N_C m_\chi^2}{\pi\Lambda_1^4}$
O_2	No	—	—	Yes	Yes	$\frac{N_C m_\chi^2 v^2}{6\pi\Lambda_2^4}$
O_3	No	—	—	Yes	No	$\frac{N_C m_\chi^2}{\pi\Lambda_3^4}$
O_4	Yes	No	Yes	Yes	Yes	$\frac{N_C m_\chi^2 v^2}{6\pi\Lambda_4^4}$
O_5	Yes	No	Yes	Yes	No	$\frac{2N_C m_\chi^2}{\pi\Lambda_5^4}$
O_6	No	—	—	Yes	No	$\frac{2N_C m_\chi^2}{\pi\Lambda_6^4}$
O_7	Yes	Yes	No	Yes	Yes	$\frac{N_C m_f^2 m_\chi^2 v^2}{8\pi\Lambda_7^6}$
O_8	No	—	—	Yes	No	$\frac{N_C m_f^2 m_\chi^2}{2\pi\Lambda_8^6}$
O_9	No	—	—	Yes	Yes	$\frac{N_C m_f^2 m_\chi^2 v^2}{8\pi\Lambda_9^6}$
O_{10}	No	—	—	Yes	No	$\frac{N_C m_f^2 m_\chi^2}{2\pi\Lambda_{10}^6}$

Effective Interactions

O_{11}	Yes	Yes	No	Yes	Yes	$\frac{\alpha_s^2 m_\chi^4 v^2}{288\pi^3 \Lambda_{11}^6}$
O_{12}	No	—	—	Yes	No	$\frac{\alpha_s^2 m_\chi^4}{72\pi^3 \Lambda_{12}^6}$
O_{13}	No	—	—	Yes	Yes	$\frac{\alpha_s^2 m_\chi^4 v^2}{128\pi^3 \Lambda_{13}^6}$
O_{14}	No	—	—	Yes	No	$\frac{\alpha_s^2 m_\chi^4}{32\pi^3 \Lambda_{14}^6}$
O_{15}	Yes	Yes	No	Yes	No	$\frac{N_C m_\chi^2 v^2}{6\pi \Lambda_{15}^4}$
O_{16}	No	—	—	Yes	No	$\frac{N_C m_\chi^2 v^2}{6\pi \Lambda_{16}^4}$
O_{17}	Yes	Yes	No	Yes	Yes	$\frac{N_C m_f^2}{4\pi \Lambda_{17}^4}$
O_{18}	No	—	—	Yes	Yes	$\frac{N_C m_f^2}{4\pi \Lambda_{18}^4}$
O_{19}	Yes	Yes	No	Yes	Yes	$\frac{\alpha_s^2 m_\chi^2}{144\pi^3 \Lambda_{19}^4}$
O_{20}	No	—	—	Yes	Yes	$\frac{4\alpha_s^2 m_\chi^2}{301\pi^3 \Lambda_{20}^4}$

Effective Interactions

- In non-relativistic limit, the spinor for χ and $\overline{\chi}$ are $\psi = \xi \begin{pmatrix} 1 \\ \varepsilon \end{pmatrix}$, $\overline{\psi} = \eta^{\dagger} (\varepsilon, \ 1) \gamma^{0}$, where $\varepsilon \approx O(v/c)$.
- For $\overline{\psi}\gamma^{\mu}\psi$ written as

$$\bar{\psi}\gamma^0\psi \simeq 2\epsilon\eta^{\dagger}\xi$$
$$\bar{\psi}\gamma^i\psi \simeq (1+\epsilon^2)\eta^{\dagger}\sigma_i\xi$$

- For $\overline{\psi}\gamma^{\mu}\gamma^{5}\psi$ written as

$$\bar{\psi}\gamma^0\gamma^5\psi \simeq (1+\epsilon^2)\eta^{\dagger}\xi$$
$$\bar{\psi}\gamma^i\gamma^5\psi \simeq 2\epsilon\eta^{\dagger}\sigma_i\xi$$

- Contract with the light fermion leg $\overline{f}\gamma^{\mu} f$ or $\overline{f}\gamma^{\mu}\gamma^{5} f$, the time-like part give almost zero the space-like part give m_{χ}^{2} .

