Constraints on Effective Dark Matter Interactions

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Outline

- Introduction
- Relic Density
- Direct Detections
- Indirect Detections
- Colliders
- Constraints on Dark Matter Effective Interactions
- Summary

Ref: Kingman Cheung, Yue-Lin Tsai, Po-Yan Tseng and TCY, JCAP 2012, arXiv:1201.3402.

Introduction

Rotation Curves of Galaxies

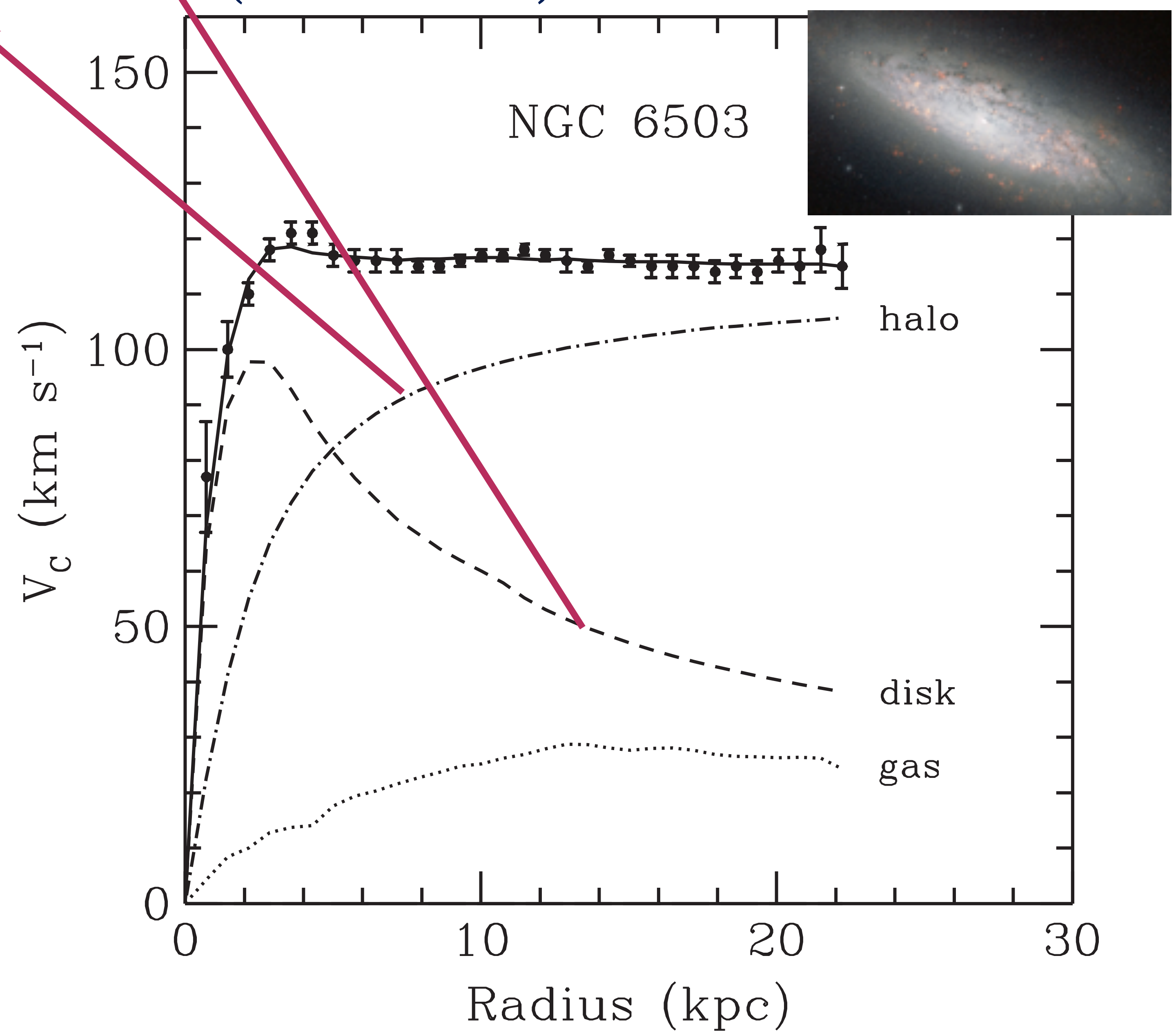
Fritz Zwicky (1898-1974)

At large r, one expects:

$$v \sim 1/\sqrt{r} \qquad \text{(Kepler)}$$

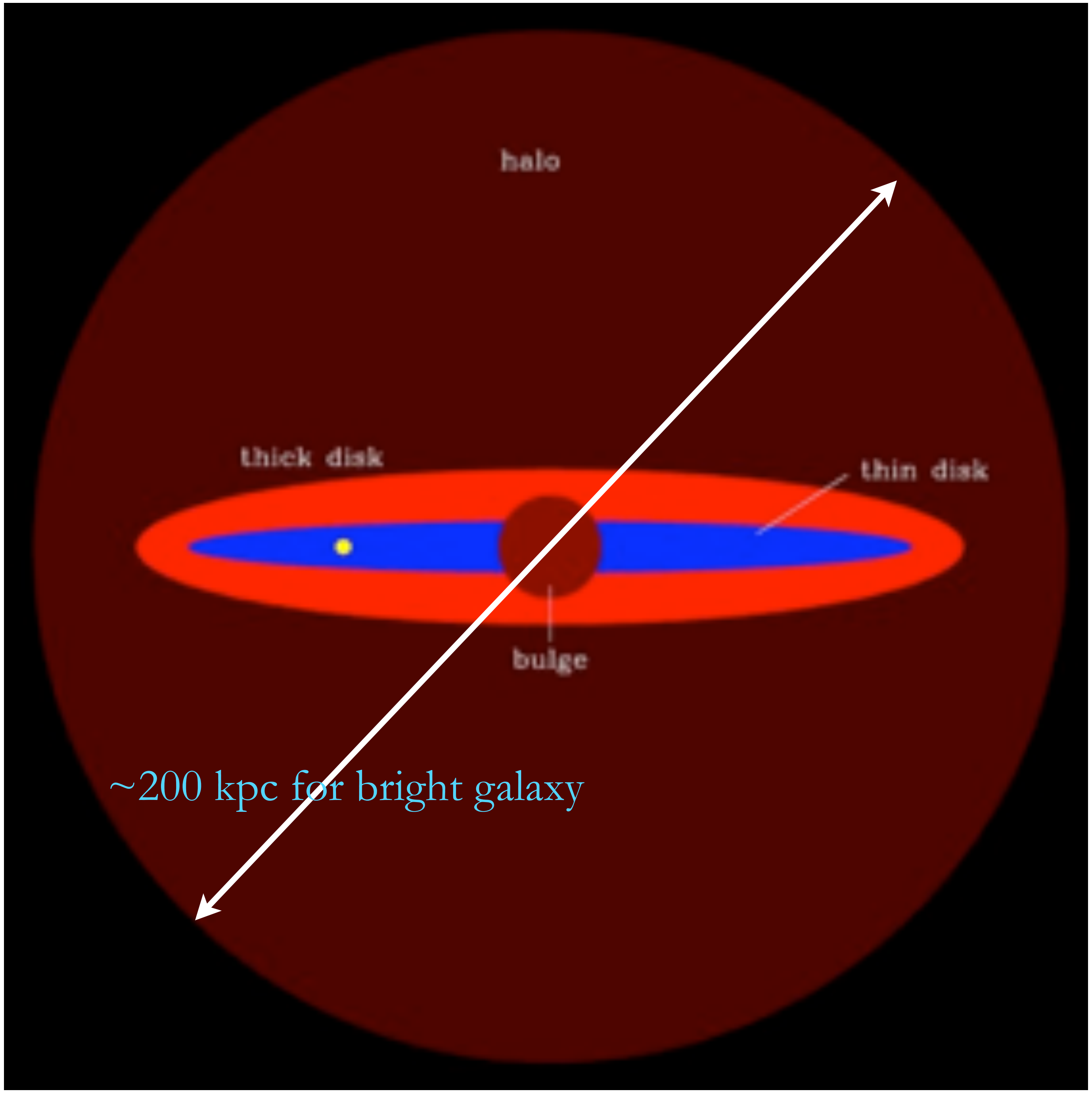
$$v \sim \text{Const} \qquad \text{(Observed)}$$

- Observed rotation curves exhibit flat behavior at large distances
- First observed for Coma cluster (more or less spherical) in 1933 by Zwicky using Virial Theorem.
- Suggested dark matter with universal halo density profile.



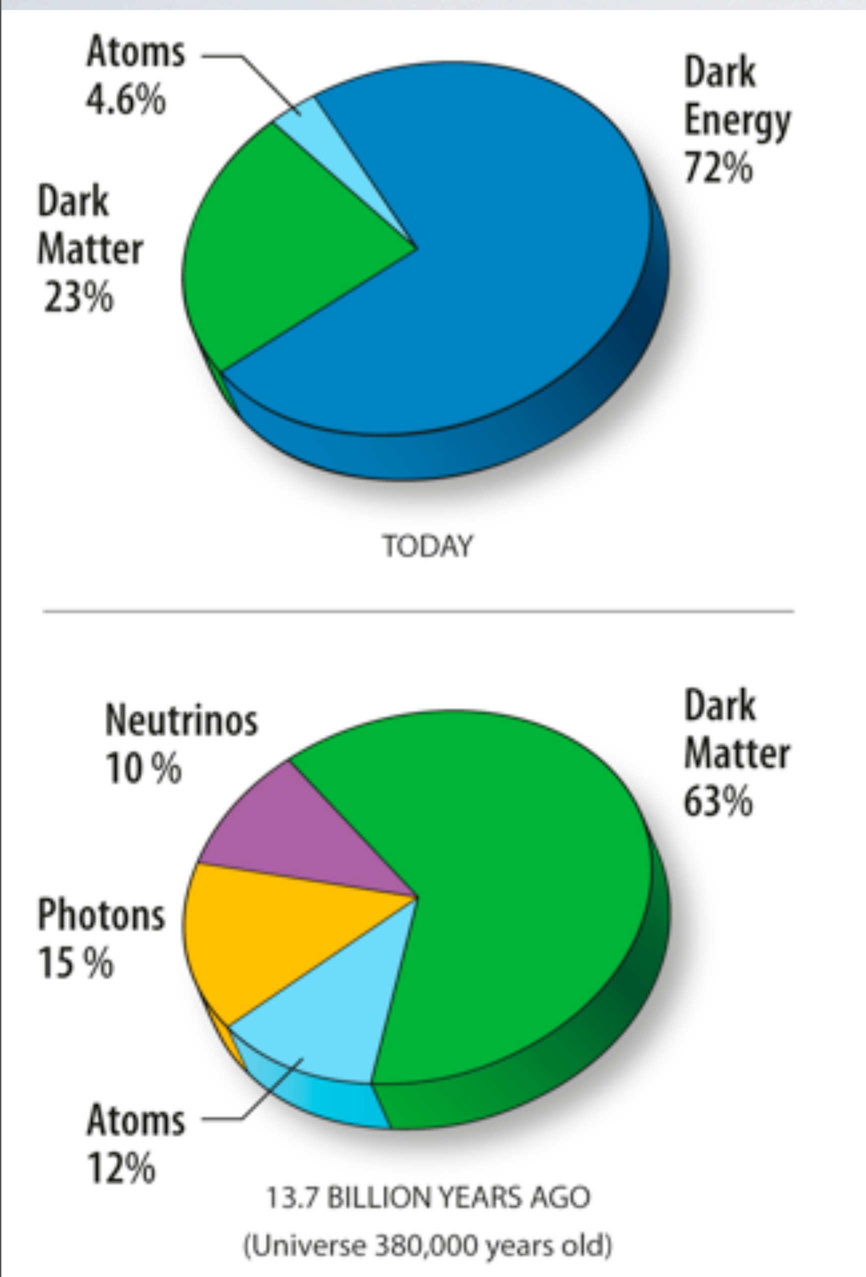
Dark Matter?

Dark Matter Hypothesis



Standard ΛCDM Model of Cosmology

Energy Budget

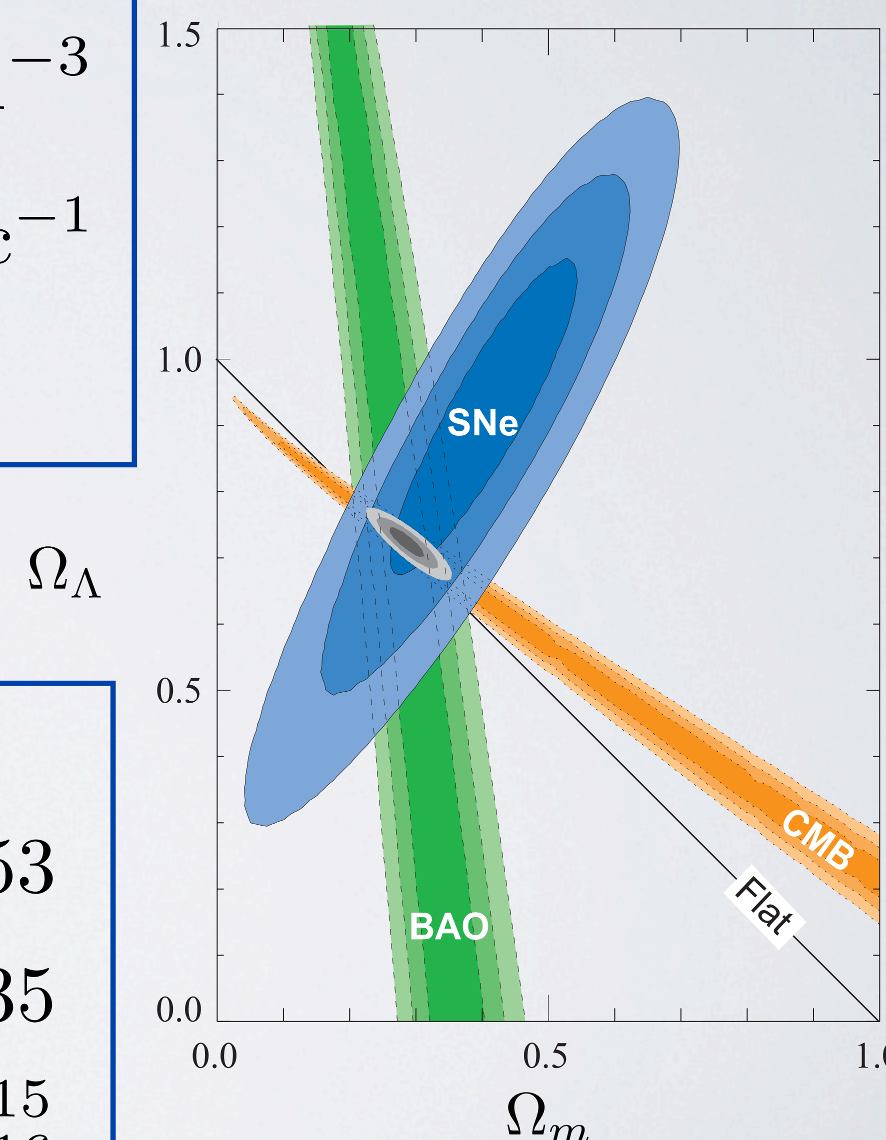


$$\rho_{cr} \equiv \frac{3H_0^2}{8\pi G} \quad , \quad \Omega_i \equiv \frac{\rho_i}{\rho_{cr}}$$

$$\rho_{cr} = 1.9 \cdot 10^{-29}\, h^2 \mathrm{g\, cm}^{-3}$$

$$H_0 = 100\, h\, \mathrm{km\, sec}^{-1}\, \mathrm{Mpc}^{-1}$$

$$h = 0.704 \pm 0.014$$



$$\Omega_m h^2 = 0.1334^{+0.0056}_{-0.0055}$$

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

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

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

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

Four Different Approaches

- Cosmology:
  CMB (Relic Density, Baryon Acoustic Oscillations (BAO)),
  Large Scale Structure, Big Bang Nucleosynthesis (BBN),
  Strong and Weak Gravitational Lensing, Bullet Cluster,
  distant Type Ia supernovae, ...
- Direct Detection (Terrestrial):
  DM scatter off nuclei in terrestrial detectors - recoil energy spectrum
- Indirect Detection (Astrophysical):
  DM annihilation into SM particles (gamma rays, electron/positron, antimatter, neutrinos etc) at massive astrophysical objects, in Sun or Earth
- Production and detected indirectly as missing energy at LHC

Relic Density

Relic Density of a Particle Species

A particle species in the early Universe has to have a sufficiently fast interaction rate to maintain its thermal equilibrium.
A particle will decouple when its annihilation rate falls below the Hubble expansion rate of the Universe.

