Dark Matter Annihilation into Fermions and a Photon

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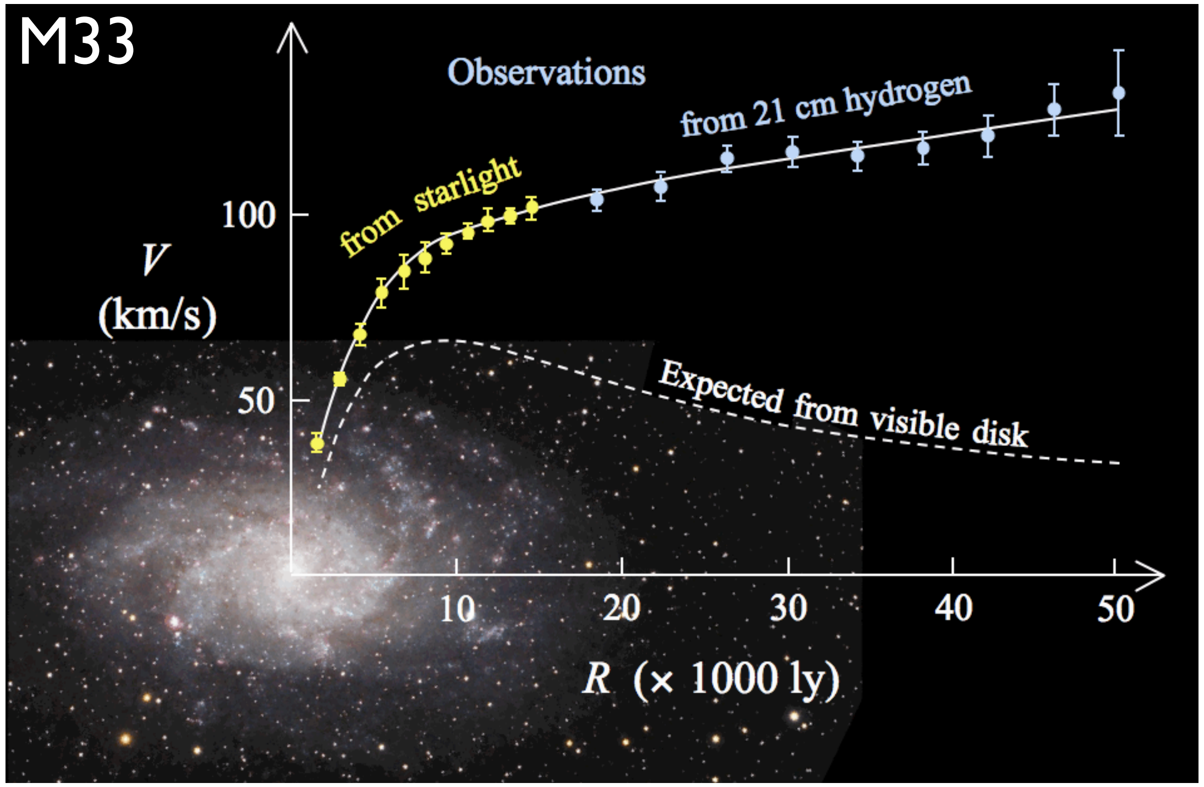
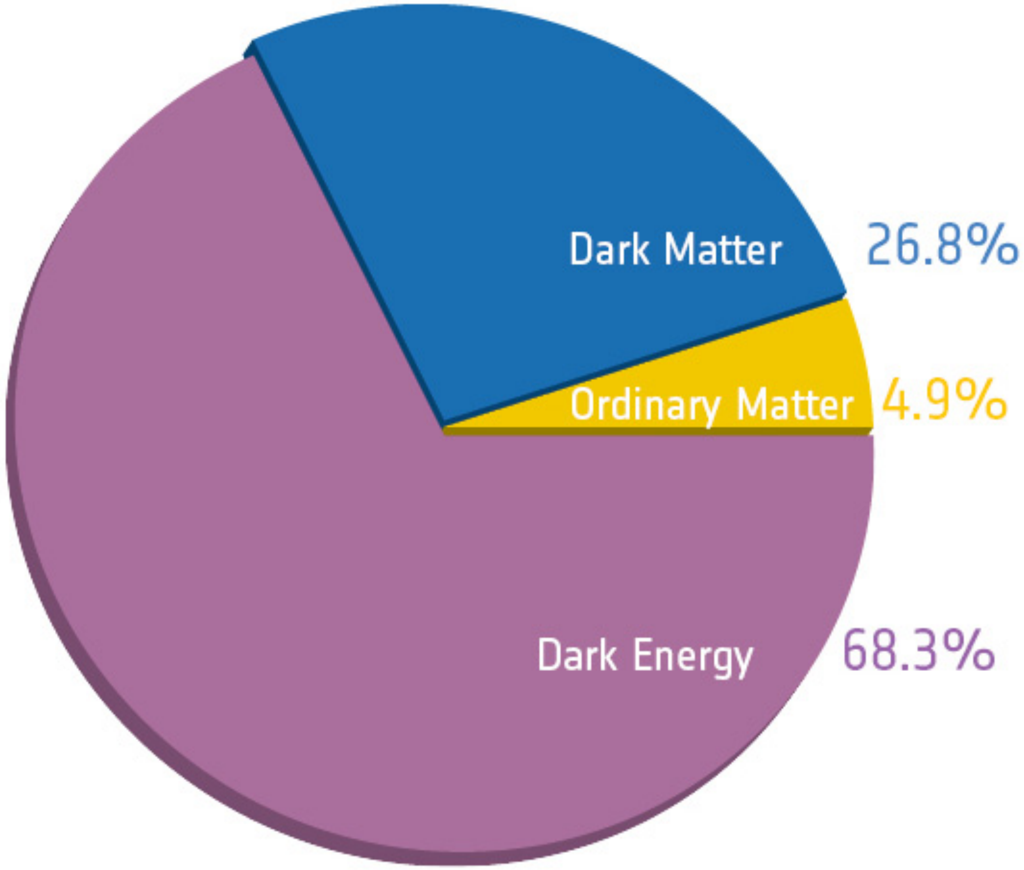
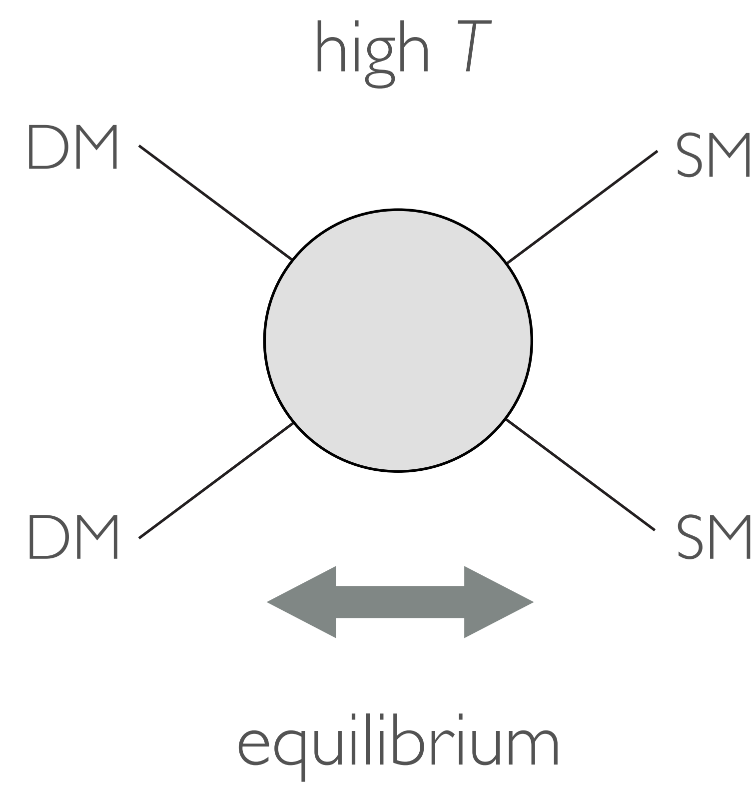
Evidence of Dark Matter