Experimental constraints

Constraints

- CDM relic density, from the CMB by WMAP7

$$\Omega_{\rm CDM}\, h^2 = 0.1126 \ \pm 0.0036\ ,$$

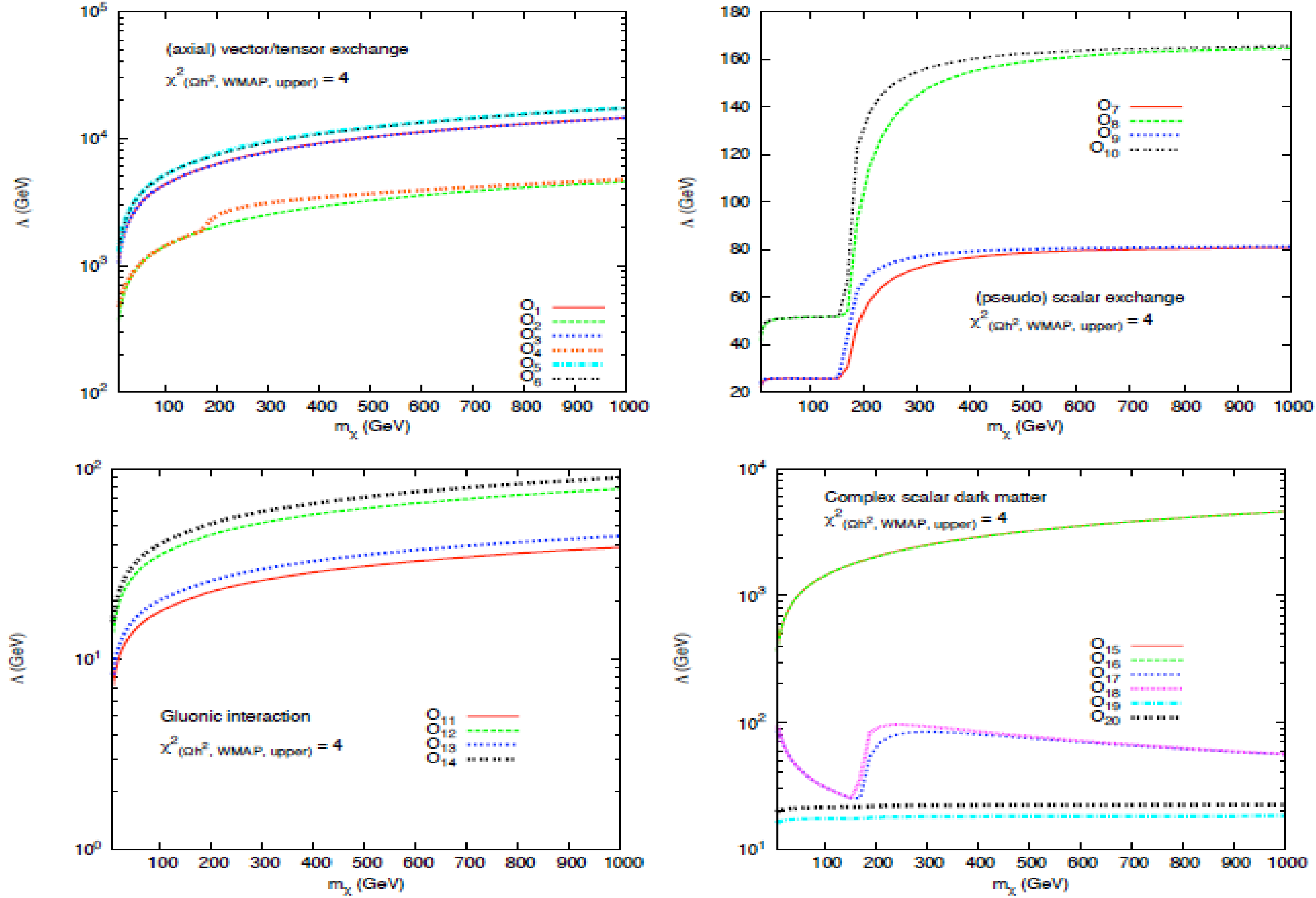
where h is the Hubble rate in unit of 100km/Mpc/s.

- Relation between DM relic density and thermal annihilation cross section around the time of freeze-out.

$$\Omega_\chi h^2 \simeq \frac{0.1\ {\rm pb}}{\langle \sigma v \rangle}$$

Constraints

- 2 σ Upper limit of Λ from WMAP7.