The abundance of a heavy particle is governed by the Boltzmann eq

$$a^{-3}\frac{d(na^3)}{dt} = \frac{dn}{dt} + 3Hn = \langle \sigma v \rangle \left(n_{\rm eq}^2 - n^2 \right)$$

Non-relativistic limit: $\mathrm{SM} + \mathrm{SM} \to \chi + \chi \qquad \chi + \chi \to \mathrm{SM} + \mathrm{SM}$

$$n_{\rm eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}, \quad m \gg T$$

$$\langle \sigma v \rangle = a + b \langle v^2 \rangle = a + 6\frac{b}{x}, \quad x \equiv \frac{m}{T}$$

$$v \sim 10^{-1}$$

a and b are S and P wave contributions

Freeze-out condition : $n\langle\sigma_A v\rangle \leq \dot{a}/a \equiv H$

$$\Rightarrow \quad x_F \equiv \frac{m}{T_F} \approx \ln\left[c(c+2)\sqrt{\frac{45}{8}}\frac{g}{2\pi^3}\frac{mM_{\rm pl}(a+6b/x_F)}{\sqrt{g_* x_F}}\right]$$

c is a order 1 constant fixed by matching later and early time evolution

$$\Rightarrow \quad \Omega_X h^2 \approx \frac{1.07\times 10^9 {\rm GeV}^{-1}}{M_{\rm Pl}}\frac{x_F}{\sqrt{g_*}}\frac{1}{a+3b/x_F}$$

Typically $x_F \approx 20-30$, and $g_* \approx 80-100$. Thus

$$\Omega_X h^2 \approx 0.1\left(\frac{x_F}{20}\right)\left(\frac{g_*}{80}\right)^{-1/2}\left(\frac{a+3b/x_F}{3\times 10^{-26}{\rm cm}^3/{\rm s}}\right)^{-1}$$

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

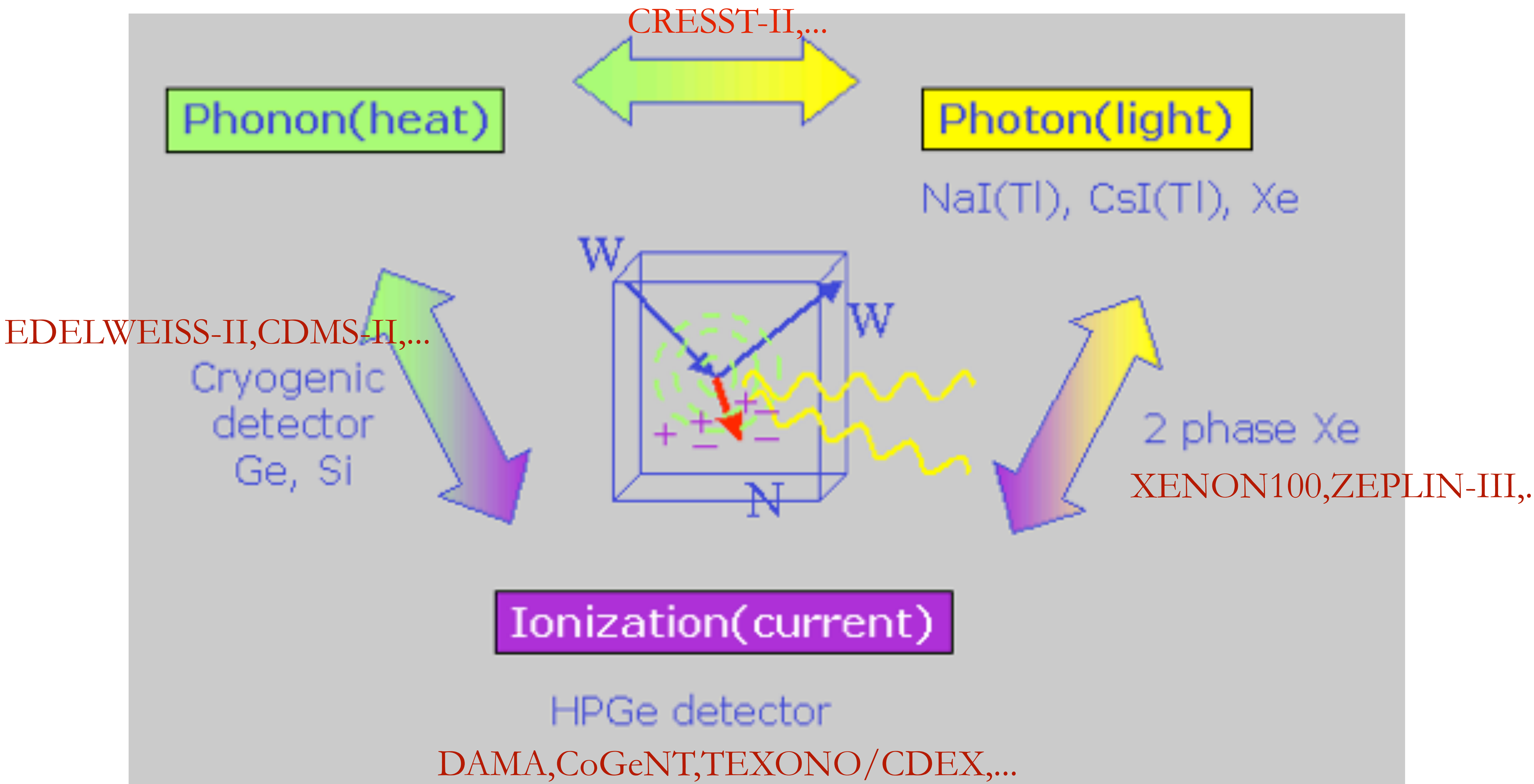
$$\Omega_{CDM}h^2({\rm WMAP}) = 0.1123 \pm 0.0035$$

→ WIMP miracle

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

Direct Detection

Direct Detection



$$v \sim 10^{-3}$$

$$\chi + N \to \chi^{(*)} + N$$

Kinematics of Direct Detection

- A WIMP striking a nucleus will induce a recoil energy

$$E_R^{\rm lab} = \frac{|\vec{q}|^2}{2M_{\rm nucleus}} = \frac{\mu_{\chi N}^2 v^2}{M_{\rm nucleus}}(1-\cos\theta^*)$$ [Exercise]

$\vec{q}$: WIMP's momentum

$\mu_{\chi N}$ = reduced mass = $\frac{m_\chi M_{\rm nucleus}}{m_\chi + M_{\rm nucleus}}$

For $m_\chi \gg M_{\rm nucleus}$ and $v \sim 300$ km/s, we have

$$E_R \sim M_{\rm nucleus} v^2 \sim 1 \text{ - } 100 \text{ keV}$$ Tiny!

Recoil Energy Spectrum
(per unit time per unit recoil energy)

$$\frac{dR}{dE_R} = \frac{\rho}{m_N m_\chi} \int_{v_{\min}}^{v_{\max}} v f(\mathbf{v}) \frac{d\sigma_{\chi N}}{dE_R}(v, E_R)\, d^3\mathbf{v}$$

Astrophysics — Particle Physics

$$v_{\max} = \text{galactic escape velocity} \approx 650 \text{km/s}$$

$$v_{\min} = \left(E_R M_N / 2\mu_{\chi N}^2\right)^{1/2}$$

DM local density $\rho = (0.30 \pm 0.05)\ \text{GeV cm}^{-3}$ (Rotation curves)

Truncated Boltzmann-Maxwell's distribution in the galactic rest frame

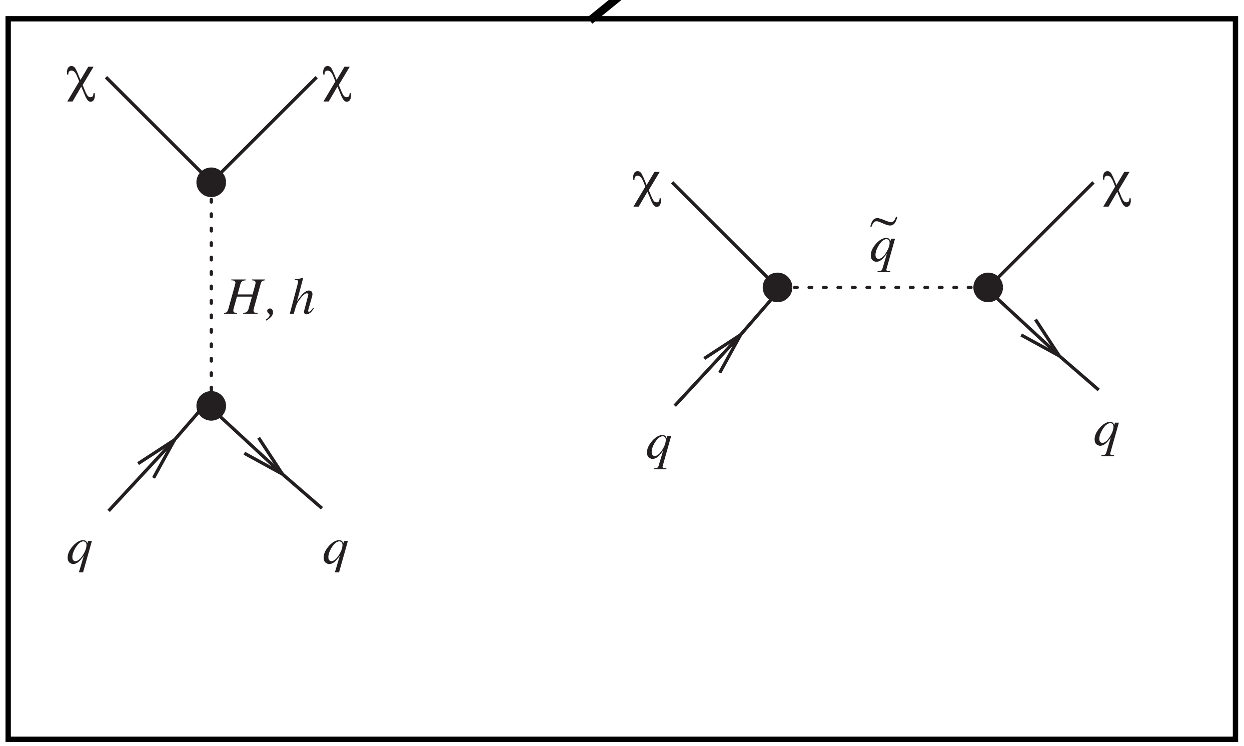
$$f(\mathbf{v}_{\rm gal}) = \frac{1}{(\sqrt{2\pi}\sigma)} \exp\left(-\frac{|\mathbf{v}_{\rm gal}|^2}{2\sigma^2}\right) \times \Theta(v_{max} - v_{gal})$$

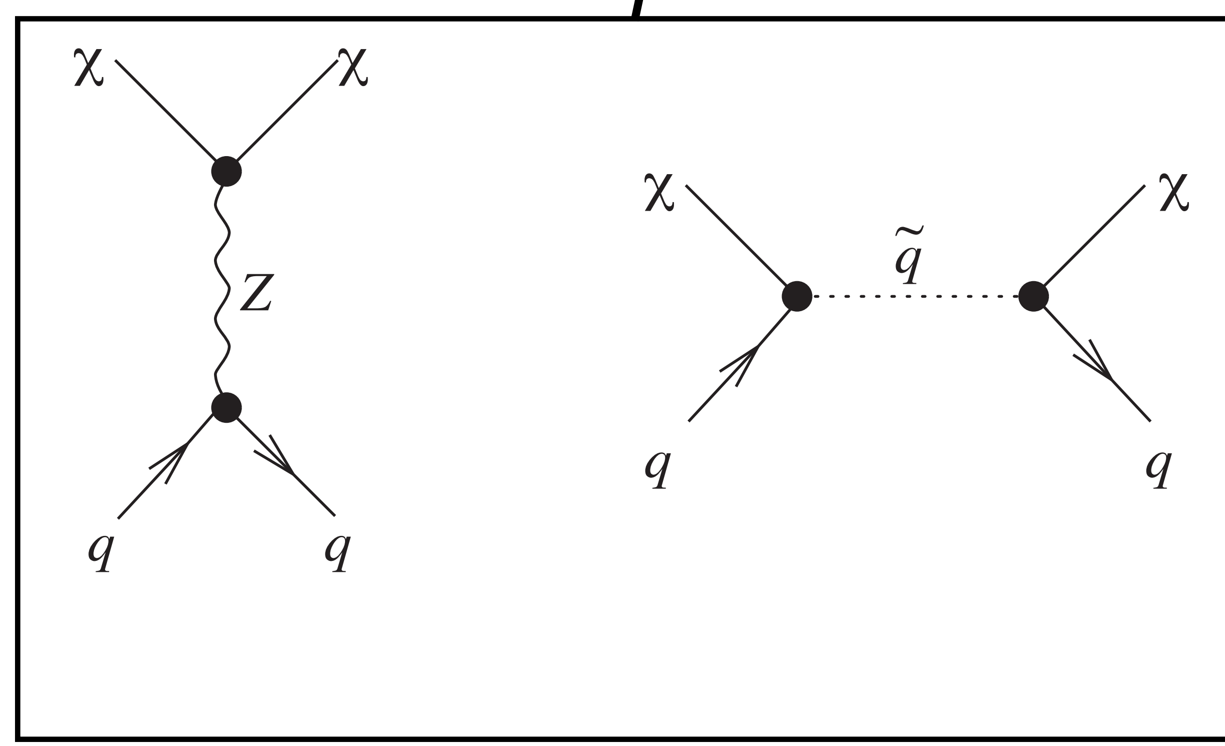
Model Example: MSSM

By integrating out heavy Higgses, Z-boson and squarks in MSSM, effective interactions between DM and SM fields are obtained

$$\mathcal{L}_{\text{eff}} = f_{SI}(\bar{\chi}\chi)(\bar{q}q) + f_{SD}(\bar{\chi}\gamma^{\mu}\gamma_5\chi)(\bar{q}\gamma_{\mu}\gamma_5 q)$$