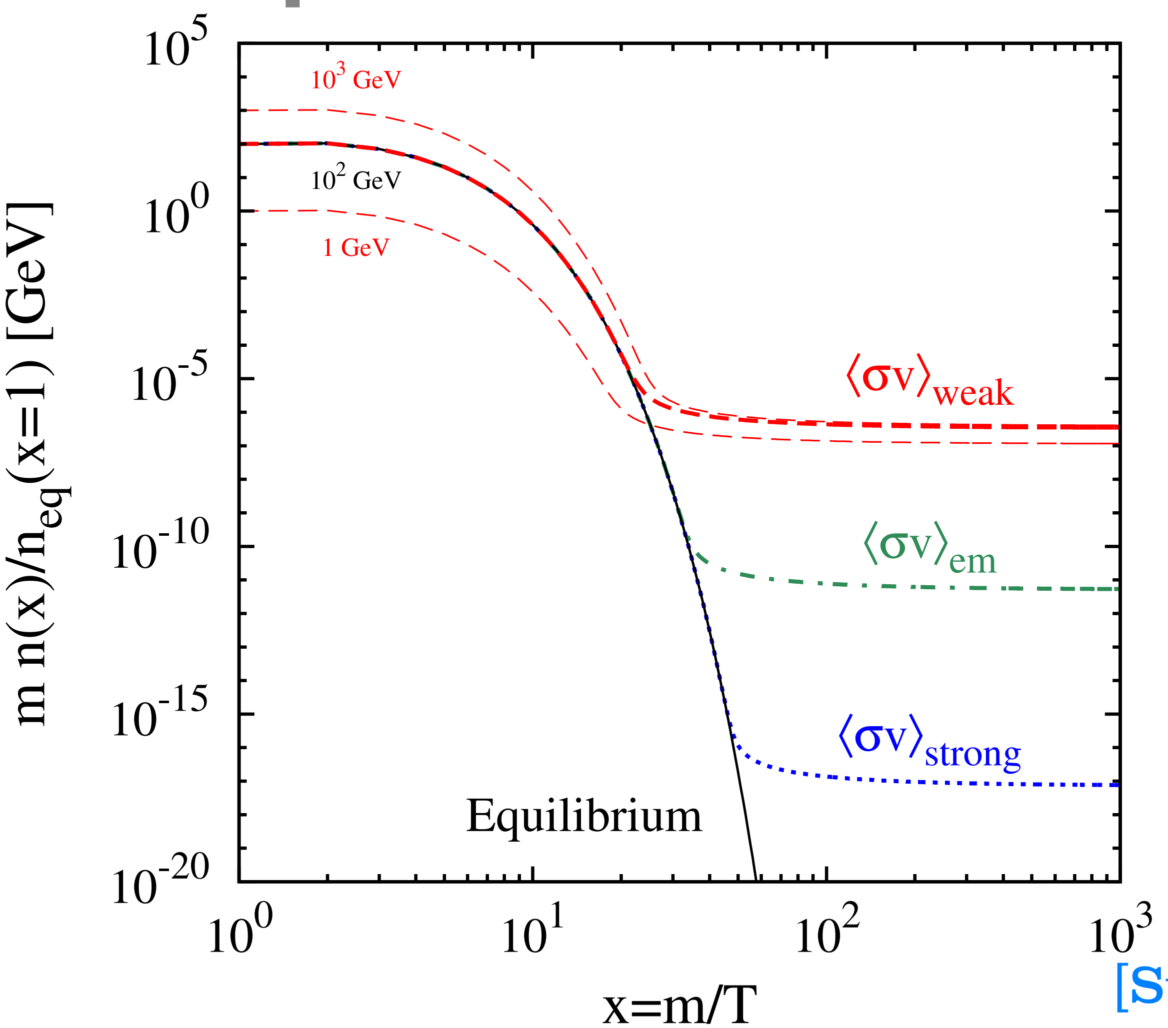




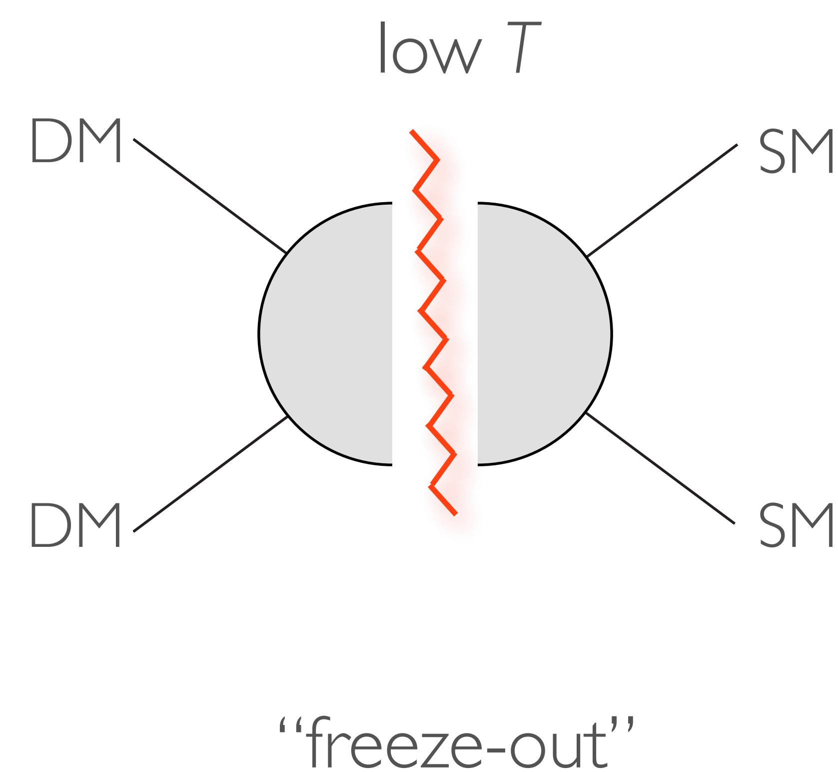
Thermal Relic

* In early Universe DM DM $\Leftrightarrow$ SM SM.
* Universe cools down DM DM $\Rightarrow$ SM SM.
* After further cooling, the interactions stop. DM **"freezes out"**.





$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$



[Steigman, Dasgupta, Beacom '12]