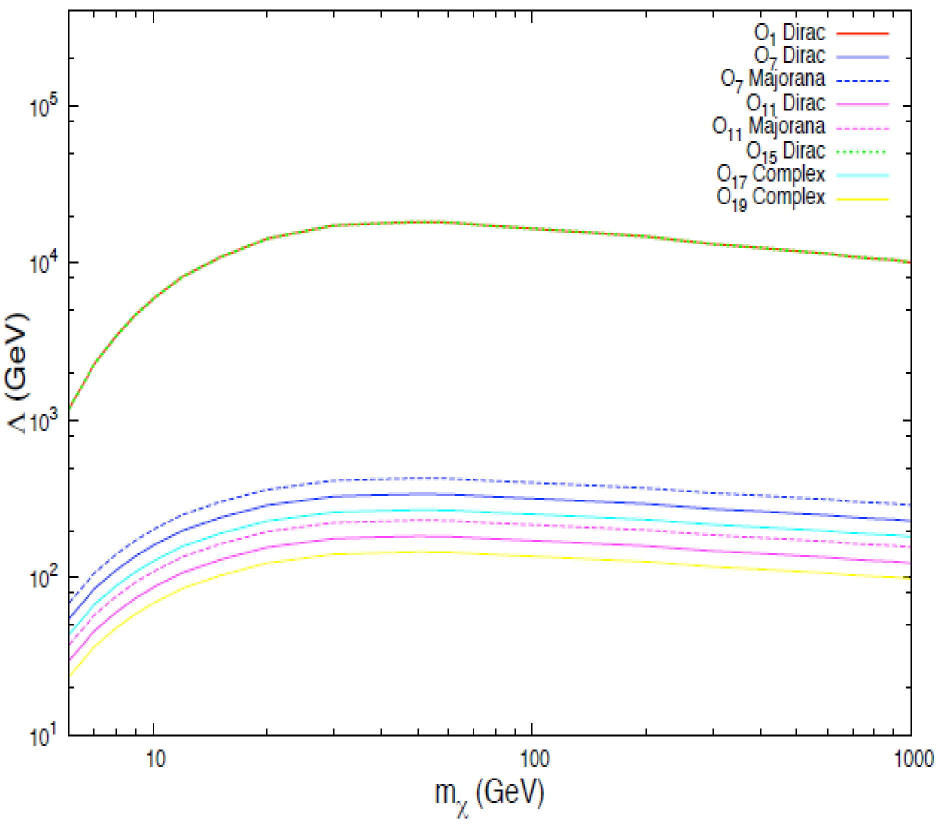


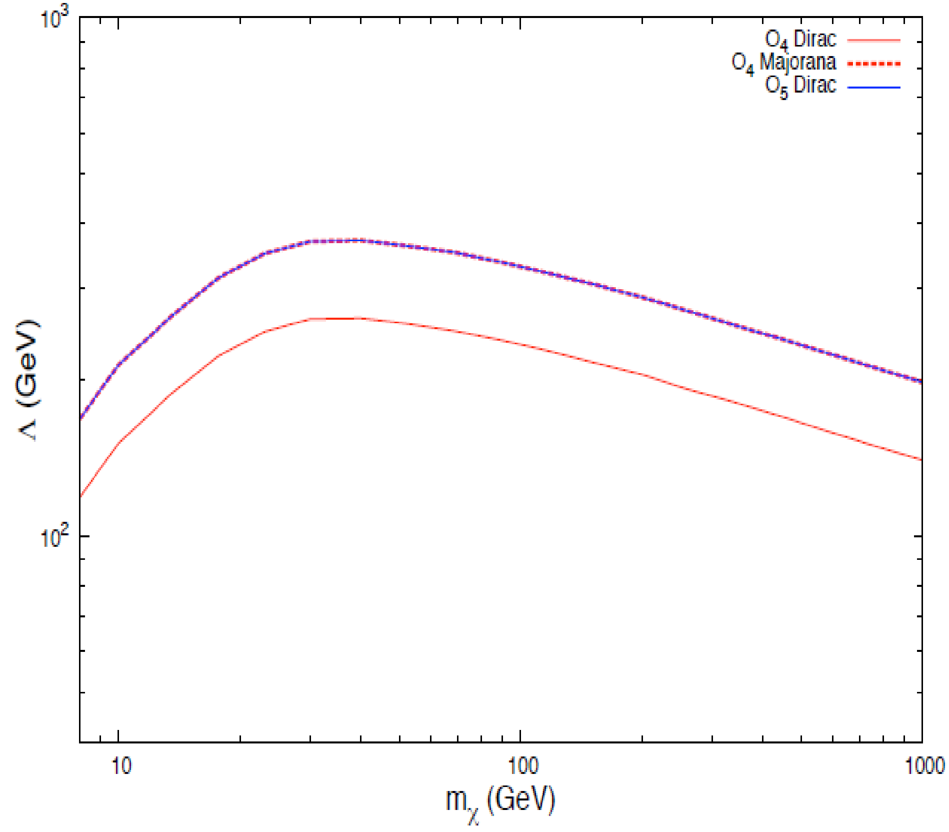
Constraints

- Direct detection. XENON100 for spin-independent(SI) DM-nucleus cross section σ_{SI} and XENON10, ZEPLIN, SIMPLE for spin-dependent(SD) cross section σ_{SD}
- O1, O7, O11, O15, O17, O19 will give the SI DM-nucleus interaction.
- O4, O5 give the SD one.