O_7 O_4





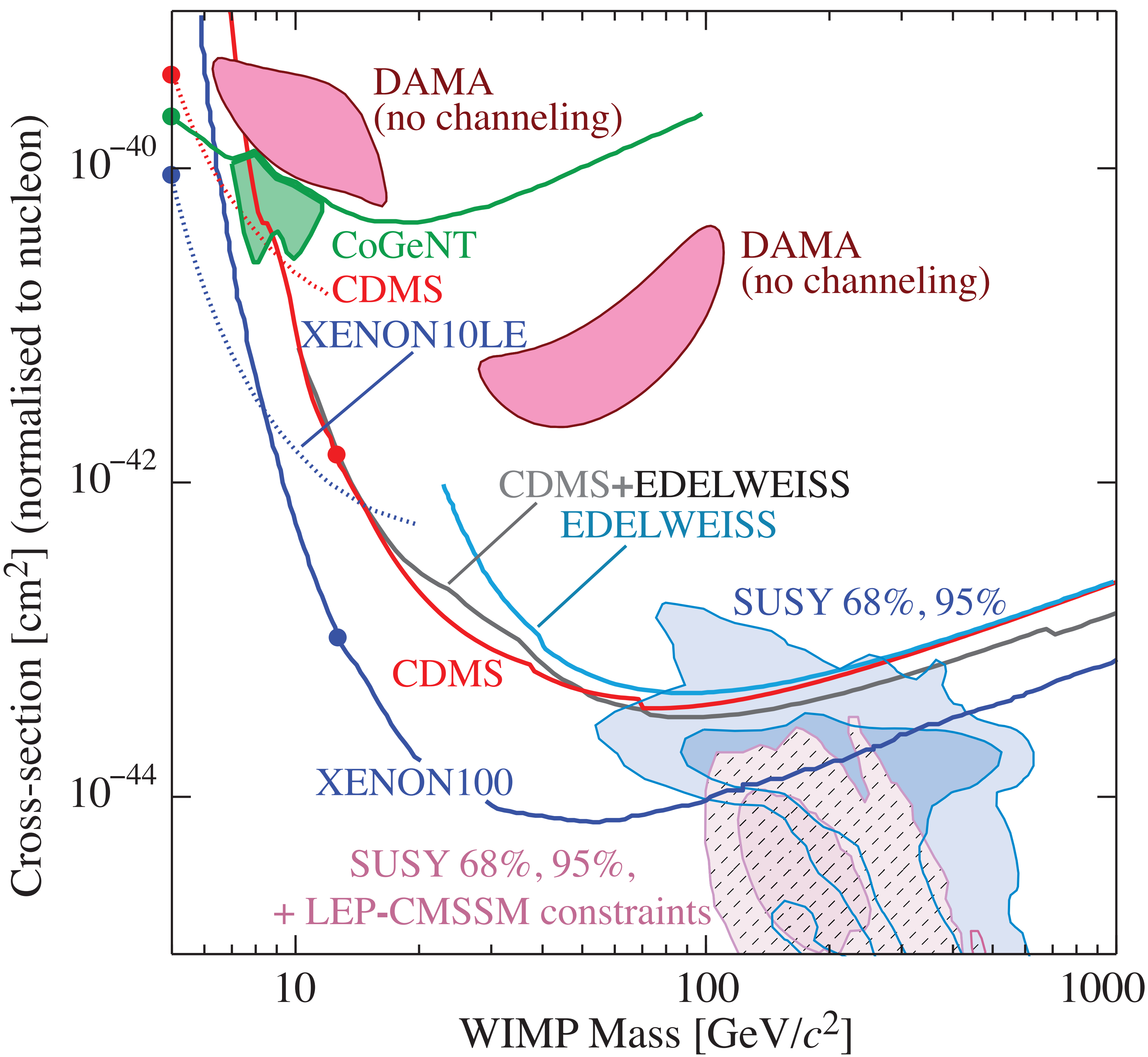
Cheng and Chiang, arXiv:1202.1292

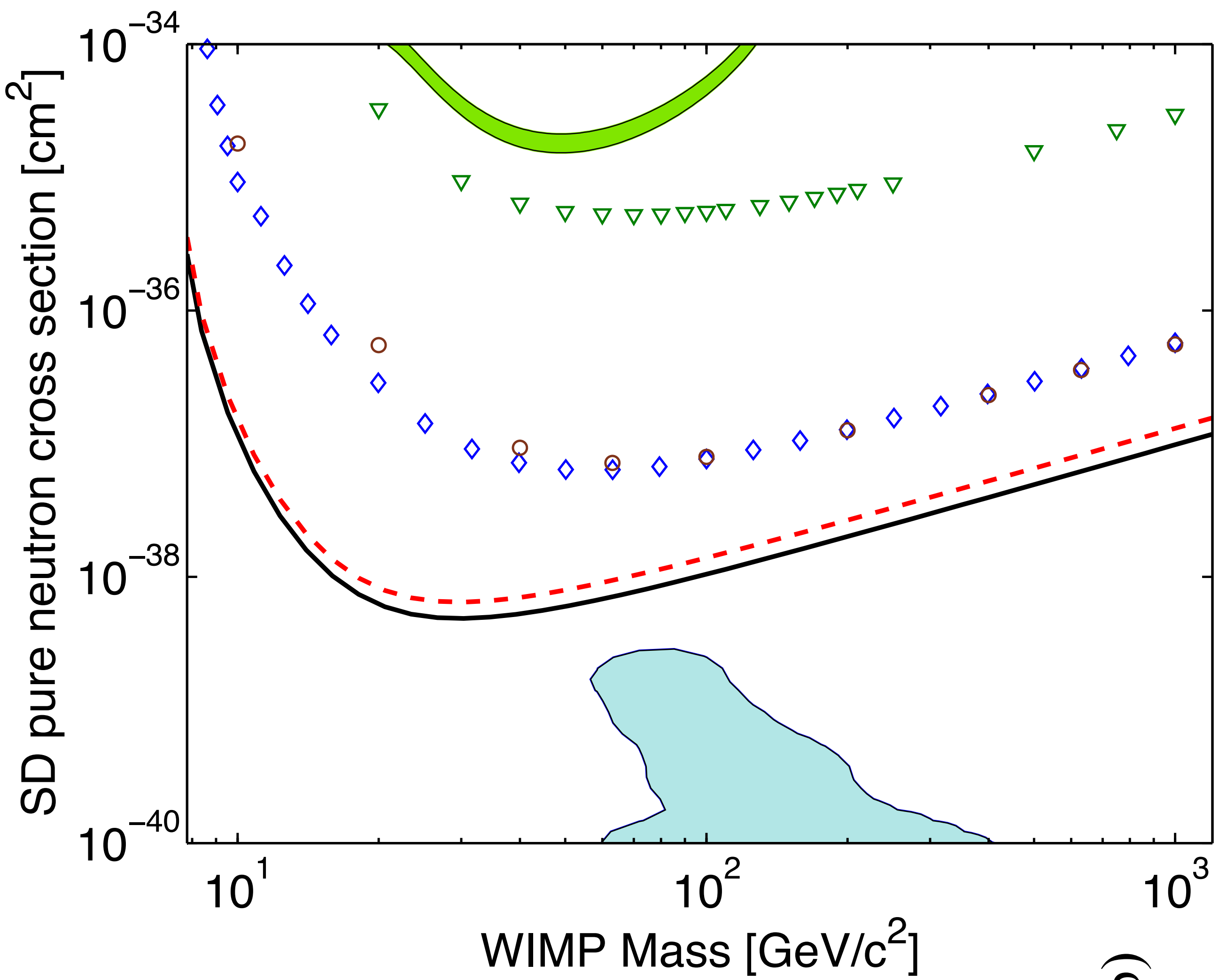
Comparison with other works

$$f_{T_q} \equiv \frac{\langle N | m_q \bar{q} q | N \rangle}{m_N} = \frac{\sigma_q}{m_N}$$

	DarkSUSY	Ellis et al	Cheng and Chiang
$f_{Tu}^{(p)}$	0.023	0.020	0.018
$f_{Tu}^{(n)}$	0.019	0.014	0.011
$f_{Td}^{(p)}$	0.034	0.026	0.021
$f_{Td}^{(n)}$	0.041	0.036	0.035
$f_{Ts}^{(p)}$	0.14	0.118	0.053
$f_{Ts}^{(n)}$	0.14	0.118	0.053
Δu	0.77	0.78	0.85 (0.84)
Δd	-0.40	-0.48	-0.42 (-0.44)
Δs	-0.12	-0.15	-0.08 (-0.03)

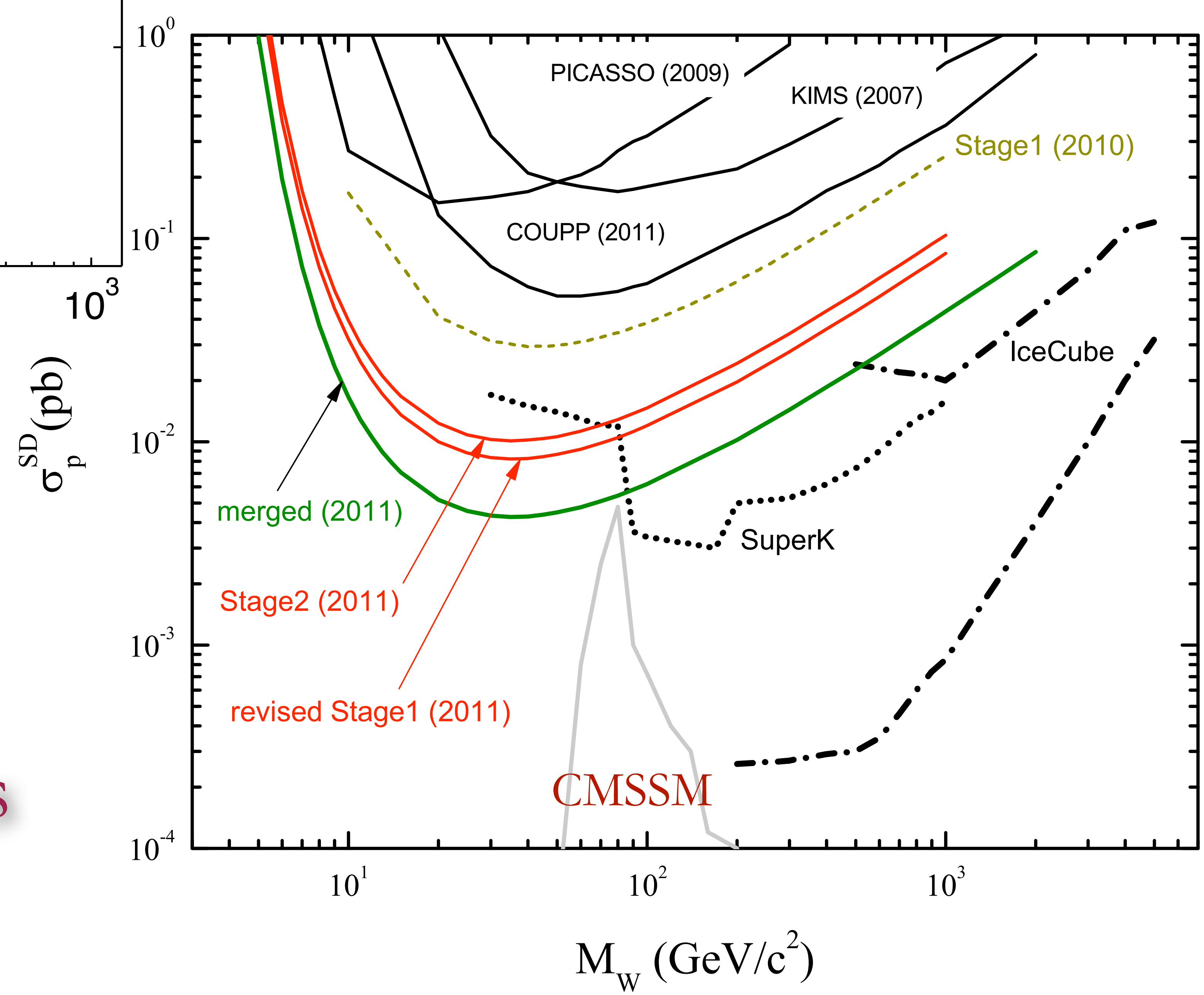
1204.2373 Drees and Gerbier





$$1\,\text{pb} = 10^{-36}\,\text{cm}^2$$

SIMPLE Collaboration



XENON10

Spin -Dependent Results

arXiv:1106.2014

Fermionic DM Effective Operators

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

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

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

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

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

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

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

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

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

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

$$O_{11} = \frac{C_{11}}{\Lambda_{11}^3} \left(\bar{\chi}\chi\right)\left(-\frac{\alpha_s}{12\pi} G^{\mu\nu}G_{\mu\nu}\right) ,$$

$$O_{12} = \frac{iC_{12}}{\Lambda_{12}^3} \left(\bar{\chi}\gamma^5\chi\right)\left(-\frac{\alpha_s}{12\pi} G^{\mu\nu}G_{\mu\nu}\right) ,$$

$$O_{13} = \frac{C_{13}}{\Lambda_{13}^3} \left(\bar{\chi}\chi\right)\left(\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde{G}_{\mu\nu}\right) ,$$

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

Cheung, Tseng, Tsai, Yuan, arXiv:1201.3402

Scalar DM Effective Operators

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

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

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

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

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

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

Cheung, Tseng, Tsai, Yuan, arXiv:1201.3402

NR reduction for Direct Detection

- At present epoch, v/c ~ 10^{-3}, NR limit is applicable
- Only O_1,O_4,O_5,O_7,O_{11},O_{16},O_{17} and O_{19} exist in NR reduction
- Furthermore, only O_1, O_4 and O_7 are independence because

$$\begin{aligned} O_5 &\longrightarrow O_4 \\ O_{11} &\longrightarrow O_7 \\ O_{15} &\longrightarrow O_1 \\ O_{17} &\longrightarrow O_7 \\ O_{19} &\longrightarrow O_7 \end{aligned}$$

- SI: O_1 and O_7; SD : O_4

O_1 (Majorana) and O_7 (Majorana or Dirac)

- Coherent spin-independent cross section

O_1

$$\sigma^{\rm SI}_{\chi\mathcal{N}}(0) = \frac{\mu^2_{\chi\mathcal{N}}}{\pi}|b_\mathcal{N}|^2$$

$$b_\mathcal{N} = Z\, b_p + (A-Z)\, b_n$$

$$b_p = 2\,\frac{C_1^u}{\Lambda_1^2} + \frac{C_1^d}{\Lambda_1^2}\,,$$

$$b_n = \frac{C_1^u}{\Lambda_1^2} + 2\,\frac{C_1^d}{\Lambda_1^2}\,.$$

O_7

$$\sigma^{\rm SI}_{\chi\mathcal{N}}(0) = \frac{\mu^2_{\chi\mathcal{N}}}{\pi}|f_\mathcal{N}|^2$$

$$f_{p,n} = \frac{m_{p,n}}{\Lambda_7^3}\left\{\sum_{q=u,d,s} C_7^q\, f_{Tq}^{(p,n)} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{Q=c,b,t} C_7^Q\right\}$$

$$f_\mathcal{N} = Z\, f_p + (A-Z)\, f_n$$

$$f_{TG}^{(p,n)} \equiv 1 - \sum_{q=u,d,s} f_{Tq}^{(p,n)}\,.$$

O_4 (Majorana or Dirac)

- Spin-dependent cross section (for Dirac DM)

$$\sigma^{\rm SD}_{\chi\mathcal{N}}(0) = \frac{8\mu^2_{\chi\mathcal{N}}}{\pi} G_F^2 \bar{\Lambda}^2 J(J+1)$$

$$\bar{\Lambda} = \frac{1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)$$

$$a_{p,n} = \sum_{q=u,d,s} \frac{1}{\sqrt{2}G_F}\frac{C_4^q}{\Lambda_4^2}\Delta q^{(p,n)}$$

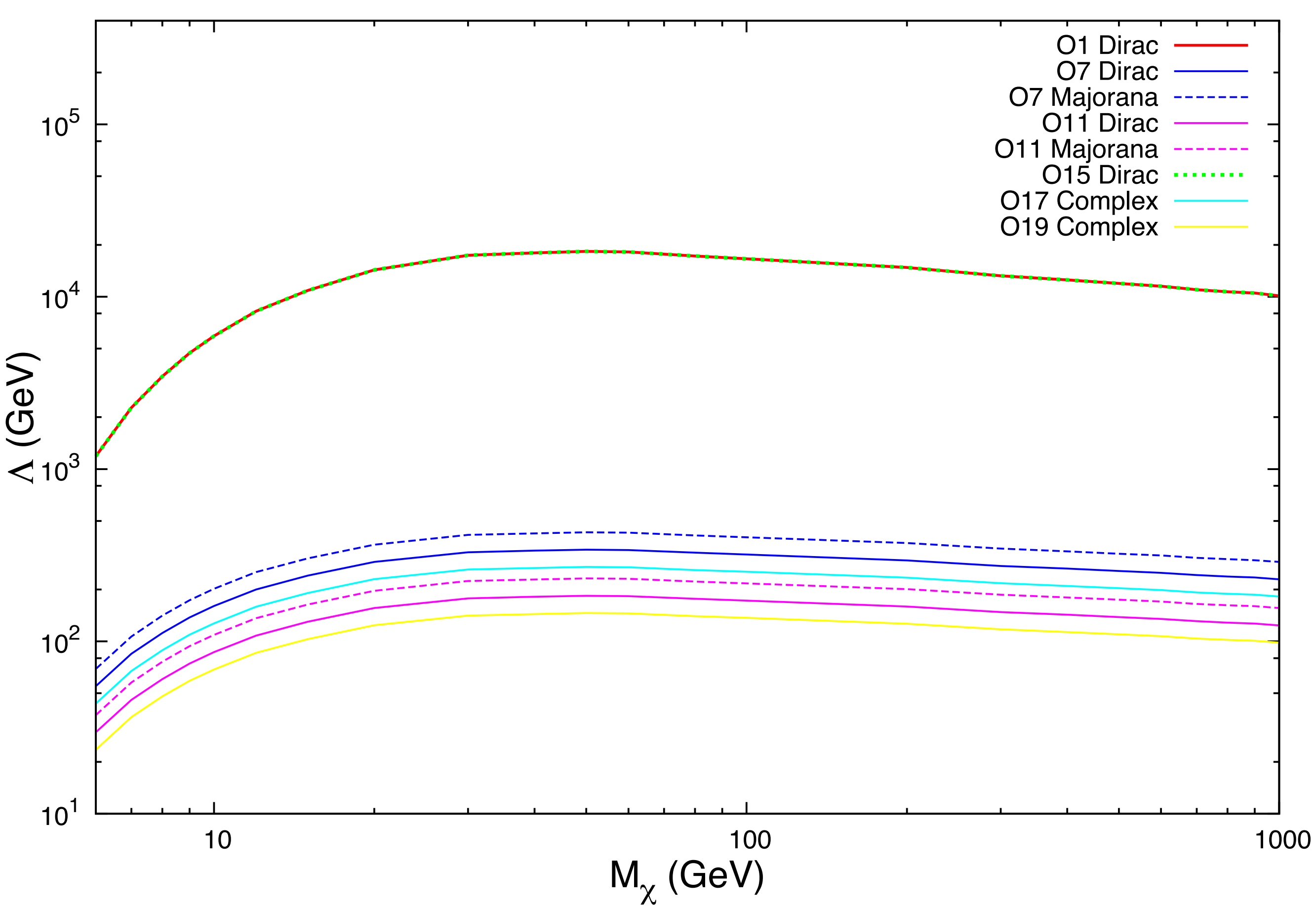
$$\begin{aligned} a_0 &= a_p + a_n\ , \\ a_1 &= a_p - a_n\ . \end{aligned}$$