Dark Matter Detection

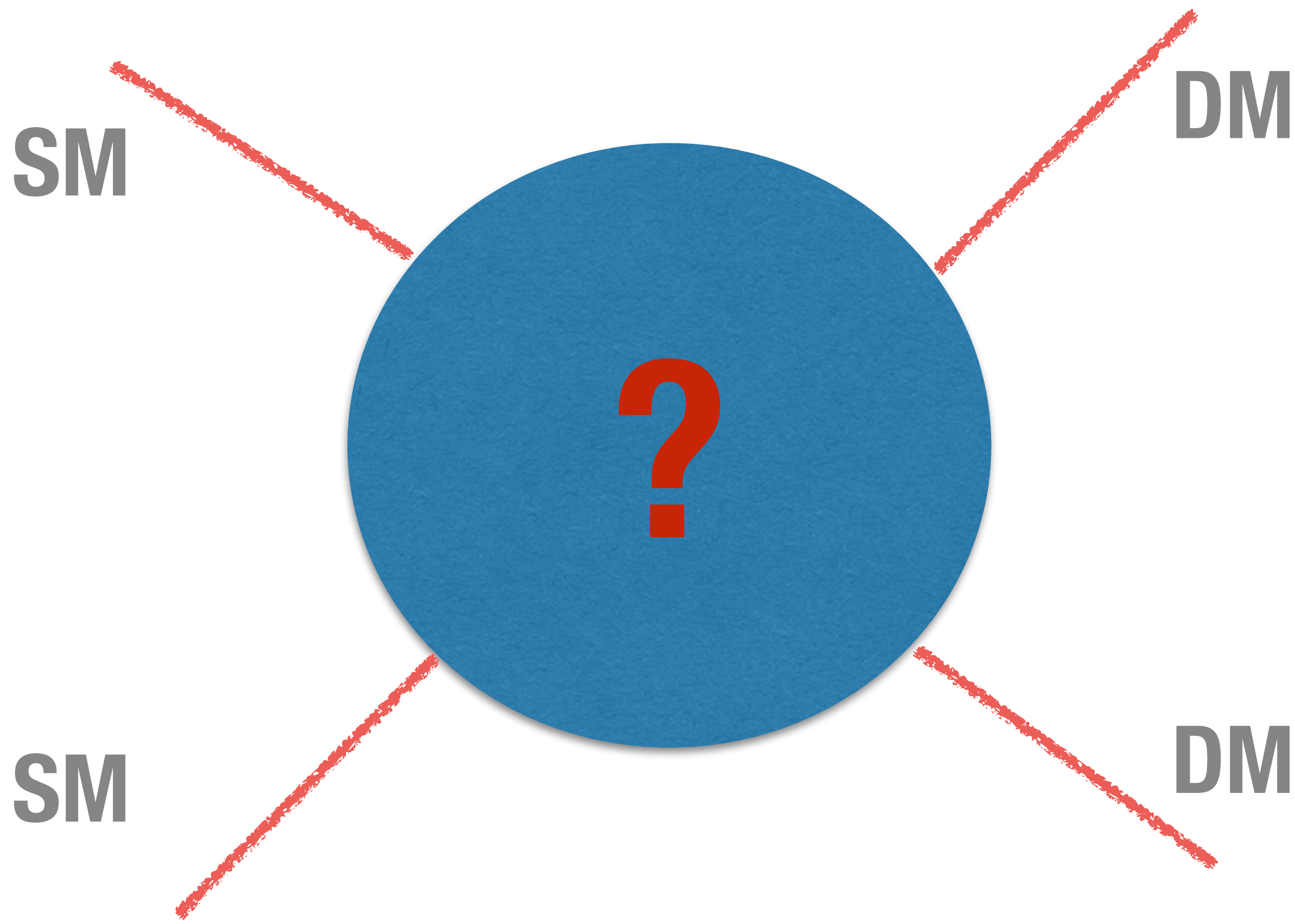
Indirect Detection

AMS-02

Fermi Gamma-ray Space Telescope

IceCube South Pole Neutrino Observatory

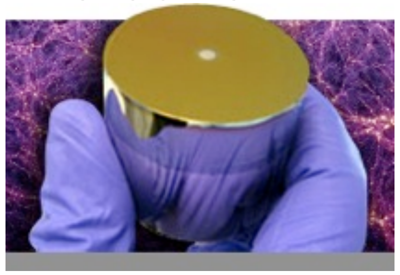
PaMeLa



Dama

LIBRA in DAMA

Direct Detection



Xe XENON Dark Matter Project

Compact Muon Solenoid experiment at CERN's LHC

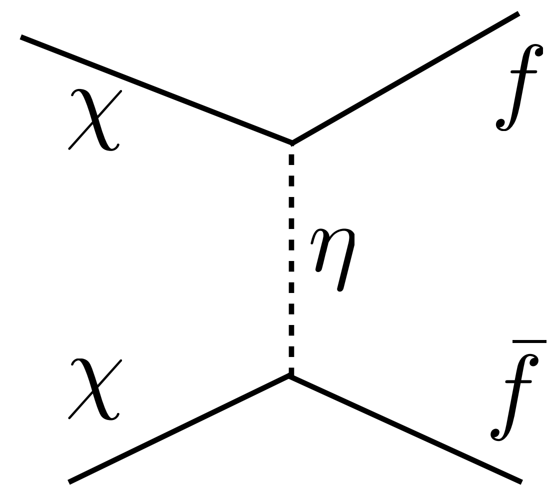
CMS

Collider

ATLAS EXPERIMENT

DM Annihilation into Fermions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\chi + \mathcal{L}_\eta + \mathcal{L}_{\rm int}$$



$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/ \chi - \frac{1}{2} m_\chi \bar{\chi}^c \chi \,,$$

$$\mathcal{L}_\eta = (D_\mu \eta)^\dagger (D^\mu \eta) - m_\eta^2 \eta^\dagger \eta$$

$$\mathcal{L}_{\rm int} = -y \bar{\chi} \Psi_R \eta + \text{h.c.}$$

$$\langle \sigma v \rangle = a + b v^2 + \mathcal{O}(v^4)$$

$$\mu \equiv (m_\eta / m_\chi)^2$$

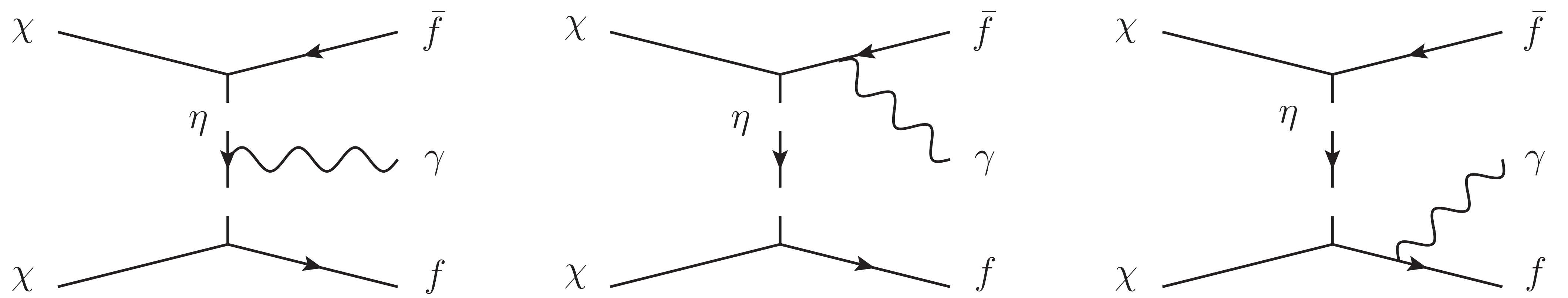
$$(\sigma v)^{s\text{-wave}}_{\text{2-body}} = \frac{y^4 N_c}{32\pi m_\chi^2} \frac{m_f^2}{m_\chi^2} \frac{1}{(1+\mu)^2}$$

$$(\sigma v)^{p\text{-wave}}_{\text{2-body}} = v^2 \frac{y^4 N_c}{48\pi m_\chi^2} \frac{1+\mu^2}{(1+\mu)^4}$$

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

[Bergstrom ’89, ...]

Virtual Internal Bremsstrahlung



$$(\sigma v)_{\text{3-body}} \simeq \frac{\alpha_{\text{em}} y^4 N_c Q_f^2}{64\pi^2 m_\chi^2} \left\{ (\mu+1) \left[\frac{\pi^2}{6} - \ln^2\left(\frac{\mu+1}{2\mu}\right) - 2\text{Li}_2\left(\frac{\mu+1}{2\mu}\right) \right] + \frac{4\mu+3}{\mu+1} + \frac{4\mu^2-3\mu-1}{2\mu} \ln\left(\frac{\mu-1}{\mu+1}\right) \right\}$$

VIB lifts the helicity suppression of DM annihilation into pair of fermions

[Bergstrom '89, ...]