Constraints

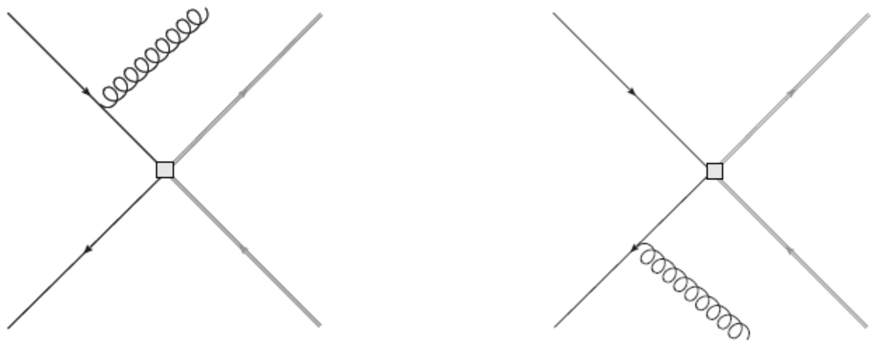
- 2σ lower limit of Λ from direct detection.





Constraints

- Monojet and monophoton + missing ET constraints from CDF, D0, Tevetron, ATLAS.

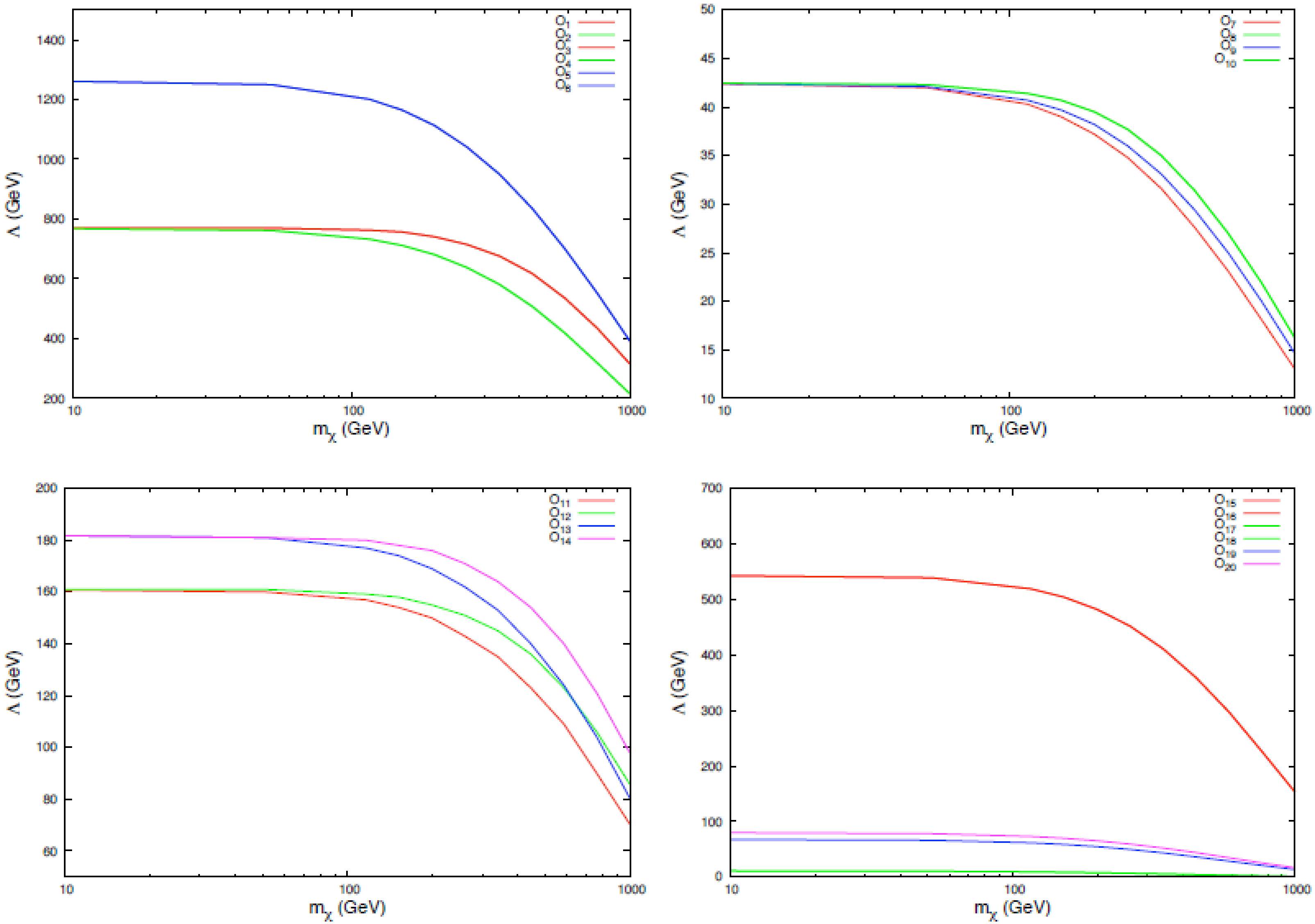


- For example, ATLAS observed 167 events and the expected SM background is $193 \pm 15 \pm 20$. The chi-square is