Constraints on Effective Interactions

- Our approach (adopted by other several groups as well):
  (1) assumption: the connector sector must be heavy and integrated out
  (2) DM can be (real/complex) scalar or (Majorana/Dirac) fermionic; vector DM not considered
  (3) effective interaction of WIMP DM with SM particles
  (4) model independent study for a large class of models
- Direct detection experiments can place upper limits on cross sections hence lower limits on effective scales Λ

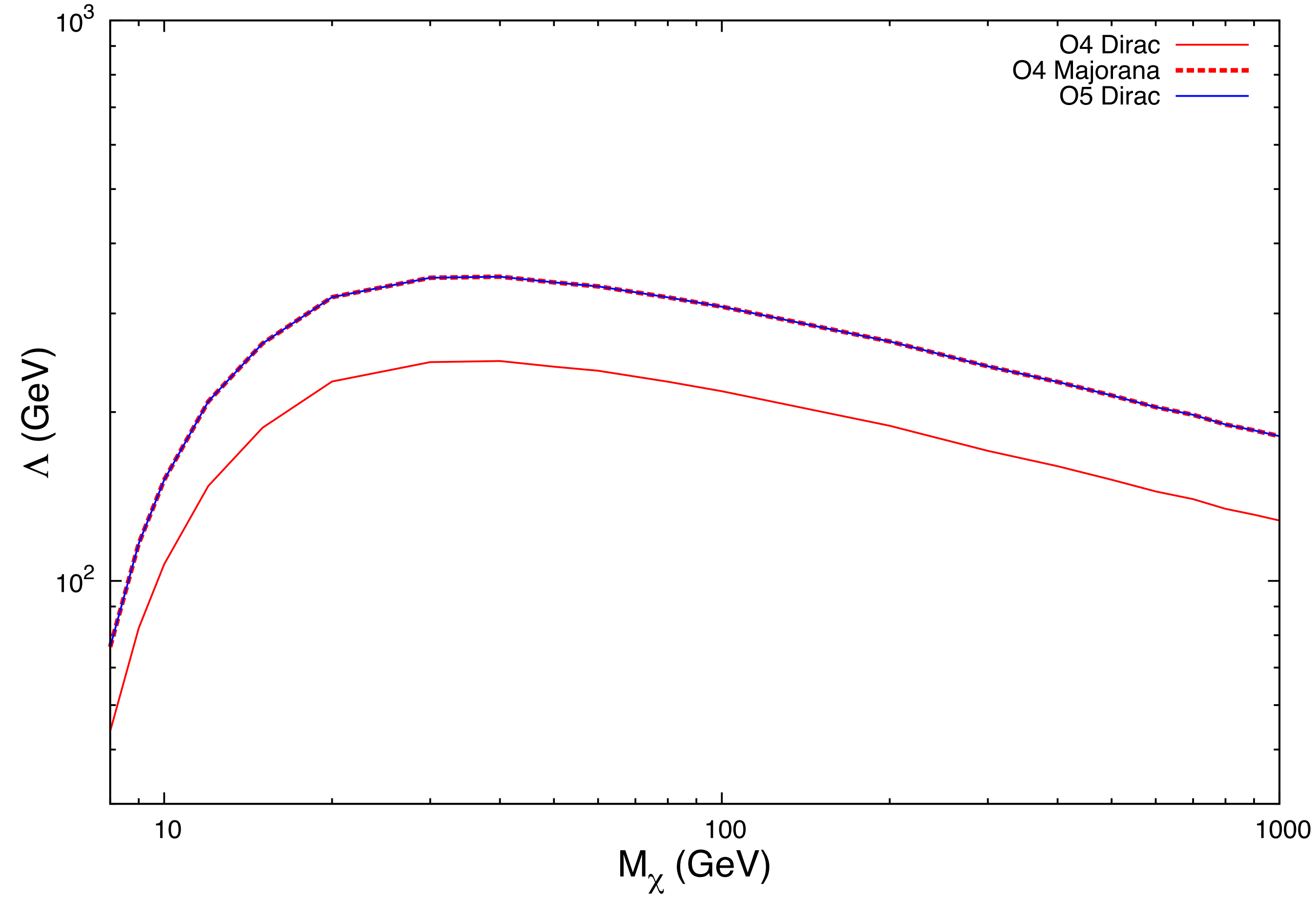
2σ Lower Limits for Λ From Direct Detection

SI (XENON100)



NR reduction: only O_1 & O_7 are independent.

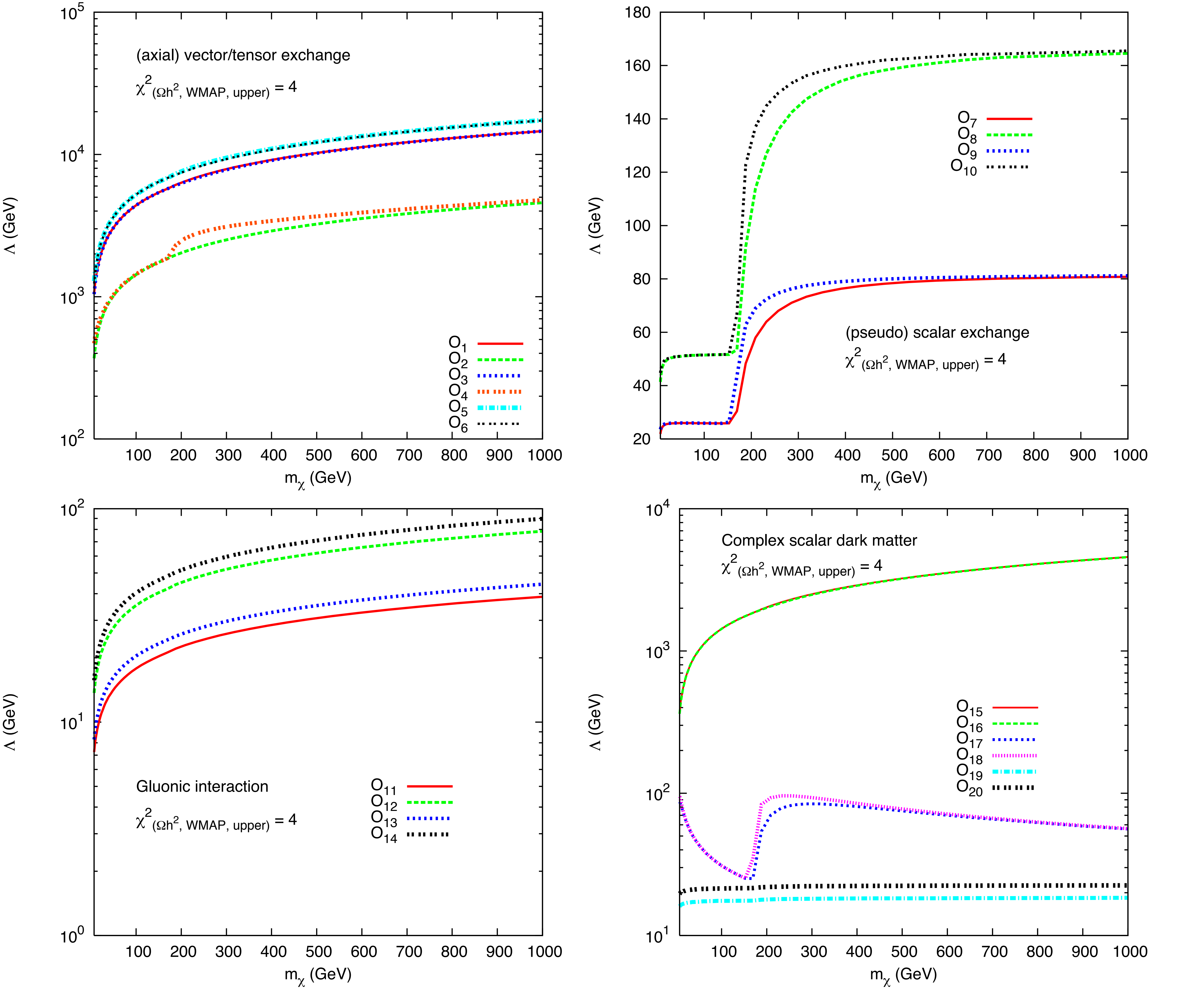
SD (XENON10, ZEPLIN, SIMPLE)



NR reduction: O_5 reduces to O_4

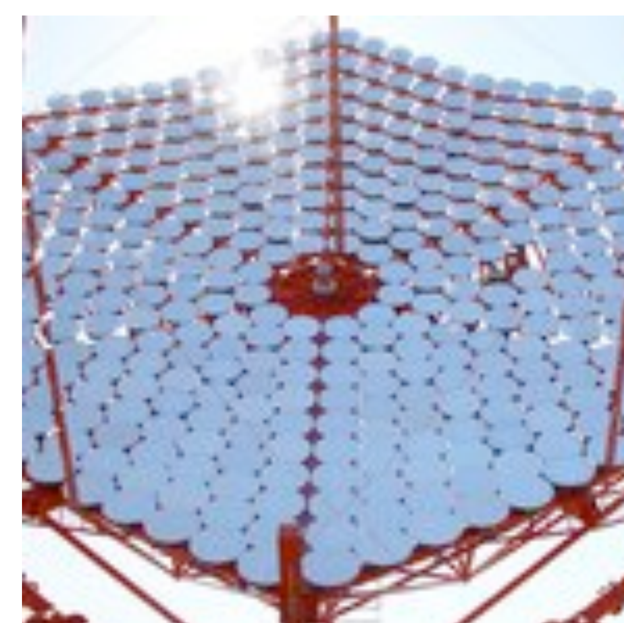
Cheung, Tseng, Tsai, Yuan, arXiv:1201.3402