VIB in Supersymmetry

Admixture of Bino/Wino/Higgsinos:

$$\chi = \alpha \widetilde{B} + \beta \widetilde{W} + \gamma \widetilde{H}_d + \delta \widetilde{H}_u$$

$\mathrm{SU}(2)_L$ *singlet* *triplet* *doublets*

$$\mathcal{L}_{\mathrm{int}}^{\chi \tilde{f} f} = y_L \bar{\chi} f_L \tilde{f}_L + y_R \bar{\chi} f_R \tilde{f}_R + \mathrm{h.c.}$$

$$y_R = \sqrt{2} Q_f g \tan\theta_{\mathrm{W}} N_{11} \qquad y_L = -\frac{2Q_f \mp 1}{\sqrt{2}} g \tan\theta_{\mathrm{W}} N_{11} \mp \frac{g}{\sqrt{2}} N_{12}$$

VIB in Effective Operator Model

$$\mathcal{L}_{\rm d=6} = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$\mathcal{L}_{\rm d=8} = \frac{1}{\Lambda^4}(\bar{\chi}\gamma^5\gamma^\mu\chi)\left[\left(\bar{f}_L\overleftarrow{D_\rho}\right)\gamma_\mu\left(\overrightarrow{D^\rho}f_L\right) + \left(\bar{f}_R\overleftarrow{D_\rho}\right)\gamma_\mu\left(\overrightarrow{D^\rho}f_R\right)\right]$$

$$\bar{f}_L\overleftarrow{D}_\mu = (\partial_\mu\bar{f}_L) - ig\frac{\sigma^i}{2}W^i_\mu\bar{f}_L - ig'Y_f B_\mu\bar{f}_L\,,$$

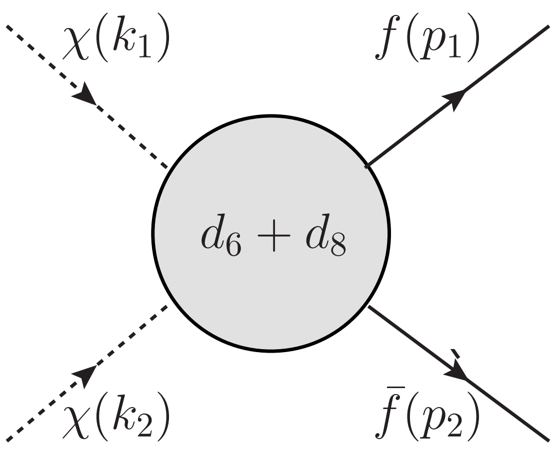
$$\overrightarrow{D}_\mu f_L = (\partial_\mu f_L) + ig\frac{\sigma^i}{2}W^i_\mu f_L + ig'Y_f B_\mu f_L\,,$$

$$\bar{f}_R\overleftarrow{D}_\mu = (\partial_\mu\bar{f}_R) - ig'Y_f B_\mu\bar{f}_R\,,$$

$$\overrightarrow{D}_\mu f_R = (\partial_\mu f_R) + ig'Y_f B_\mu f_R\,,$$

$$\mathcal{L} = d_6\,\mathcal{L}_{\rm d=6} + d_8\,\mathcal{L}_{\rm d=8}$$

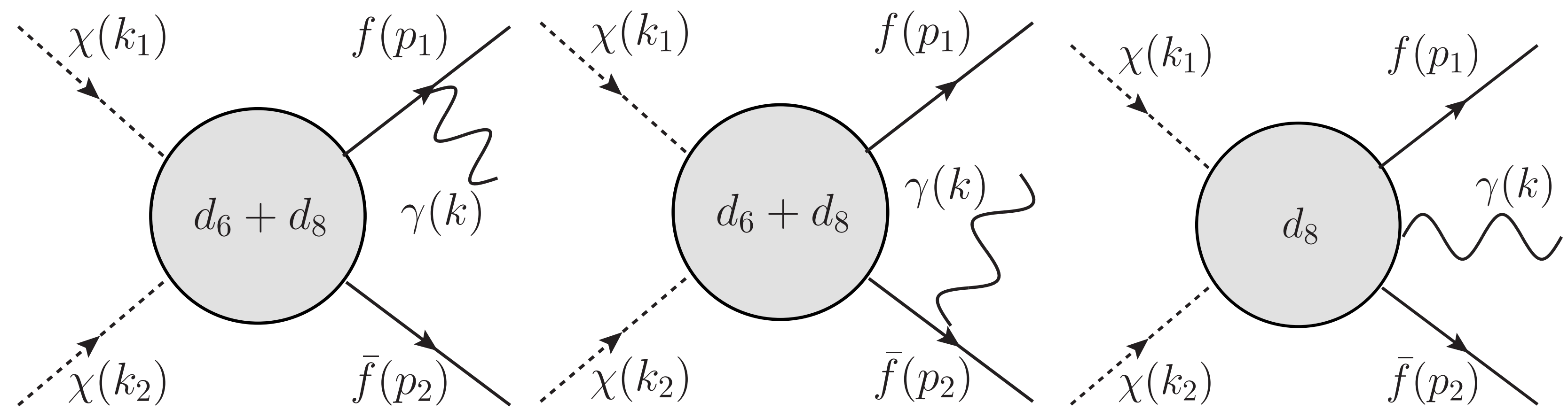
$\chi\chi \to f\bar{f}$



$$\mathcal{L} = \frac{d_6}{\Lambda^2}(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{f}\gamma_\mu f) + \frac{d_8}{\Lambda^4}(\bar{\chi}\gamma^5\gamma^\nu\chi)\Big[(\partial_\rho\bar{f})\,\gamma_\nu\,(\partial^\rho f)\Big]$$

$$\sigma v = \frac{v^2}{3\pi\Lambda^8}\sqrt{1-\frac{m_f^2}{m_\chi^2}}\,(2m_\chi^2+m_f^2)\Big\{|d_6|^2\Lambda^4 + |d_8|^2(2m_\chi^2+m_f^2)^2 - \Lambda^2(d_6 d_8^* + d_6^* d_8)(2m_\chi^2 - m_f^2)\Big\}$$