$$\chi^2 = \frac{(N(\Lambda) + N_{SM} - N_{\rm obs})^2}{(15^2 + 20^2 + 167)}$$

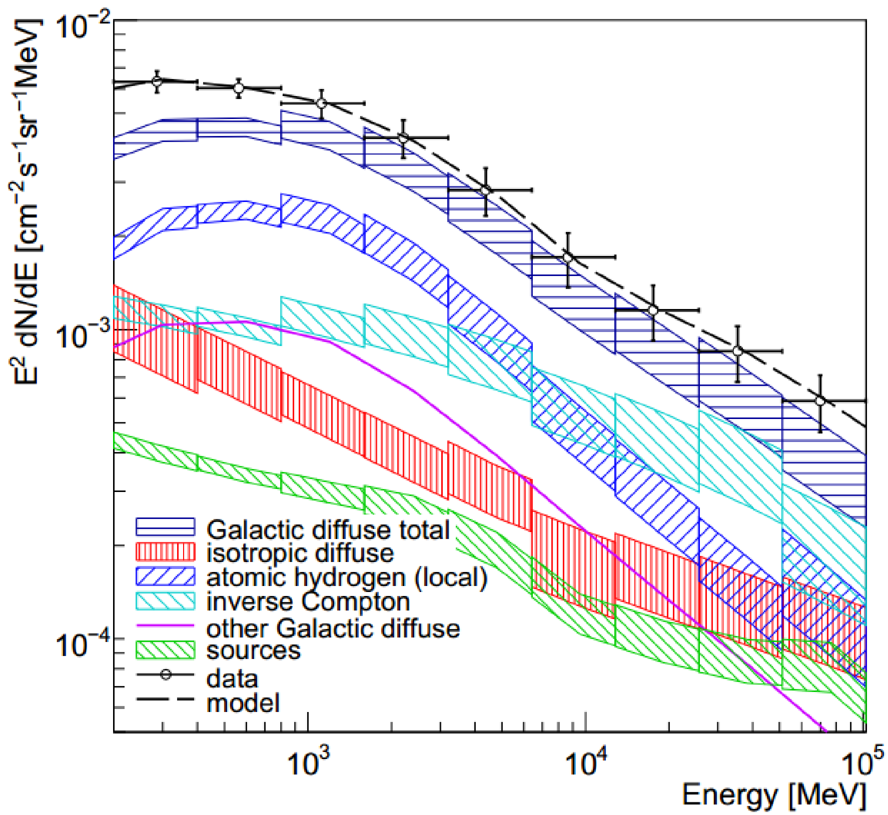
Constraints

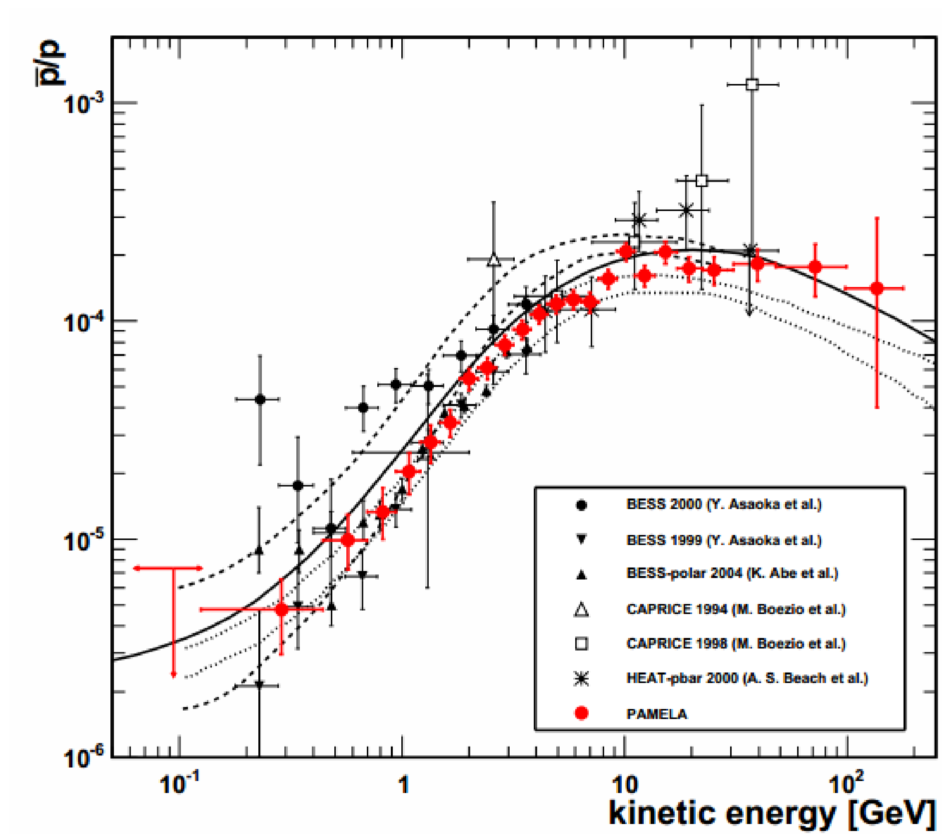
- 2 σ lower limit of Λ from colliders.