2σ Upper Limits for Λ From Relic Density



Cheung, Tseng, Tsai, Yuan, arXiv:1201.3402

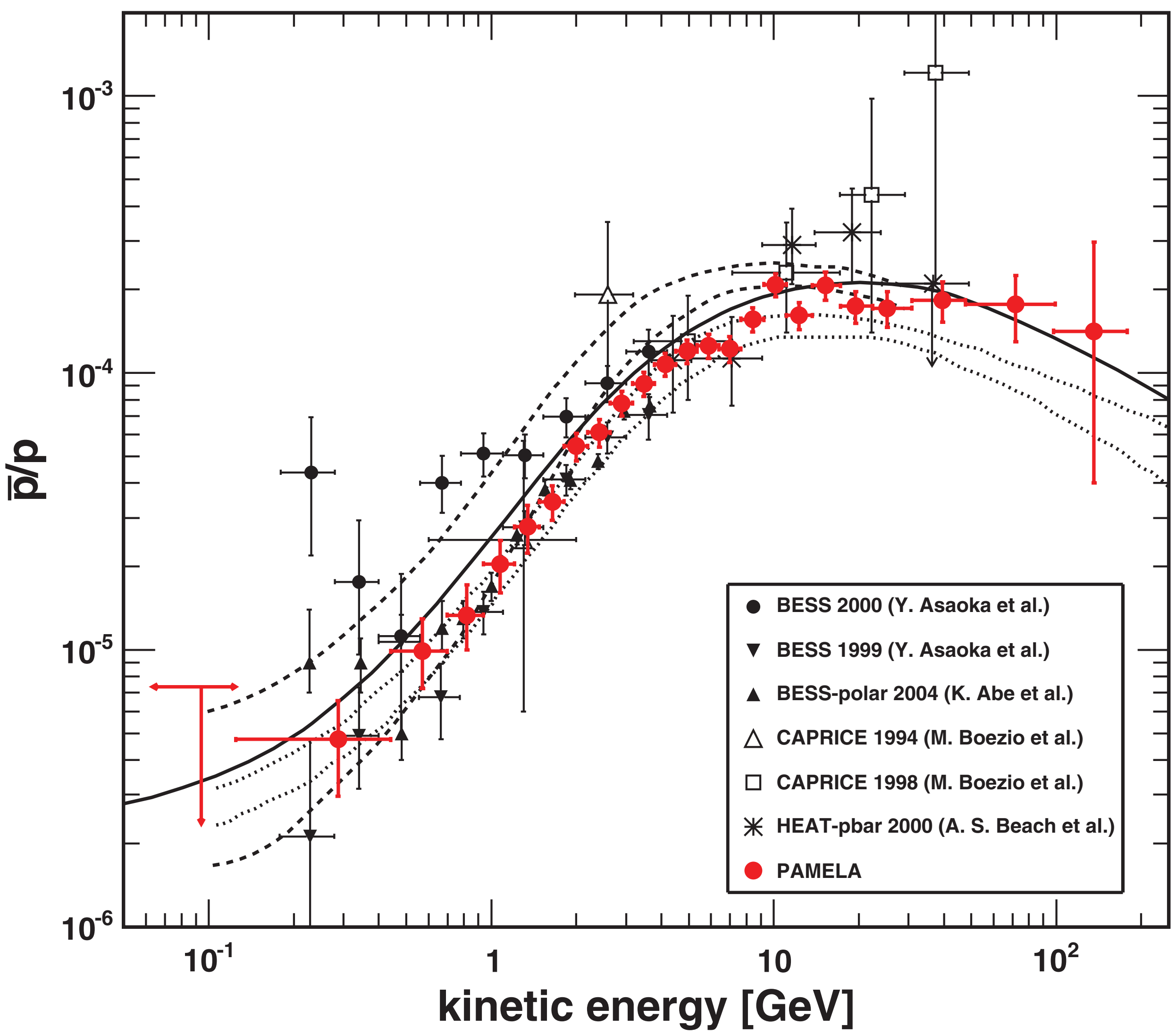
Indirect Detection

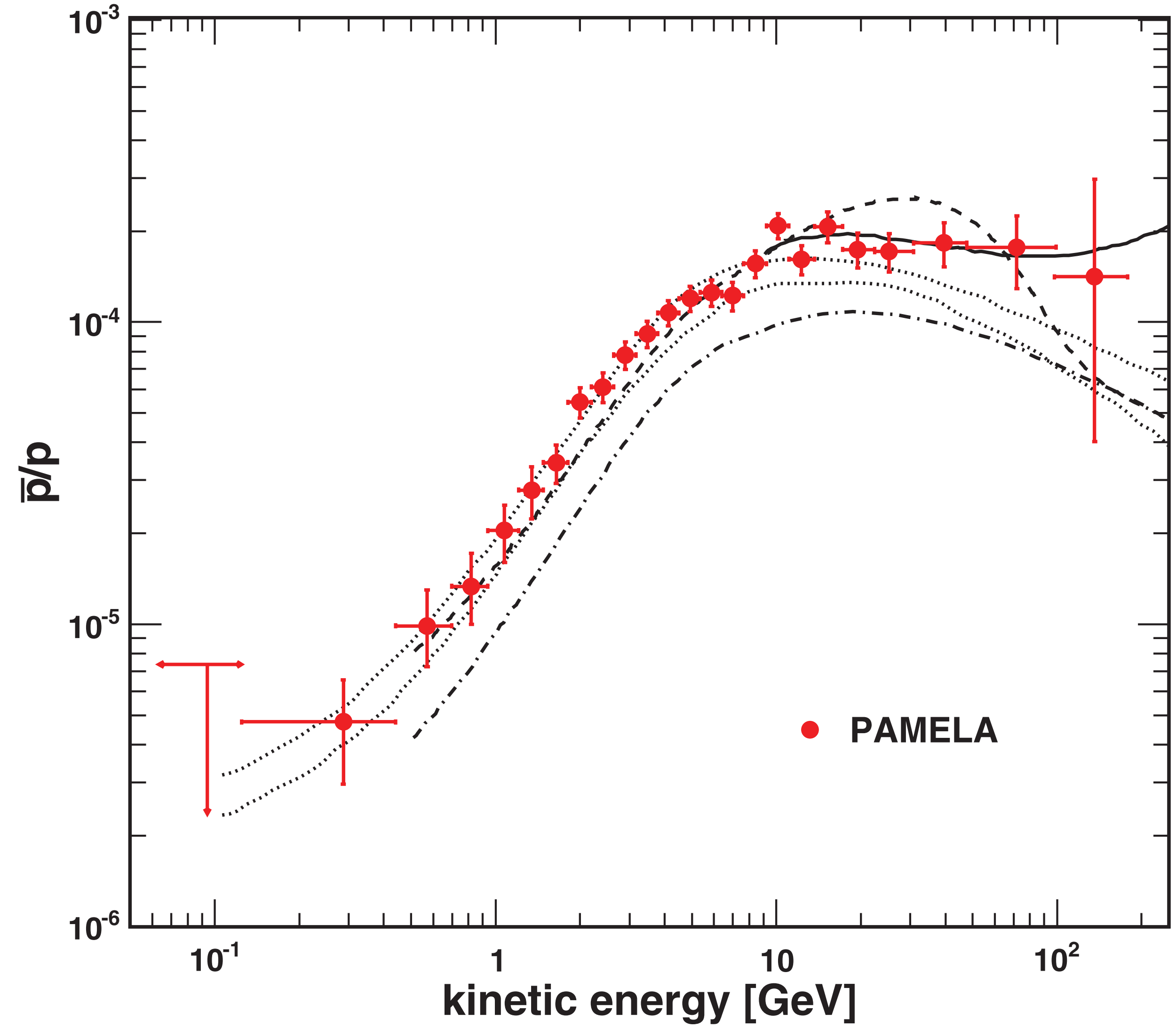


Indirect Detection

- Indirect signals from DM annihilation into gamma rays (line or continuum), neutrinos, antimatter like positrons and antiproton, ...
- Ambiguous due to possible astrophysical sources like pulsars, cosmic rays, ...
- If the final states are charged (positron, antiproton, etc), predictions depend on parameters in propagation model, since they can lose energy while traversing in the cosmic medium
- Gamma rays and neutrinos have lesser propagation effects
- Pamela, Fermi-LAT, AMS-02, HESS, Veritas, ...
- Neutrino telescopes: IceCube, ANTARES, ...

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

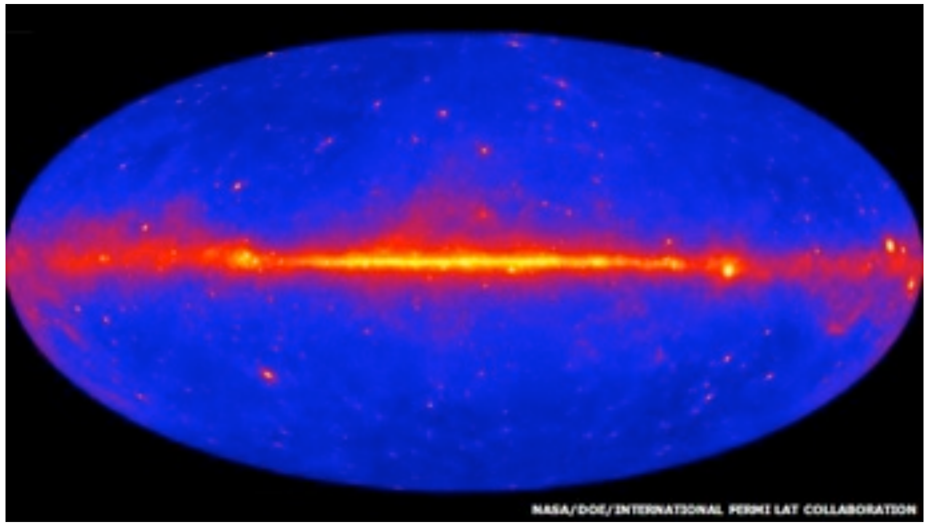


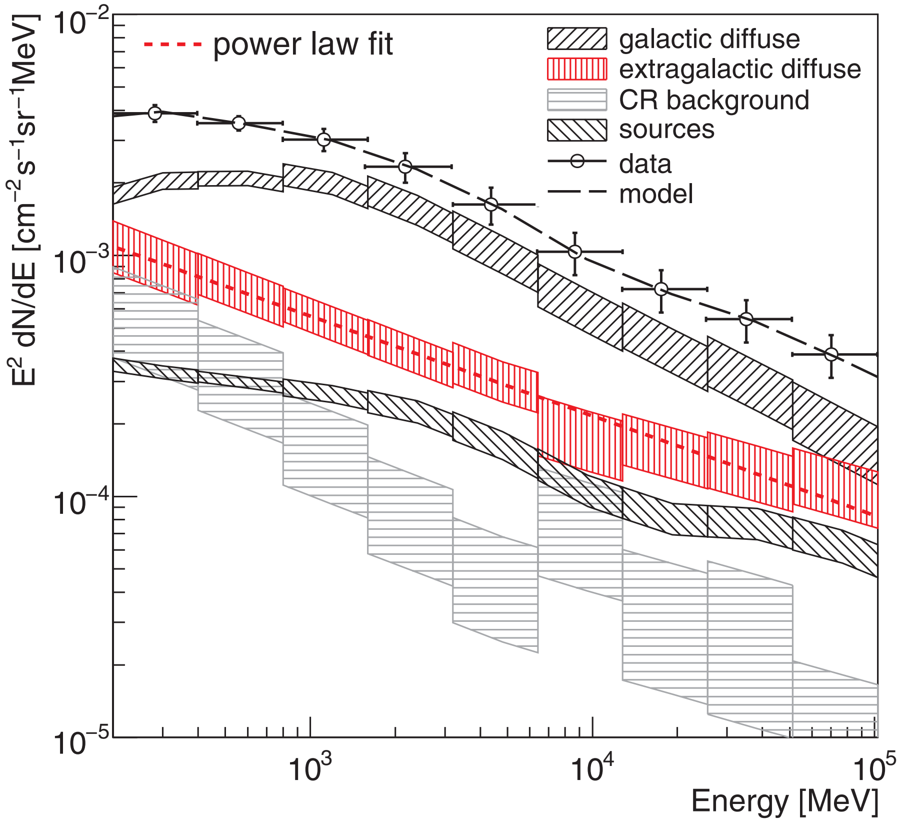


* Data very close to background.
* It can provide stringent constraints on contributions from DM.

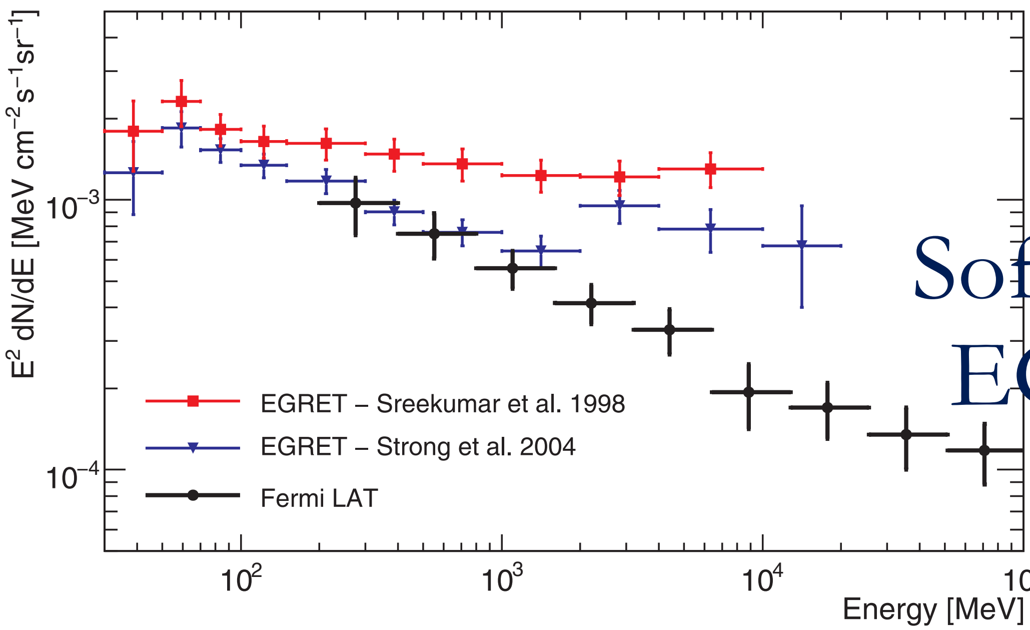
Diffuse Gamma Rays Spectrum (Fermi-LAT)

PRL **104,** 101101 (2010)



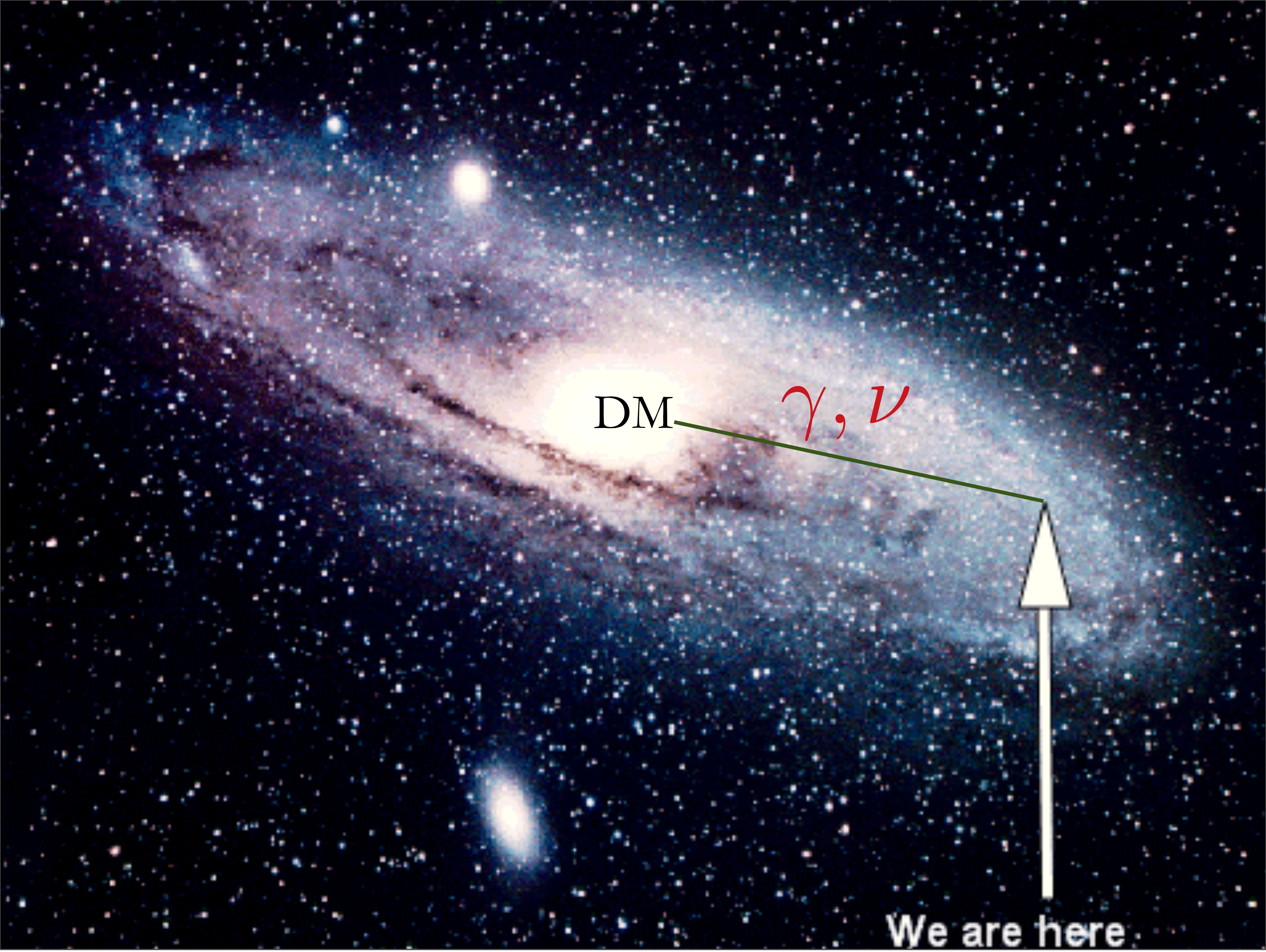


EGB

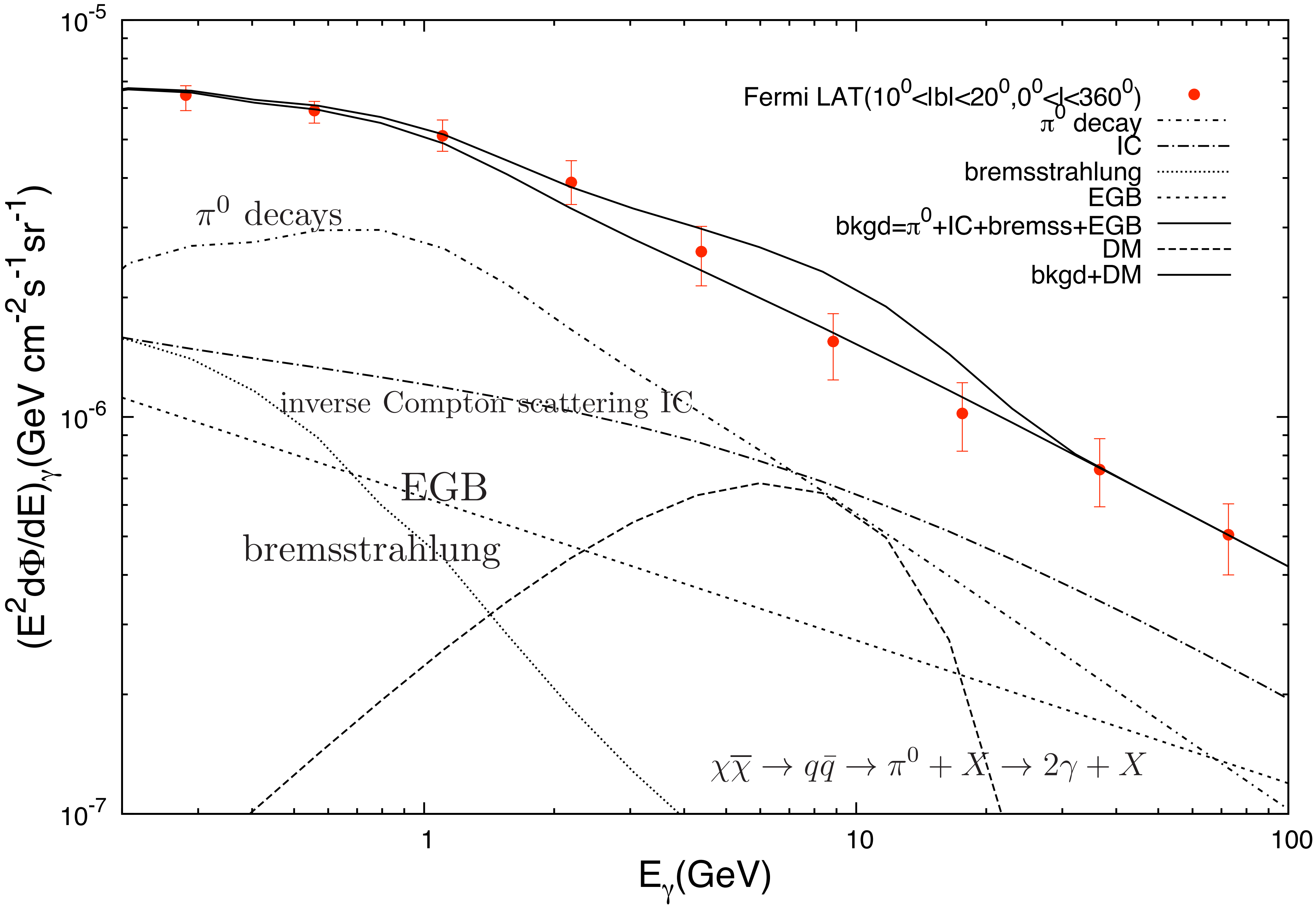


Softer than EGRET!