$\chi\chi \to f\bar{f}\gamma$

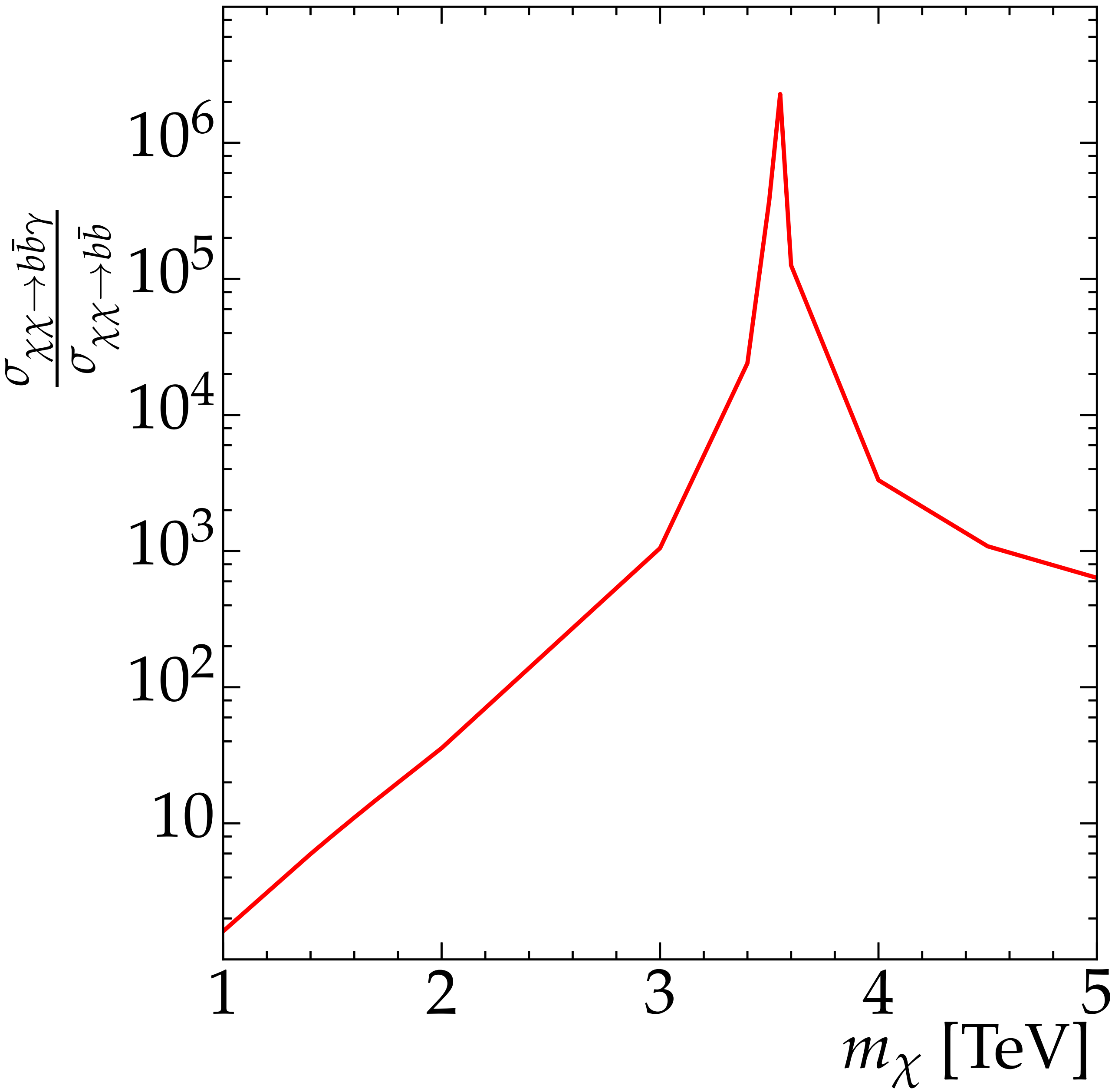


$$\mathcal{L}_{\rm eff} = \frac{d_6}{\Lambda^2}(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{f}\gamma_\mu f) + \frac{d_8}{\Lambda^4}(\bar{\chi}\gamma^5\gamma^\nu\chi)\Big[(\partial_\rho\bar{f})\gamma_\nu(\partial^\rho f) + i\,e\,Q\,A_\rho\Big\{(\partial^\rho\bar{f})\gamma_\nu f - \bar{f}\gamma_\nu(\partial^\rho f)\Big\}\Big]$$

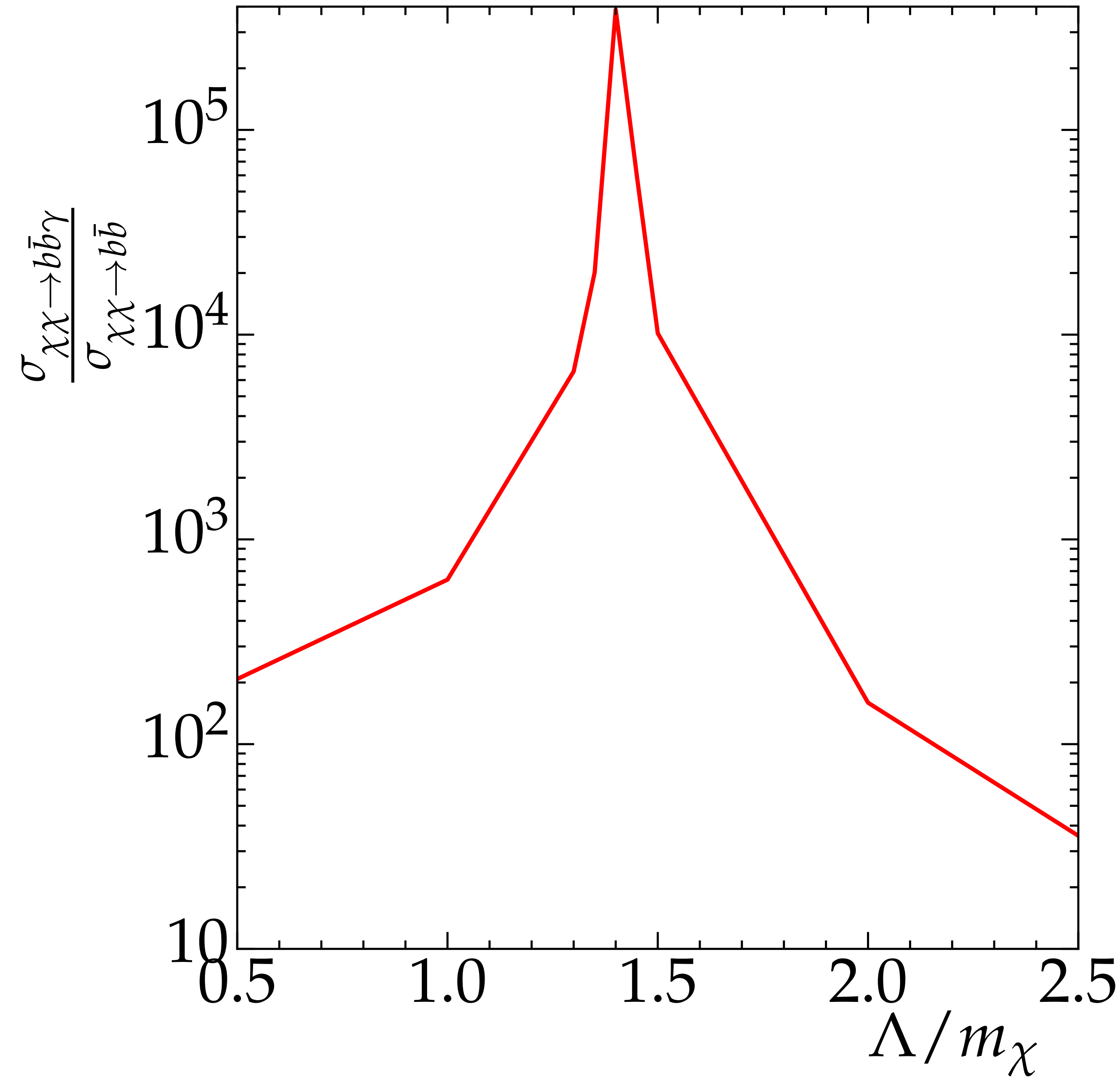
$$\mathcal{M} = -i\,eQ\,\bar{u}(k_1)\gamma^5\gamma^\mu v(k_2)\Bigg[\left(\frac{d_6}{\Lambda^2} - \frac{d_8}{\Lambda^4}\,p_2.(p_1+k)\right)\bar{u}(p_1)\not{\epsilon}(k)\frac{\not{p}_1 + \not{k} + m_f}{(p_1+k)^2 - m_f^2 + i\epsilon}\gamma_\mu v(p_2) + \left(\frac{d_6}{\Lambda^2} - \frac{d_8}{\Lambda^4}\,p_1.(p_2+k)\right)\bar{u}(p_1)\gamma_\mu\frac{-\not{p}_2 - \not{k} + m_f}{(p_2+k)^2 - m_f^2 + i\epsilon}\not{\epsilon}(k)v(p_2) - \frac{d_8}{\Lambda^4}\bar{u}_{p_1}\epsilon_\rho(k)\gamma_\mu v_{p_2}(p_1^\rho - p_2^\rho)\Bigg]$$