Constraints

- Indirect detection: cosmic gamma-ray and anti-proton flux from Fermi-LAT and PAMELA, respectively.





Fermi-LAT **PRL 104 (2010) 101101**

PAMELA **PRL 105 (2010) 121101**

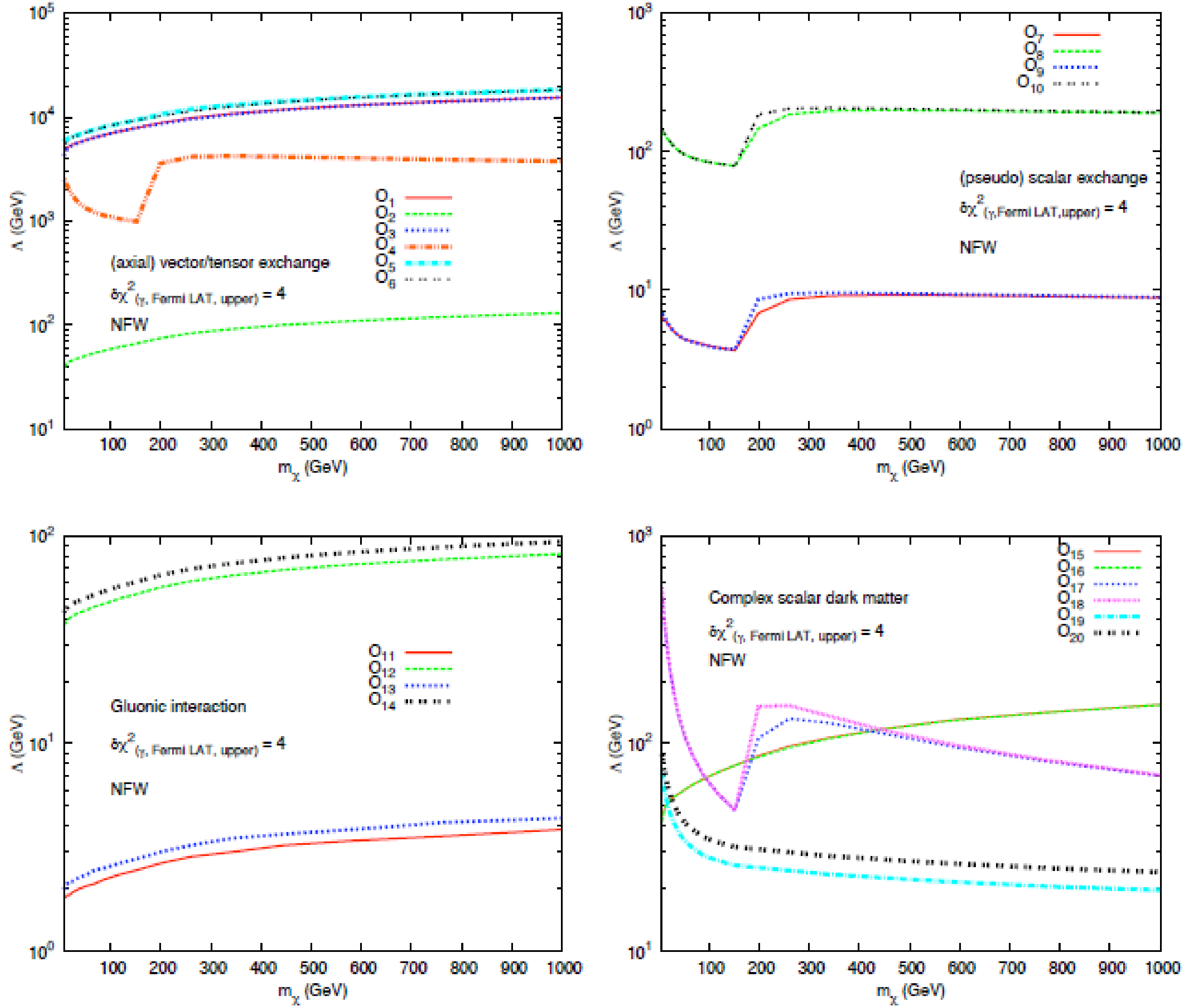
Constraints

- The final state quarks from DM annihilation can fragment into neutral pion π^0, then π^0 decay into two photons. The final state quark can fragment into anti-proton as well.