* DM can make contribution to diffuse γ rays; hence constrained by Fermi-LAT measurement

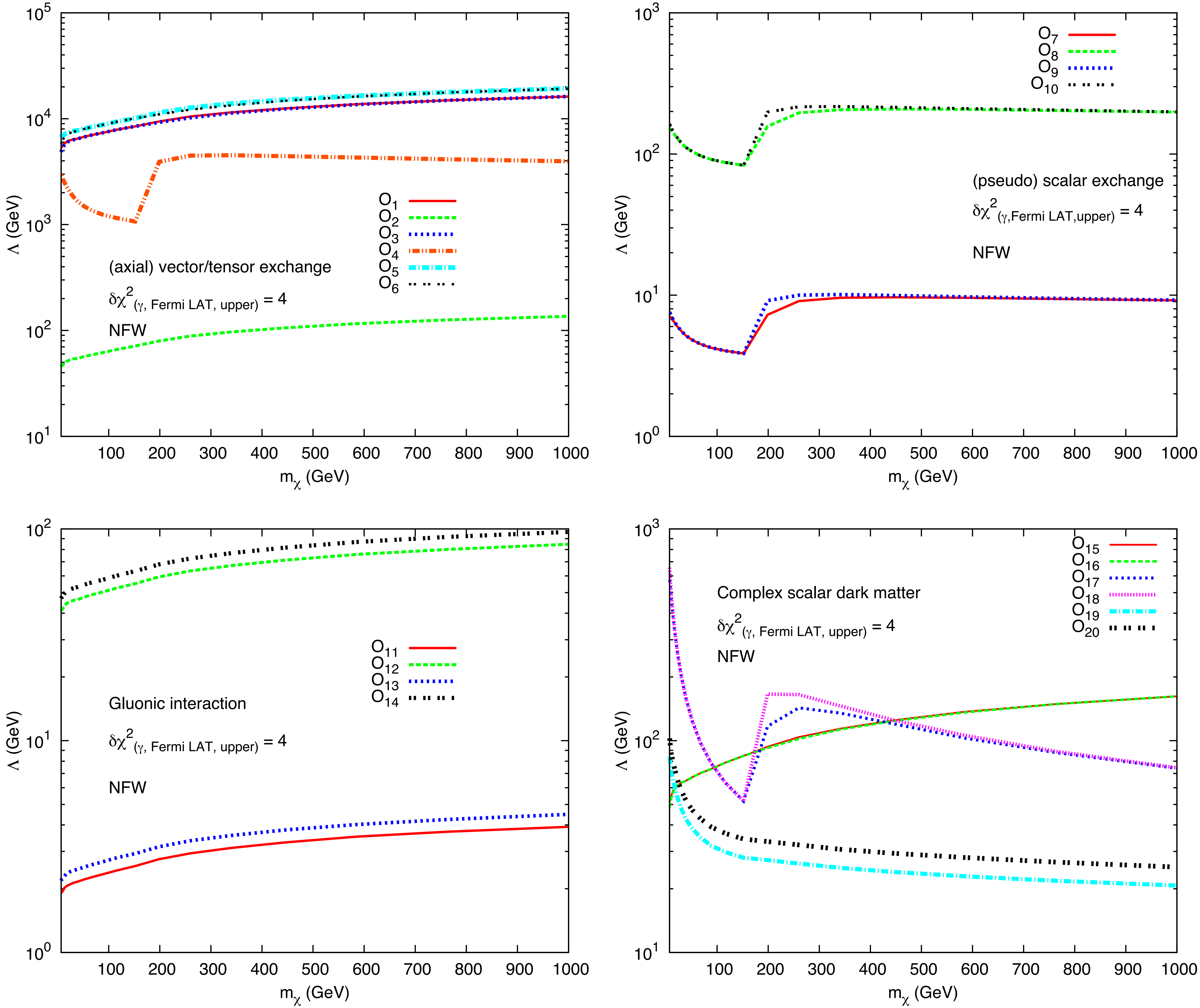

DM
γ, ν
We are here

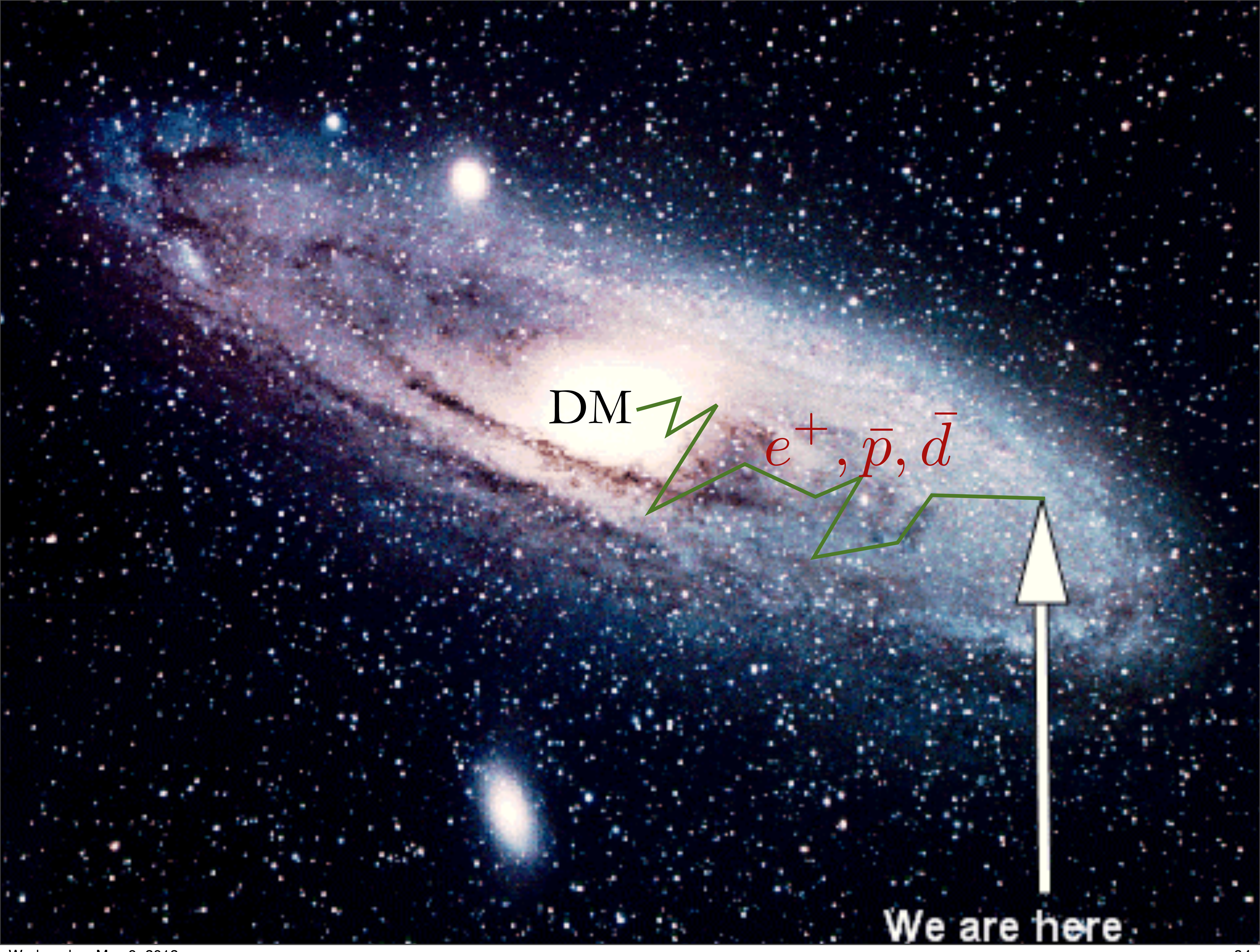
The photon spectrum $E^2(d\Phi/dE_\gamma)$ versus the photon energy



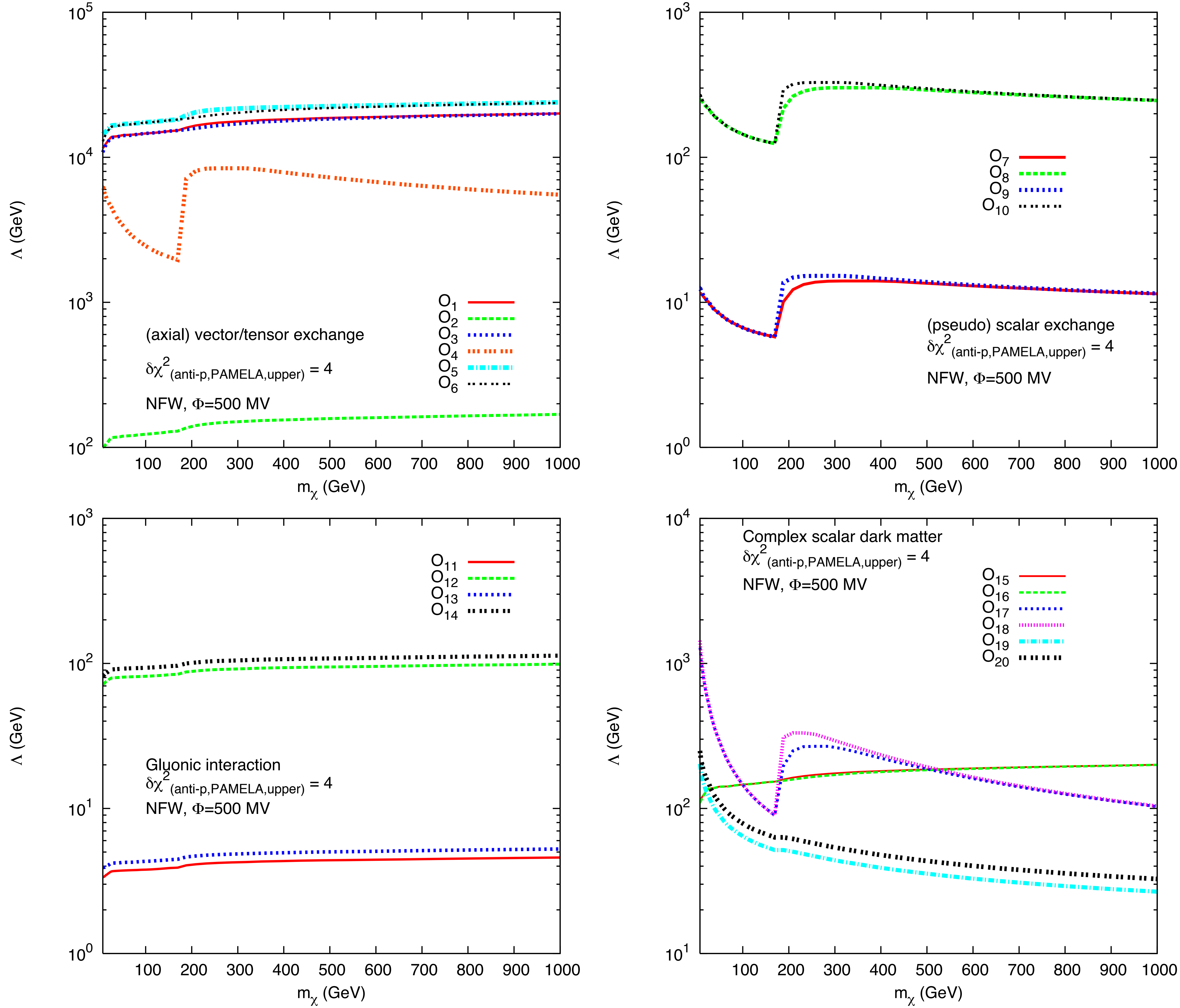
$m_\chi = 50$ GeV; O_1 with $\Lambda = 0.87$ TeV (3σ)

2σ Lower Limits for Λ From Diffuse Gamma Ray Flux




DM
$e^+, \bar{p}, \bar{d}$
We are here

2σ Lower Limits for Λ From PAMELA Antiproton Flux



Colliders

Runs at 4 + 4 Now

Mono-jets/Mono-photons

The effective DM interactions can contribute by attaching either a gluon or a photon to one of the quark legs of the relevant operators

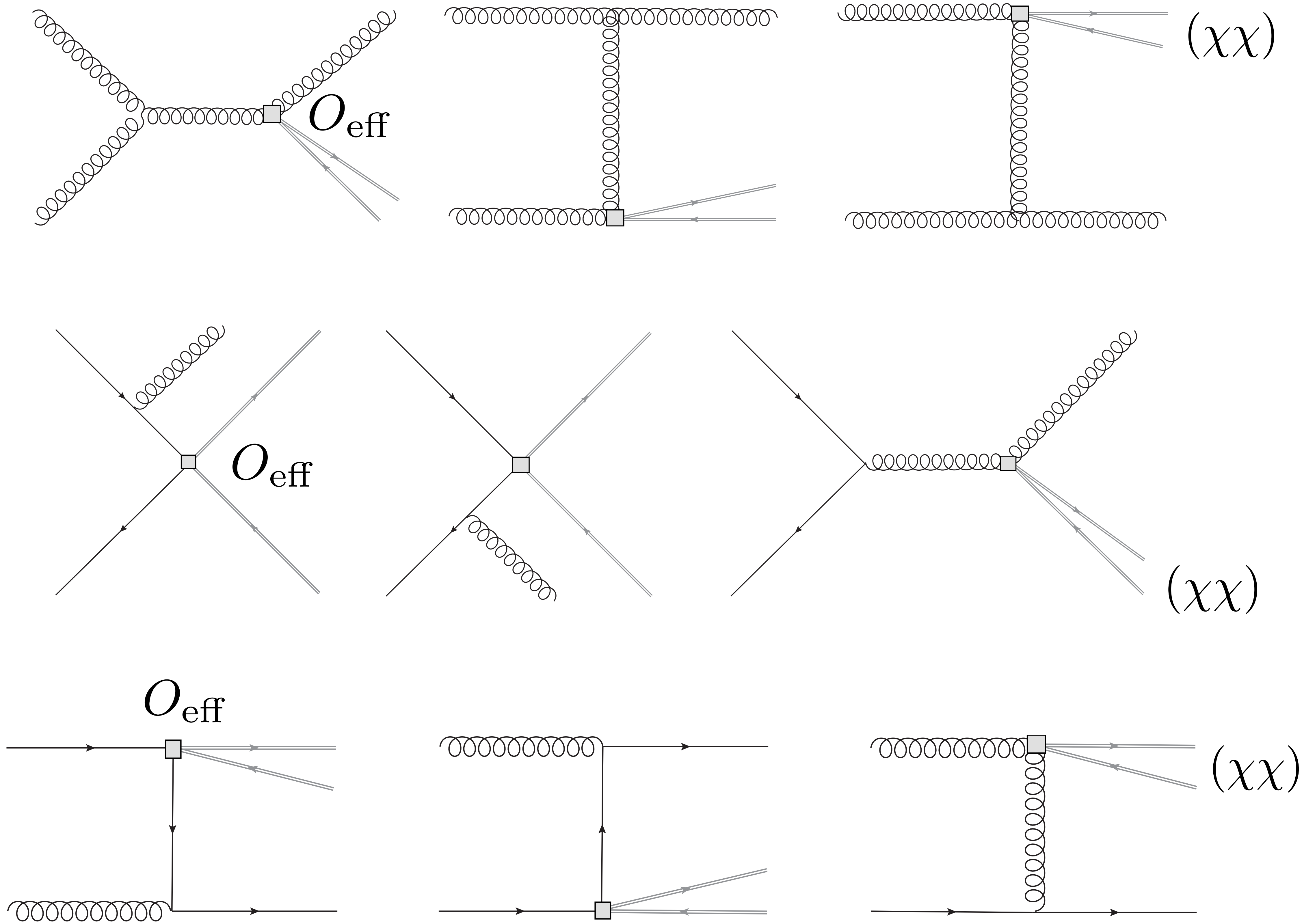
DM Signals : Missing Energy

Data sets:

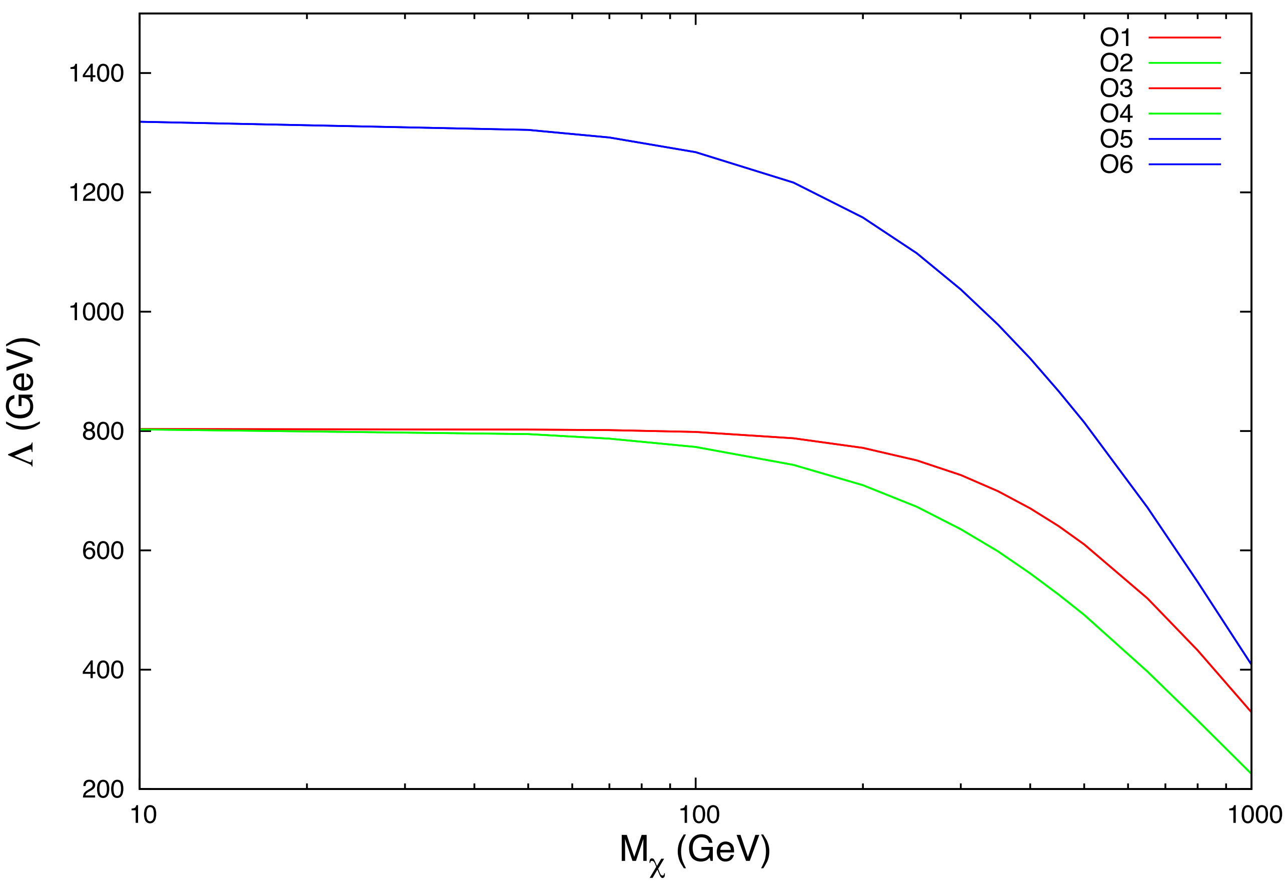
- Mono-jet and mono-photon from CDF and D0
- Mono-jet from ATLAS

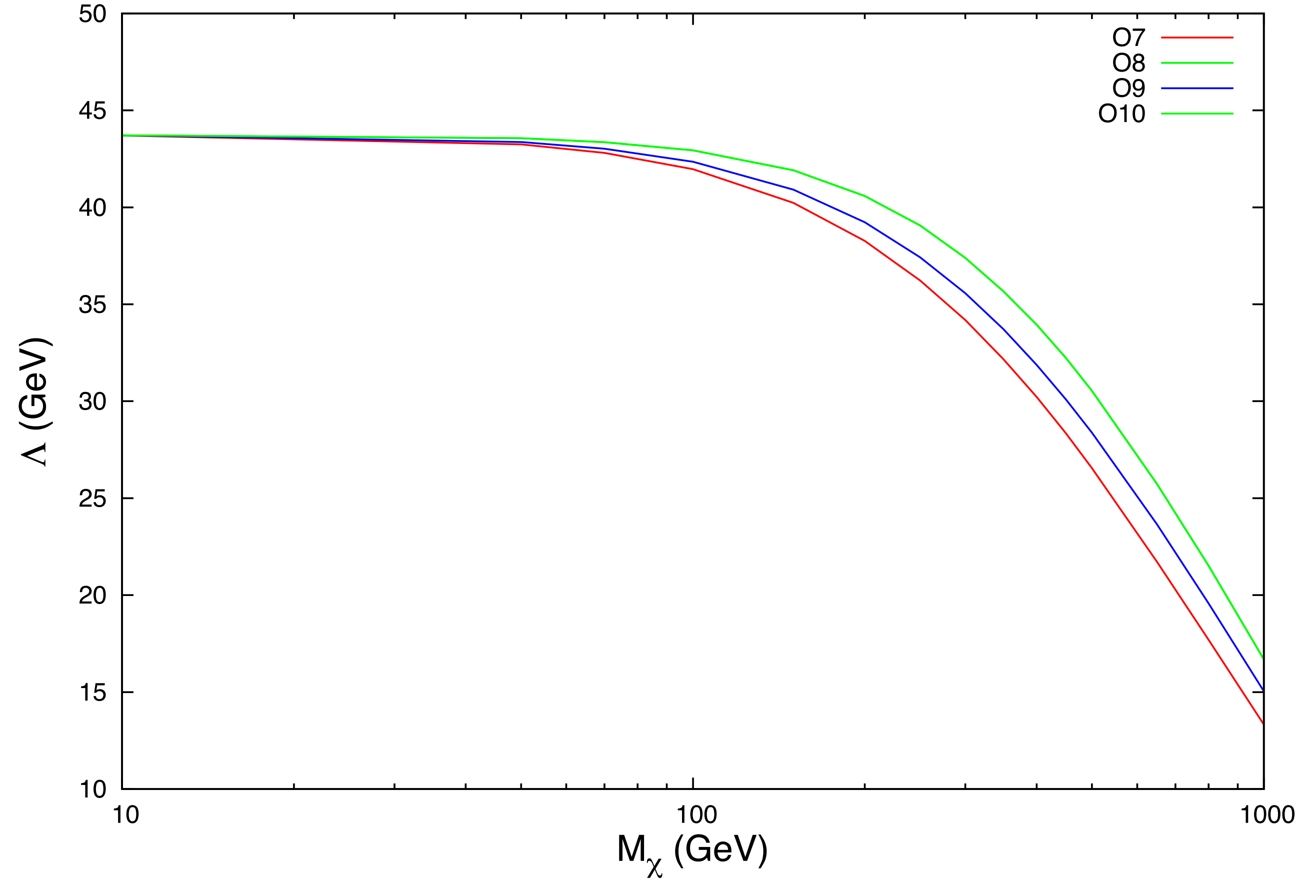
No excess is found. Put lower limits on effective scales.

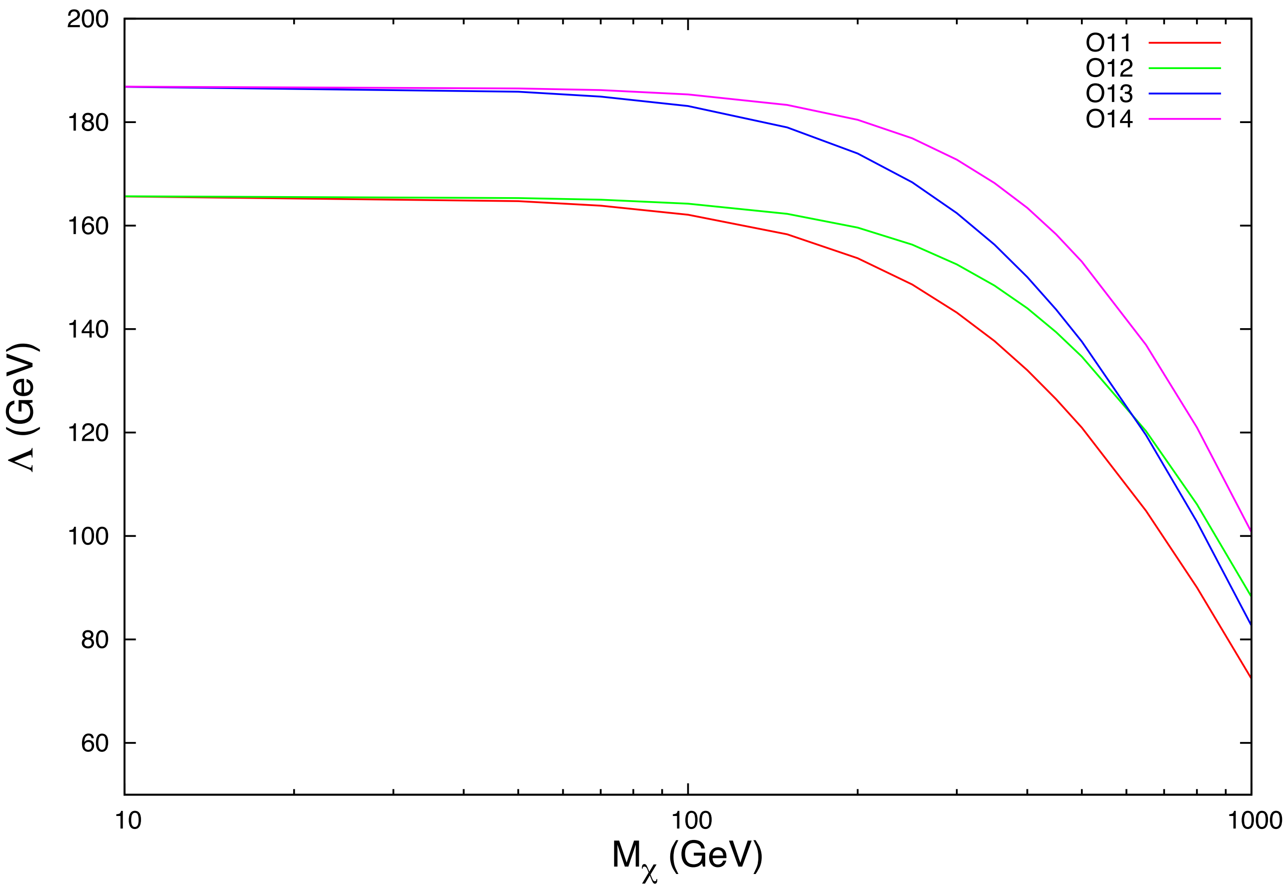
Monojet + Missing ET

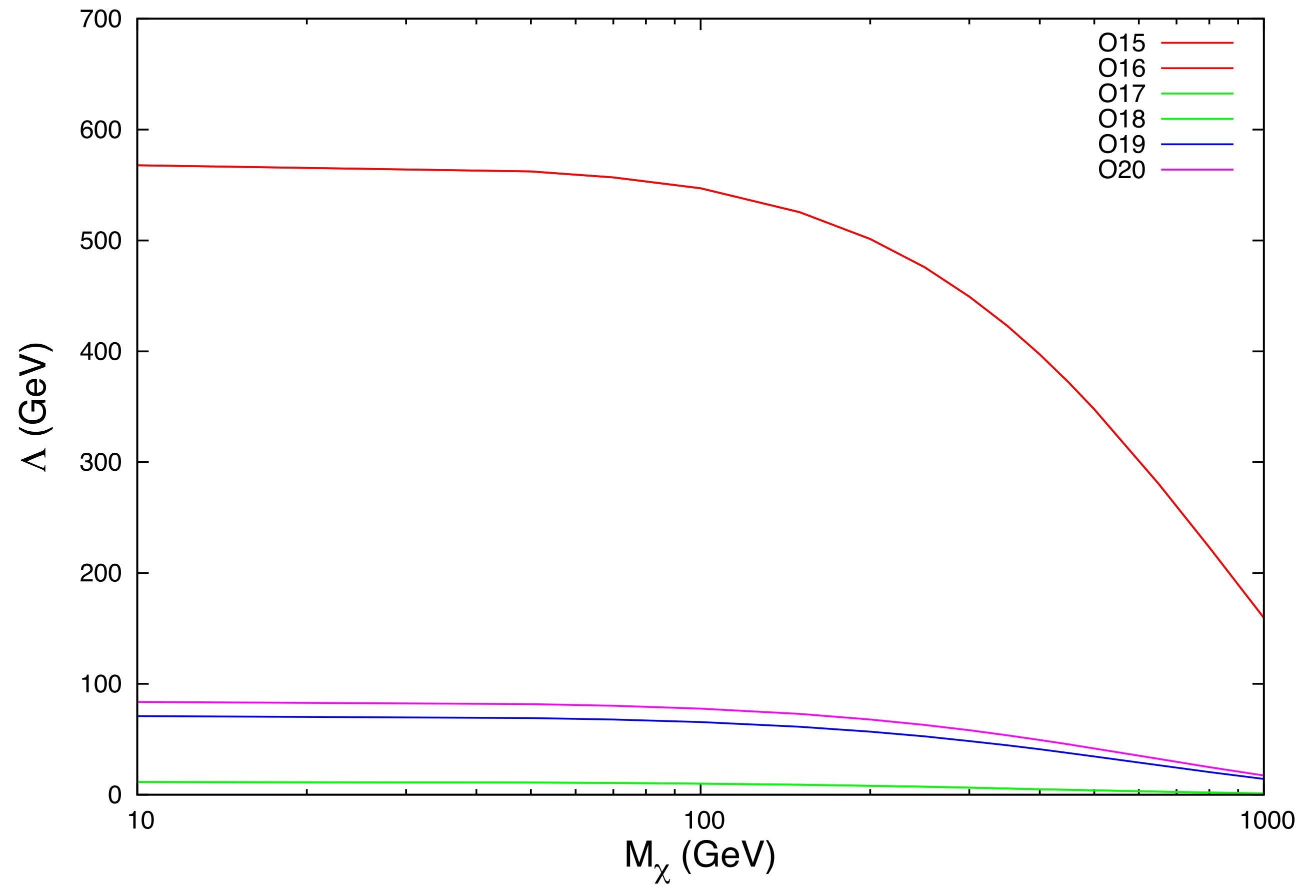


2σ Lower Limits for Λ From Mono-jet/photon









Global Fittings

- WMAP relic density can provide upper limits on Λ
- Direct detection, indirect detection and collider mono-photon/jet can provide lower limits on Λ
- Global fittings by combing all experiments can provide both upper and lower limits on Λ
- Idea works for any explicit model of dark matter too