Ratio of the cross-sections

$$d_6 = 1, d_8 = 1, v = 10^{-3}$$

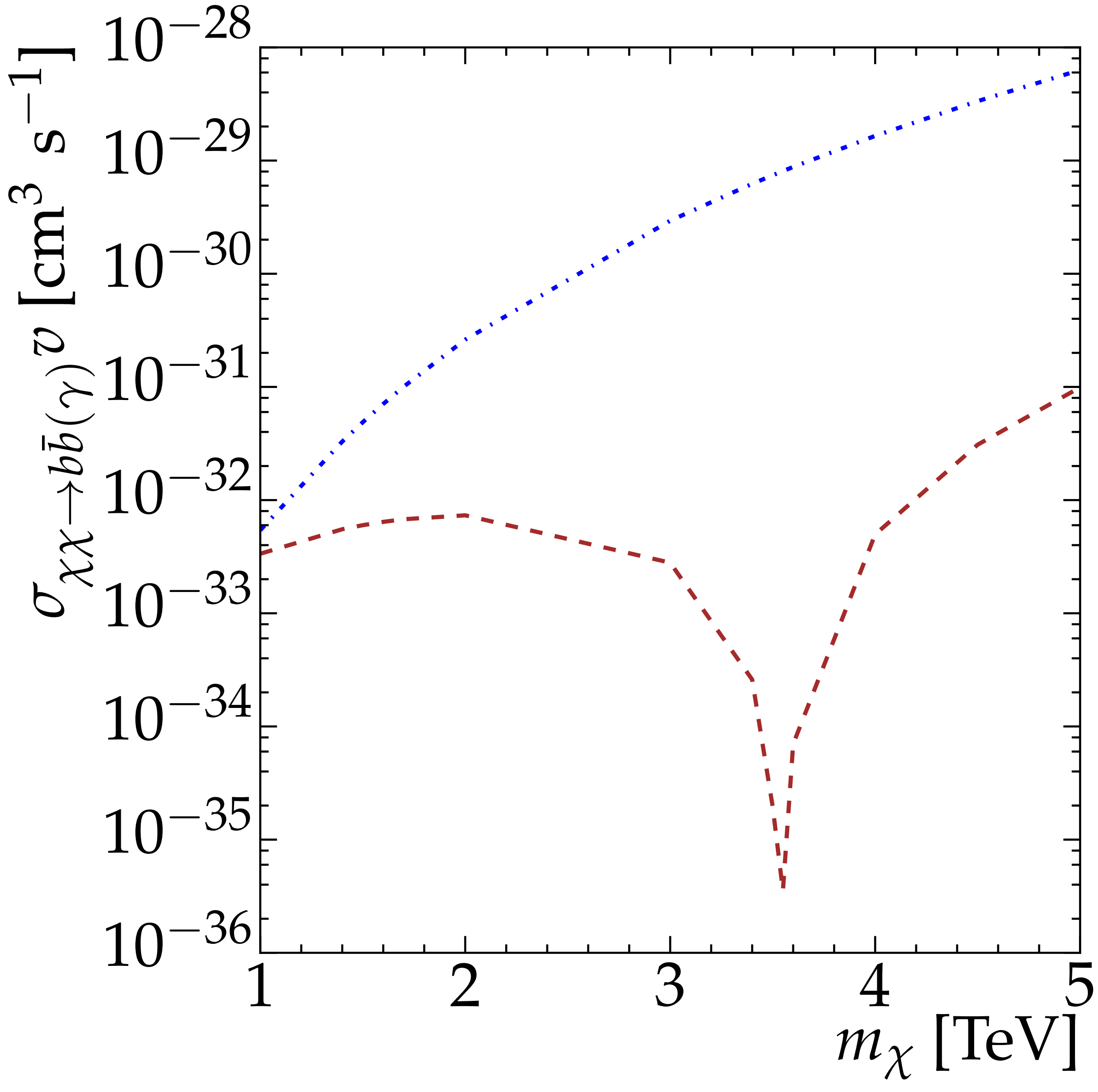


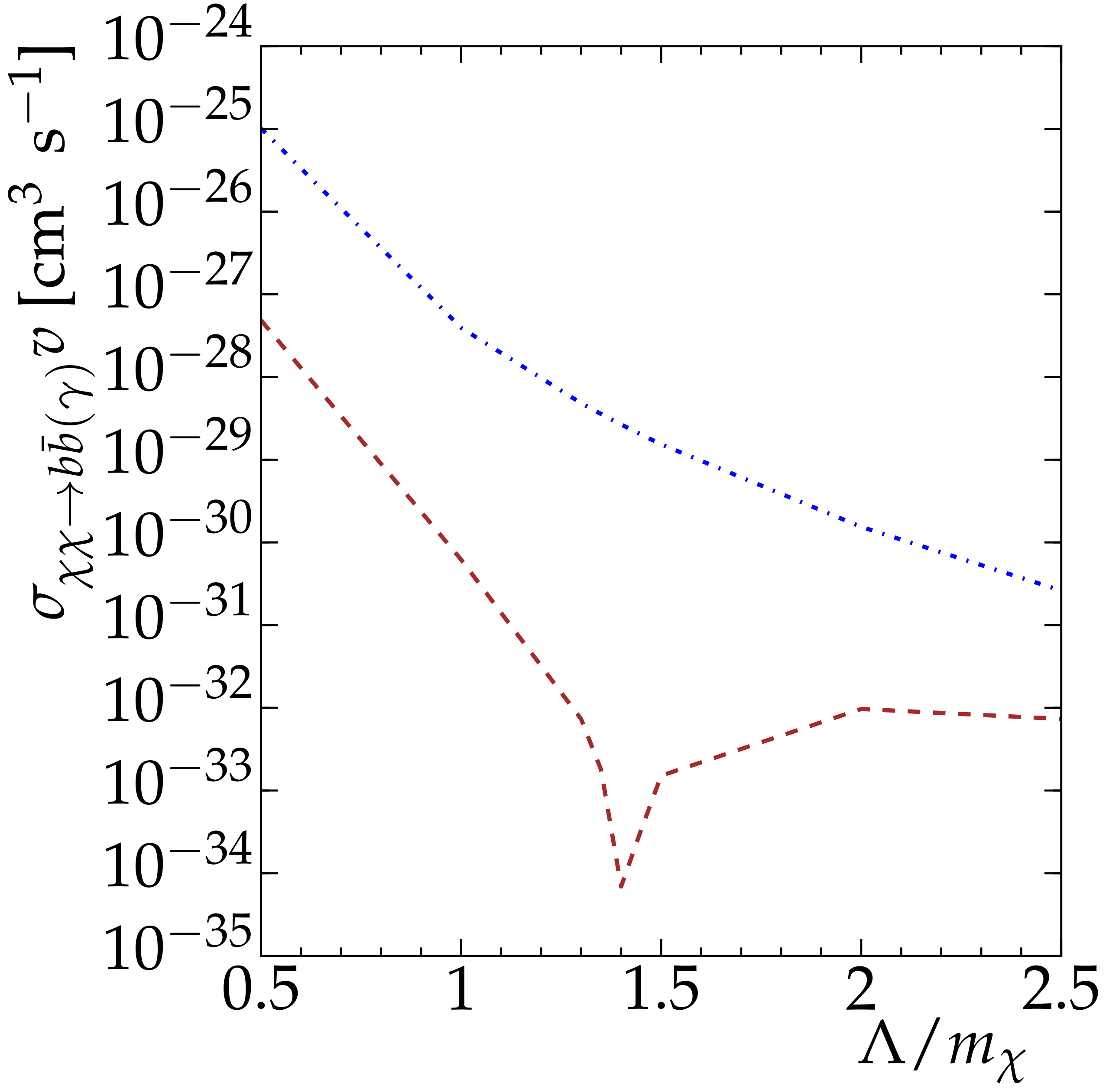
$\Lambda = 5$ TeV



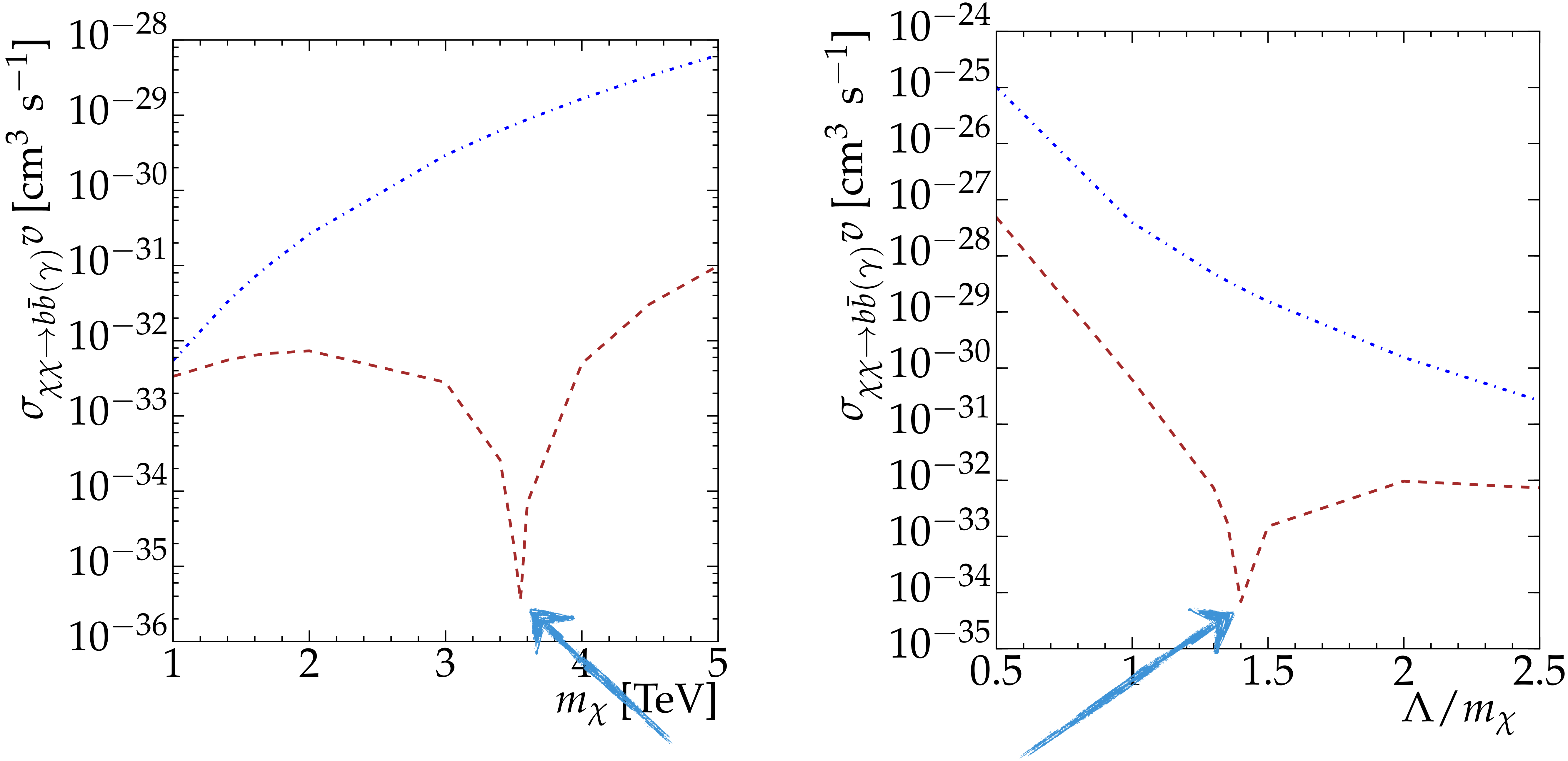