- If these are $e^{\pm}$ been produced from DM annihilation. $e^{\pm}$ could produced gamma-ray flux by inverse Compton scattering or bremsstrahlung.

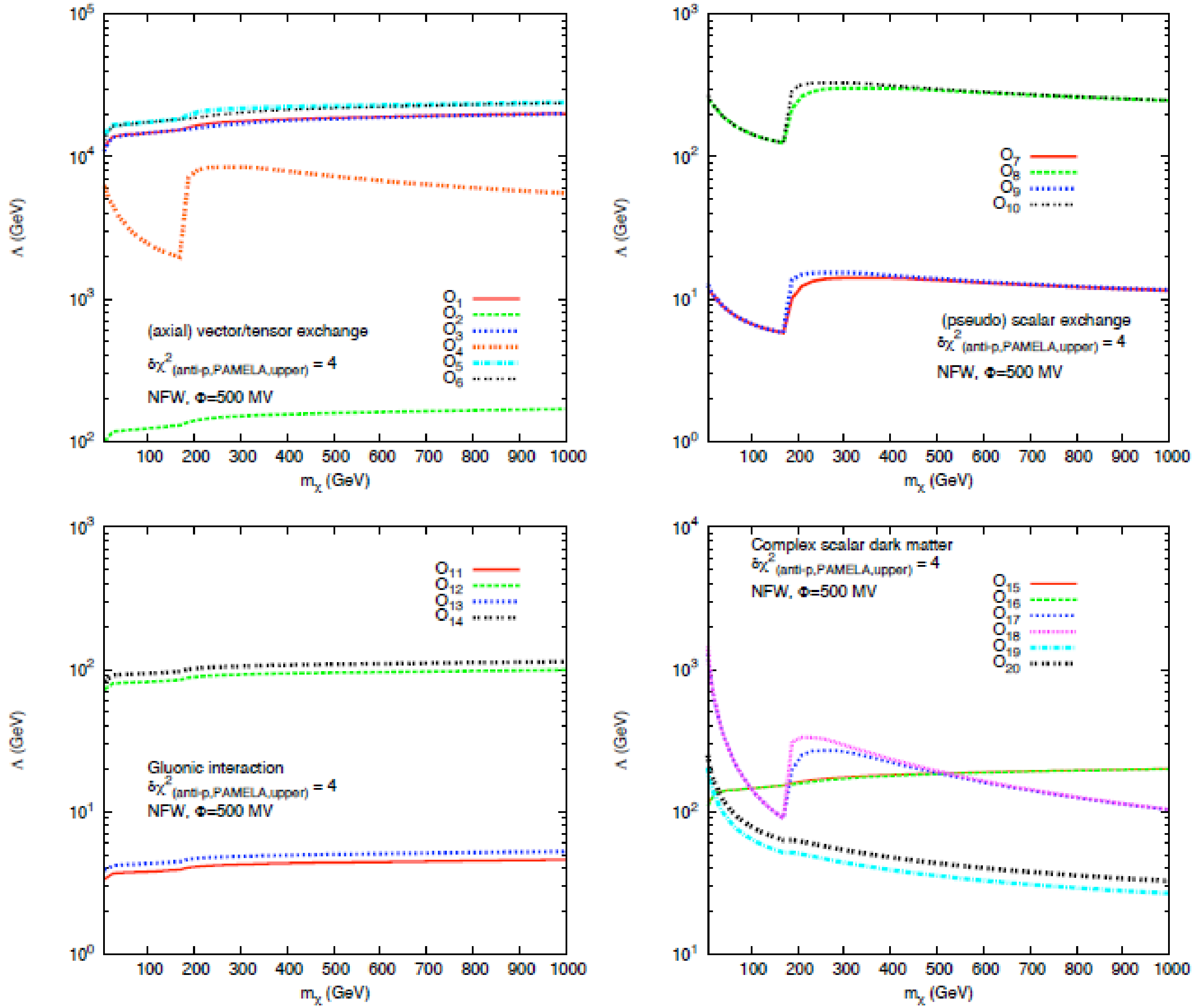
Constraints

- 2 σ lower limit of Λ from gamma-ray.



Constraints

- 2 σ lower limit of Λ from anti-proton.