Combining χ^2

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

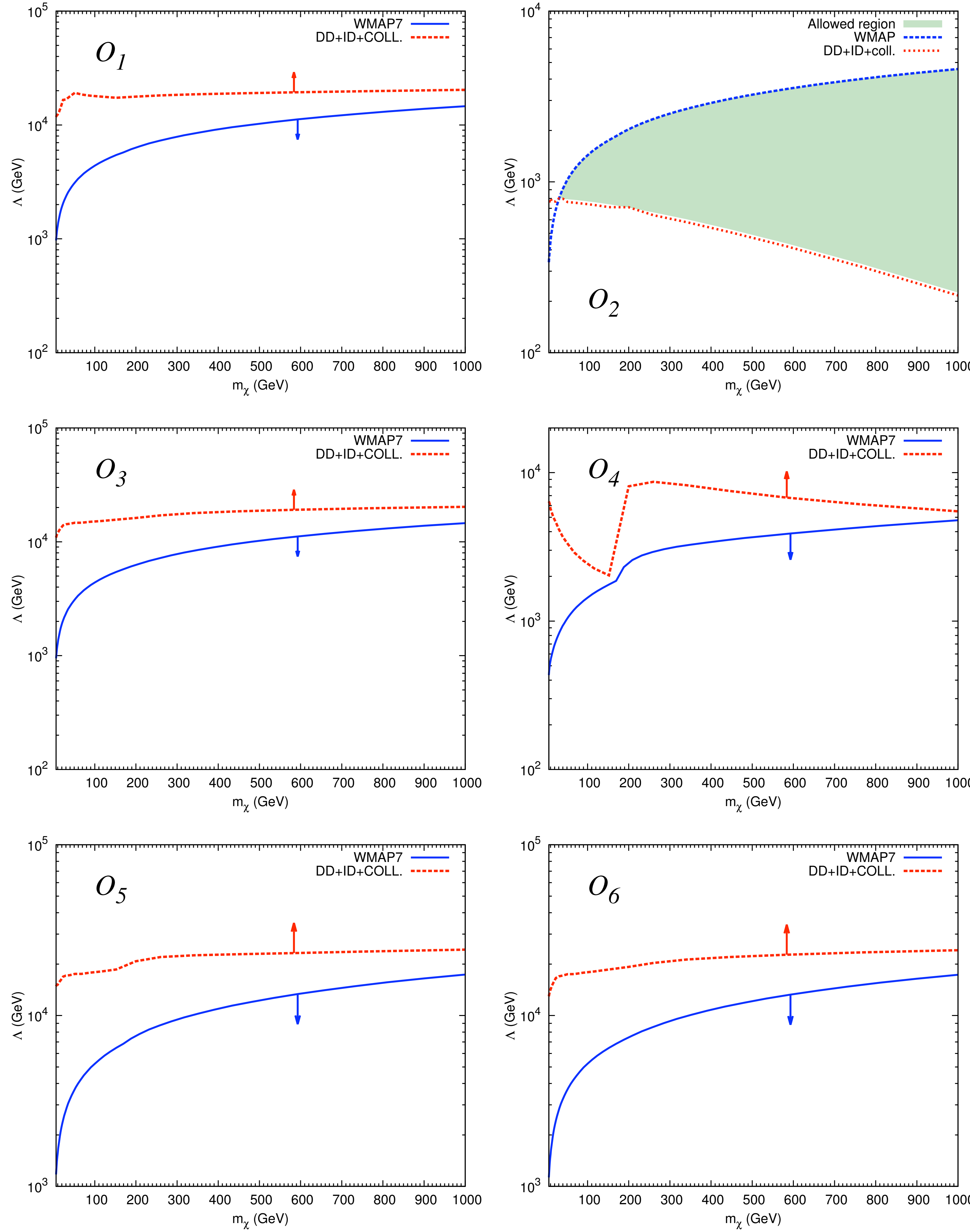
- For mixed m_χ, varying Λ^2 for each operator until

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

- WMAP constrains Λ from above.

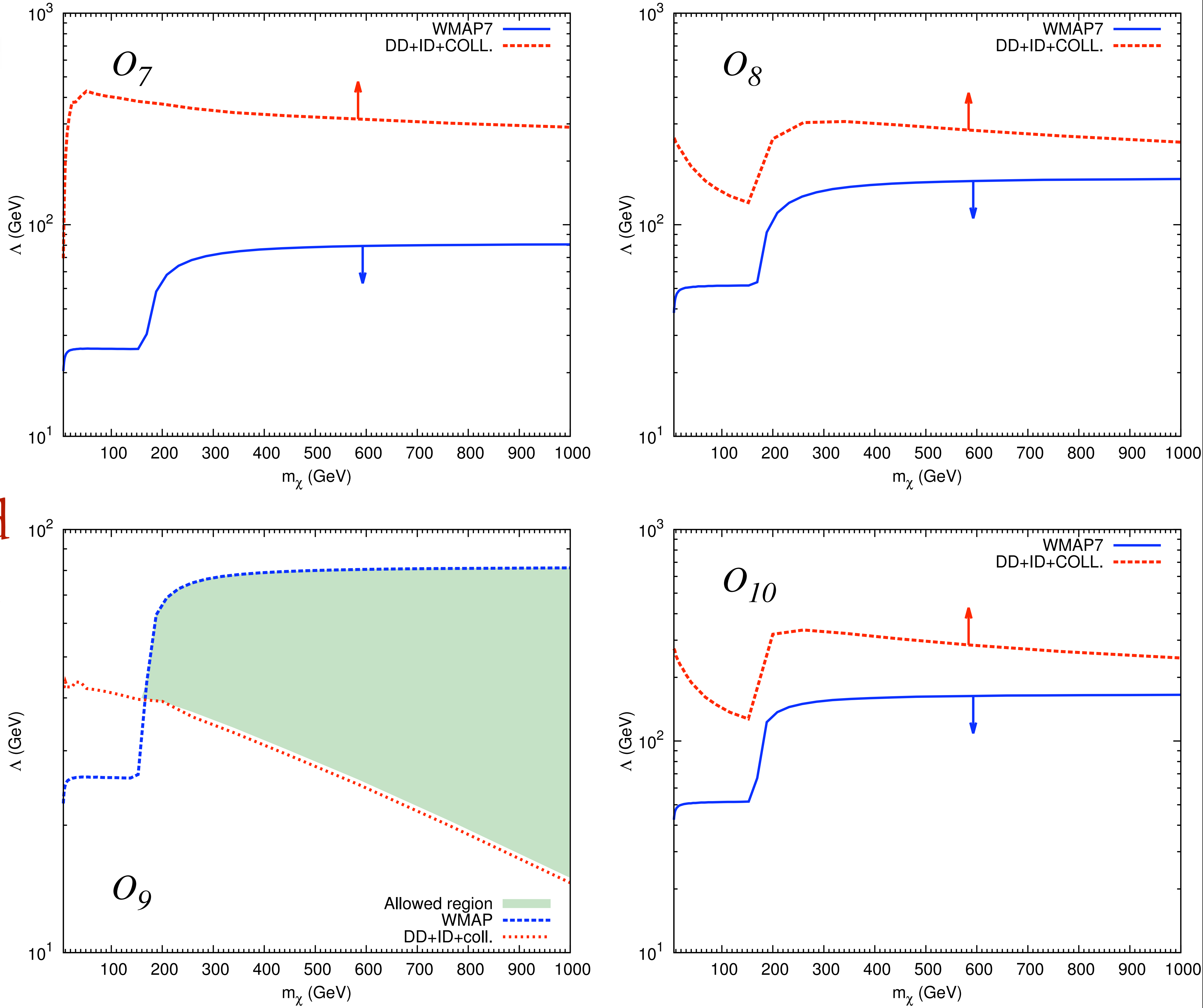
Fermionic DM

- Arrow direction is allowed region
- Only O_2 has allowed region from global fittings
- Other operators have lower limits higher than upper limits



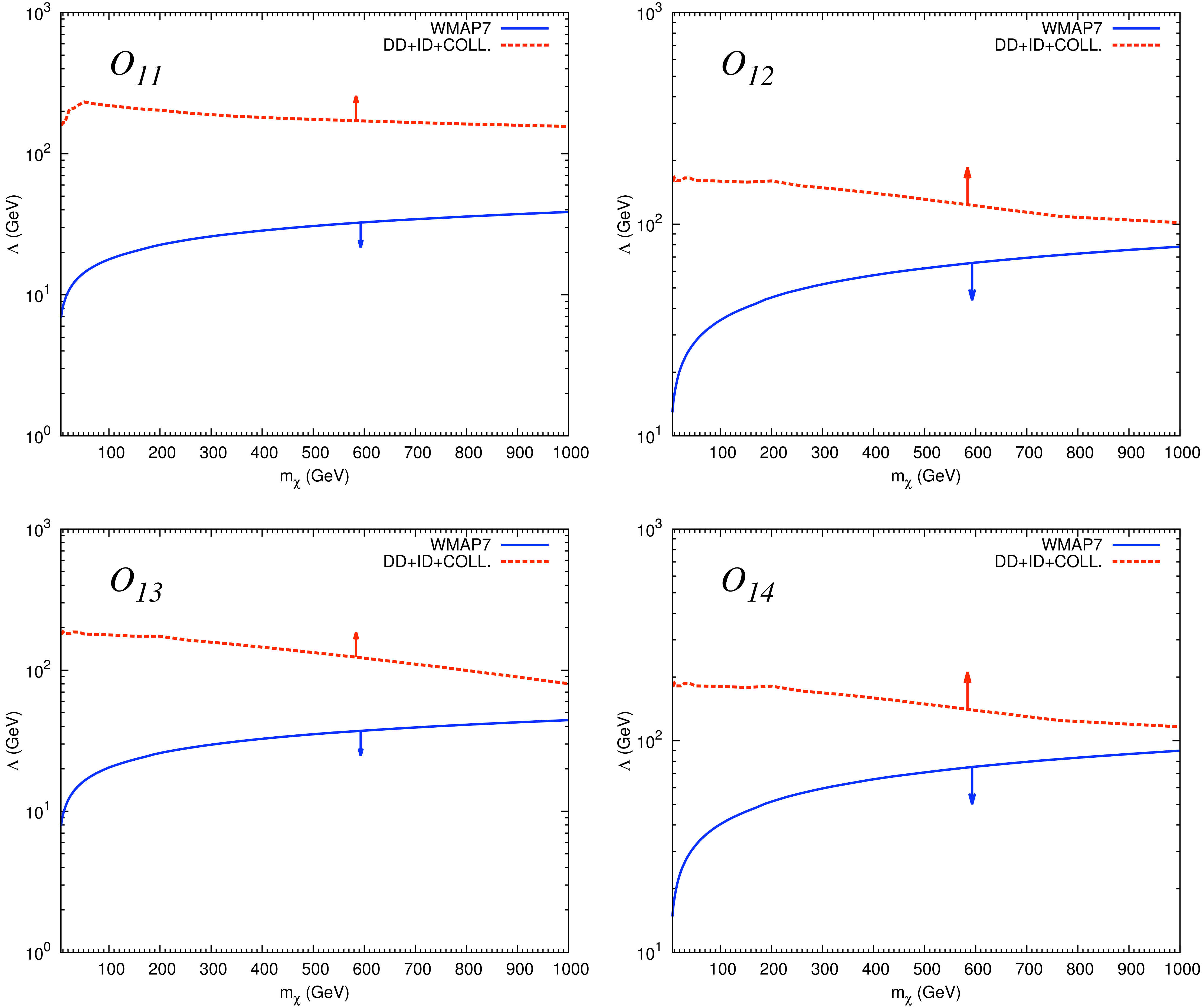
Fermionic DM (cont.)

- Only O9 has allowed regions from global fittings



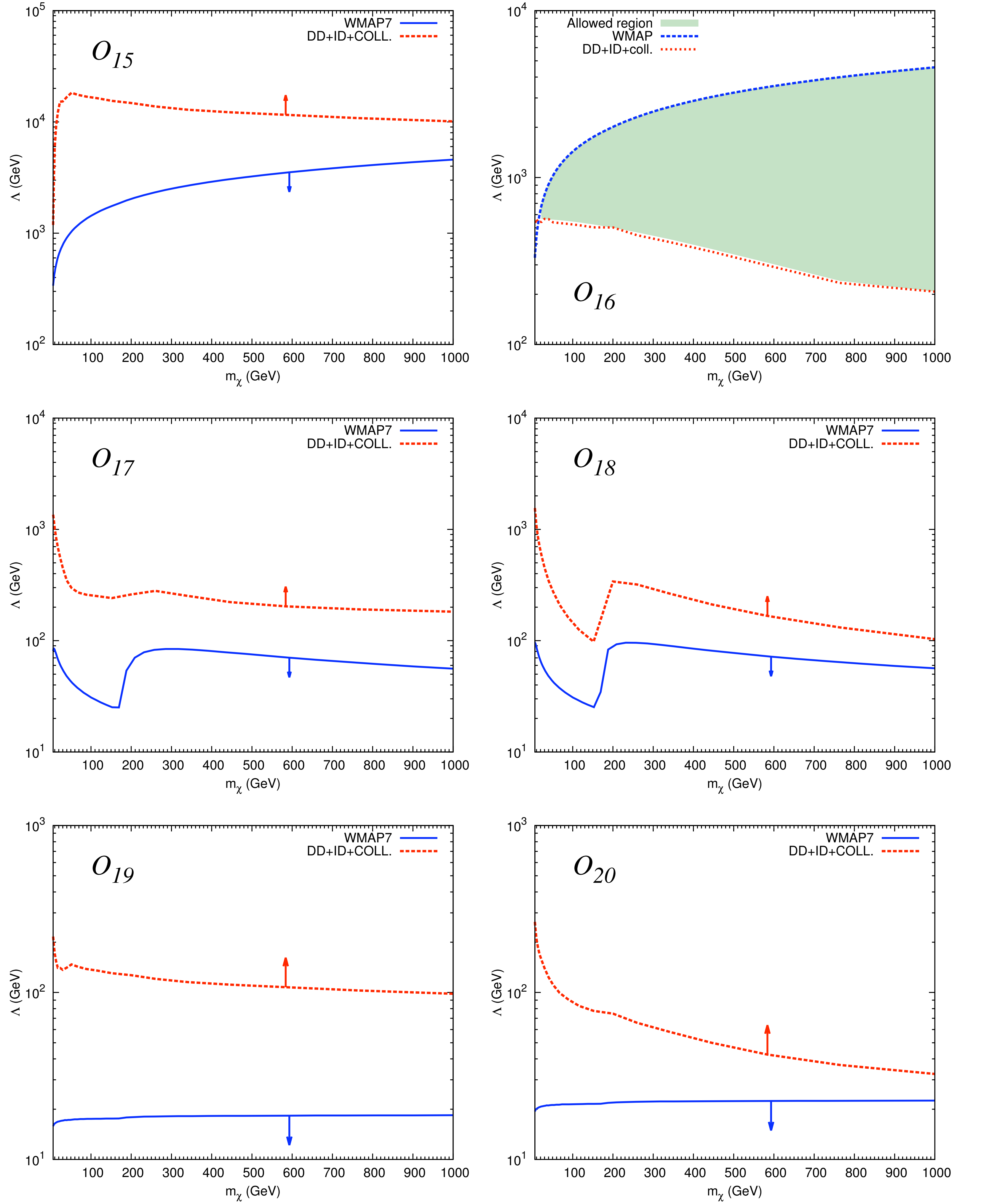
Fermionic DM (Gluonic Operators)

- No allowed regions are found



Scalar DM

- Only O_{16} has allowed region from global fittings



Summary

- No evidence of DM from particle physics yet!
- All evidences are from heaven so far! (I know. We can't ignore DAMA/LIBRA and CoGeNT yet.)
- Particle DM is definitely needed at various scales (1) largest cosmological scales (WMAP), (2) galaxy cluster scales (Coma Cluster), (3) dwarf galaxies, (4) Bullet Clusters, ...
- Three important complementary particle DM probes: direct detection, indirect detection, and collider.
- No lack of theoretical ideas for particle DM candidates. Popular model like MSSM is highly constrained now.
- Effective DM interaction -- model independent approach but has limitations.
- Combing results from different experiments provide important constraints on DM models or effective interactions.
- We live in exciting time!! Stay tuned for new results from LHC8 and AMS-02.

References

1. China group:
   Q.H. Cao, C.R. Chen, C.S. Li, H. Zhang (JHEP, 0912.4511)
   Zheng, Yu, Shao, Bi, Li, Zhang (NPB, 1012.2022)
   Wang, C.S. Li, Shao, Zhang (1107.2048)
2. Fermilab group:
   Y. Bai, P.J. Fox, R. Harnik (JHEP, 1005.3797)
   Fox, Harnik, Kopp, Tsai (PRD, 1103.0240)
   Fox, Harnik, Kopp, Tsai (1109.4398)
3. UC-Urvine group:
   Goodman, Ibe, Rajaraman, Shepherd, Tait, YU (PLB, 1005.1286)
   Goodman, Ibe, Rajaraman, Shepherd, Tait, YU (PRD, 1008.1783)
   Goodman, Ibe, Rajaraman, Shepherd, Tait, YU (NPB, 1009.0008)
   Rajaraman, Shepherd, Tait, Wijangro (1108.1196)
4. Taiwan group:
   KC, Song, P.Y. Tseng (JCAP, 1007.0282)
   KC, Mawatari, Senaha, Tseng, TC Yuan (JHEP, 1009.0618)
   KC, P.Y. Tseng, TC Yuan (JCAP, 1011.2310)
   KC, P.Y. Tseng, TC Yuan (JCAP, 1104.5329)
   KC, P.Y. Tseng, Tsai, TC Yuan (JCAP, 2012)

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