$m_\chi = 2$ TeV

Ratio of the cross-sections





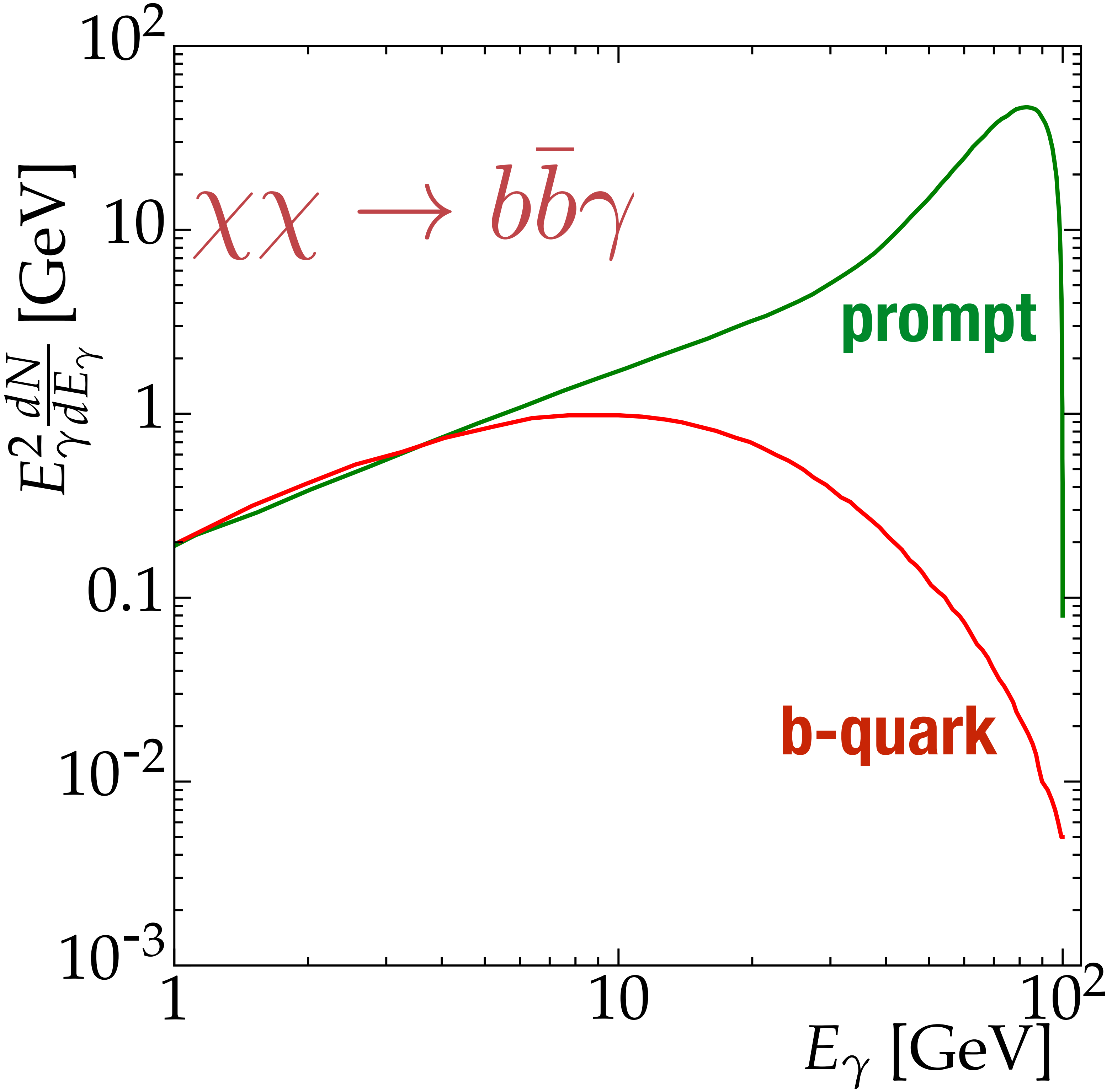
Ratio of the cross-sections



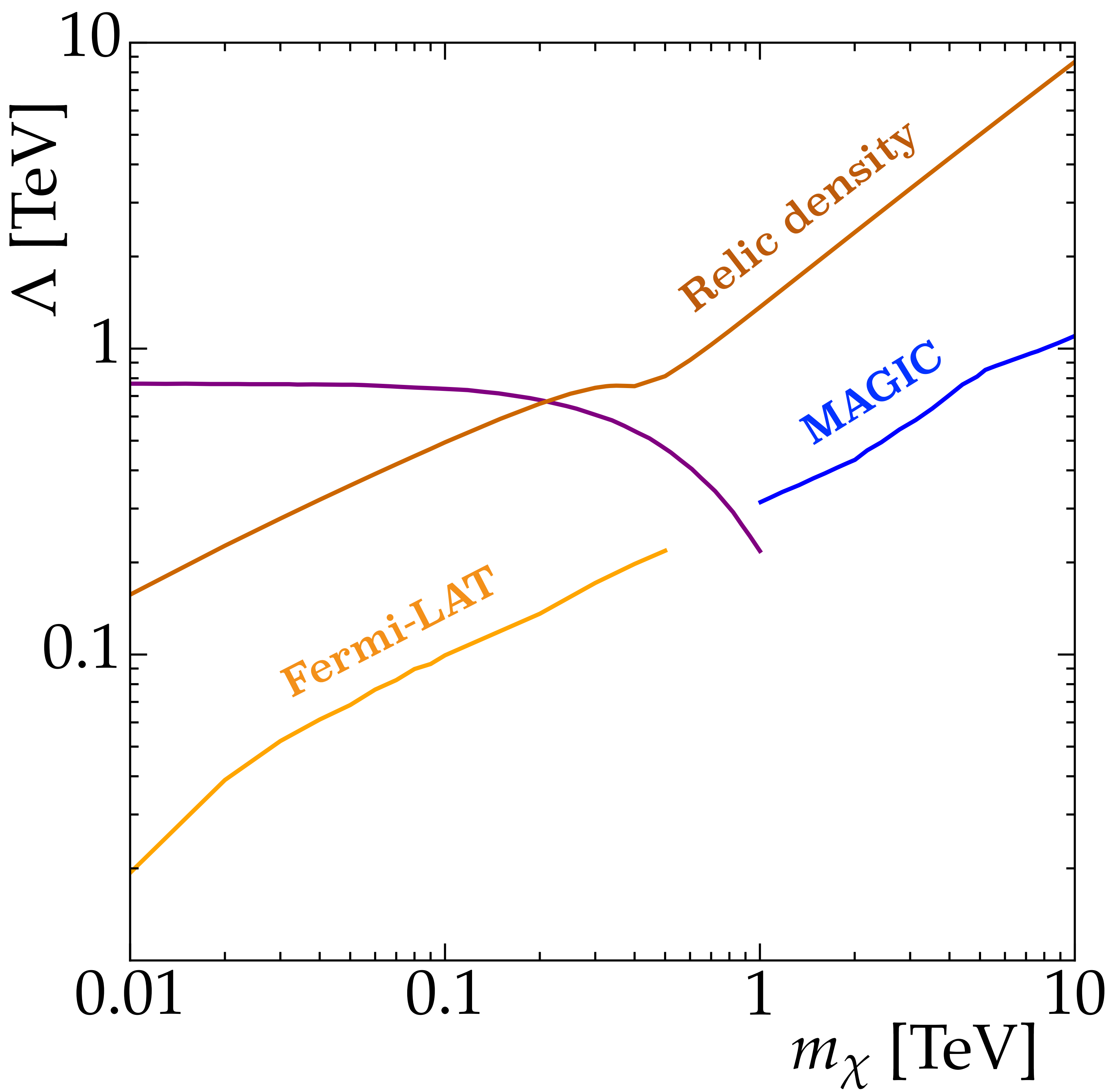
$\Lambda/m_\chi \simeq 1.4$