Constraints

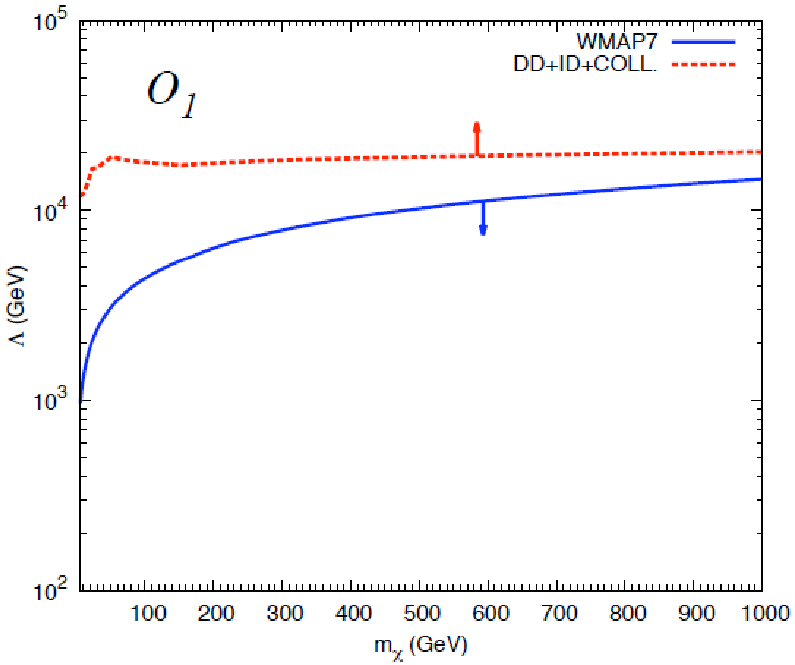
- We combined the all the experimental constraints except the DM relic density from WMAP, because it constrain the opposite direction from others.
- We add up the chi-square from each experiments and require the $\Delta\chi^2 = 4$ to obtain the 2 σ lower limit of Λ .

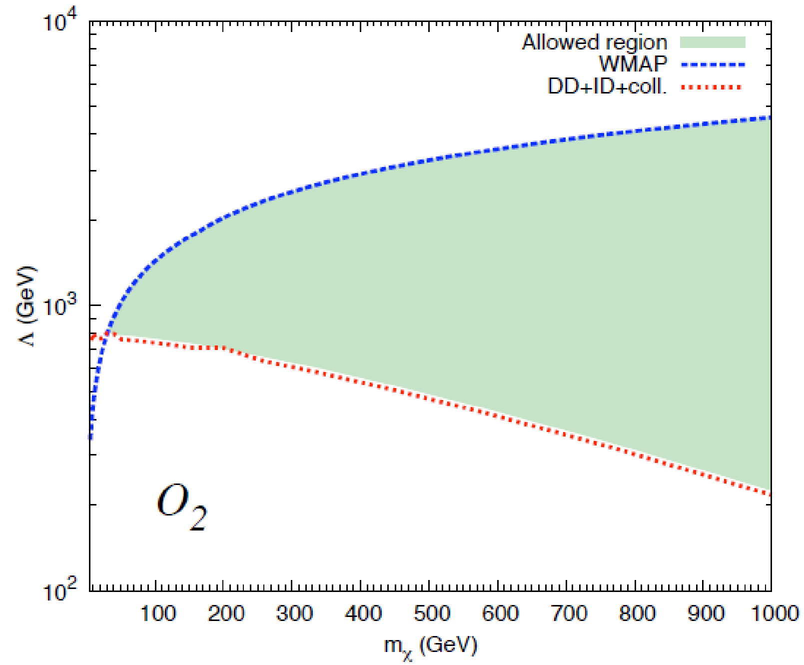
$$\chi^2(\mathrm{total}) = \chi^2(\mathrm{direct}) + \chi^2(\mathrm{collider}) + \chi^2(\mathrm{gamma}) + \chi^2(\mathrm{antiproton})$$

$$\Delta\chi^2 \equiv \chi^2(\mathrm{total}) - \chi^2(\mathrm{total})_{\mathrm{min}} = 4$$

Constraints

- Combined limits of O1 and O2.





- Only O2, O9, O16 have the allowed region to give the right thermal relic density under the direct, indirect detection, and collider constraints.

Conclusions

- dominated by direct detection: O_7, O_{15}
- by collider: $O_2, O_9, O_{13}, O_{14}, O_{16}$
- by indirect detection ($\bar{p}$ and γ-ray): $O_1, O_3, O_4, O_5, O_6, O_8, O_{10}, O_{17}, O_{18}, O_{20}$
- by collider at low m_χ and direct detection at high m_χ: O_{11}
- by collider at low m_χ and indirect detection at high m_χ: O_{12}
- by indirect detection at low m_χ and direct detection at high m_χ: O_{19}

- O2, O9, O16, in non-relativistic limit, are highly suppressed and cannot contribute to direct and indirect detection significant.

Conclusions

- We consider one operator at once in this work. The results may change, if there are several operators appear at the same time.

Thank you !

Happy New Year 2013