Photon Energy Spectrum

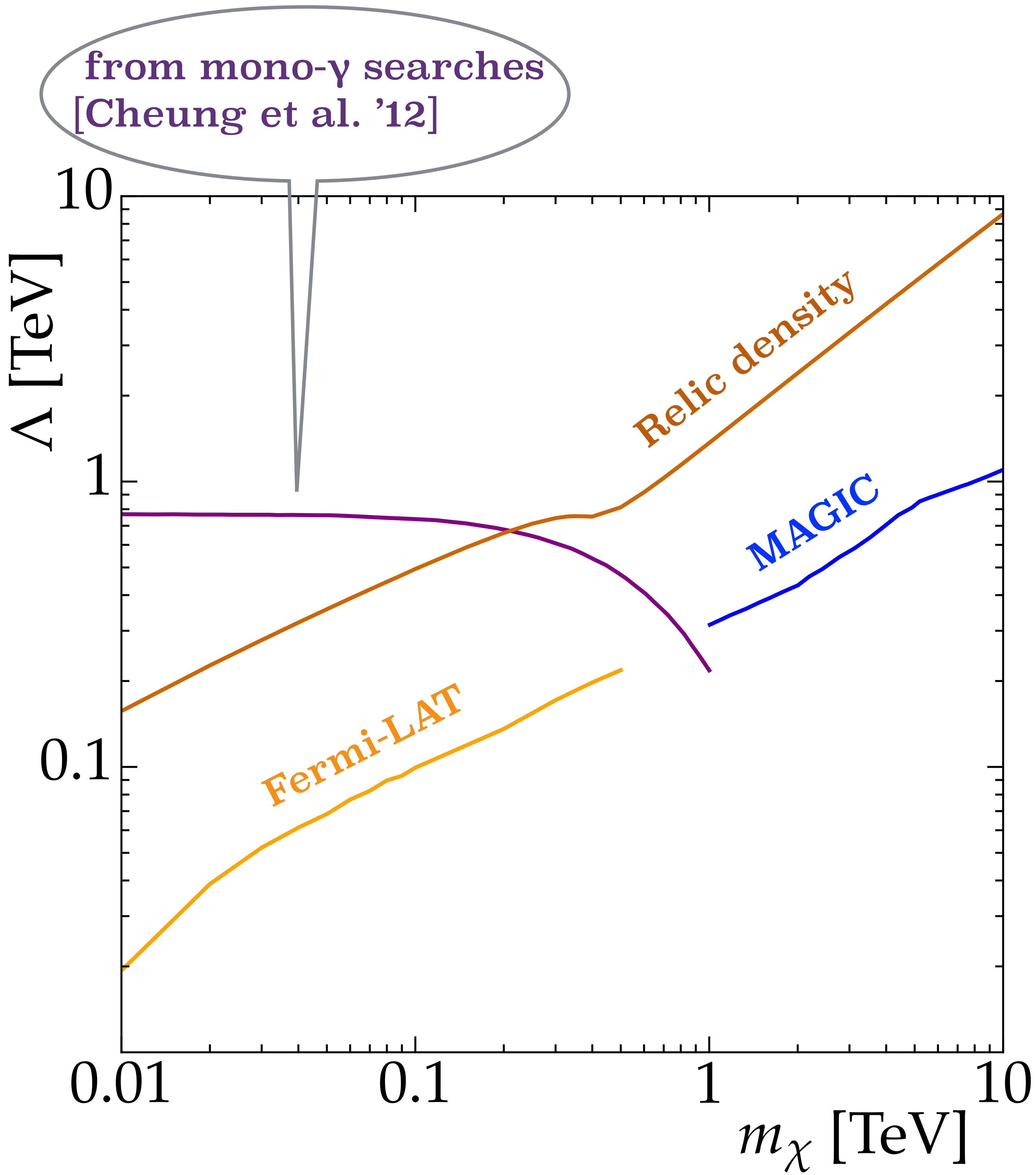
$d_6 = 1$, $d_8 = 1$, $v = 10^{-3}$, $M_{DM} = 100$ GeV, $\Lambda = 1$ TeV



Bound on effective operator scale



Bound on effective operator scale



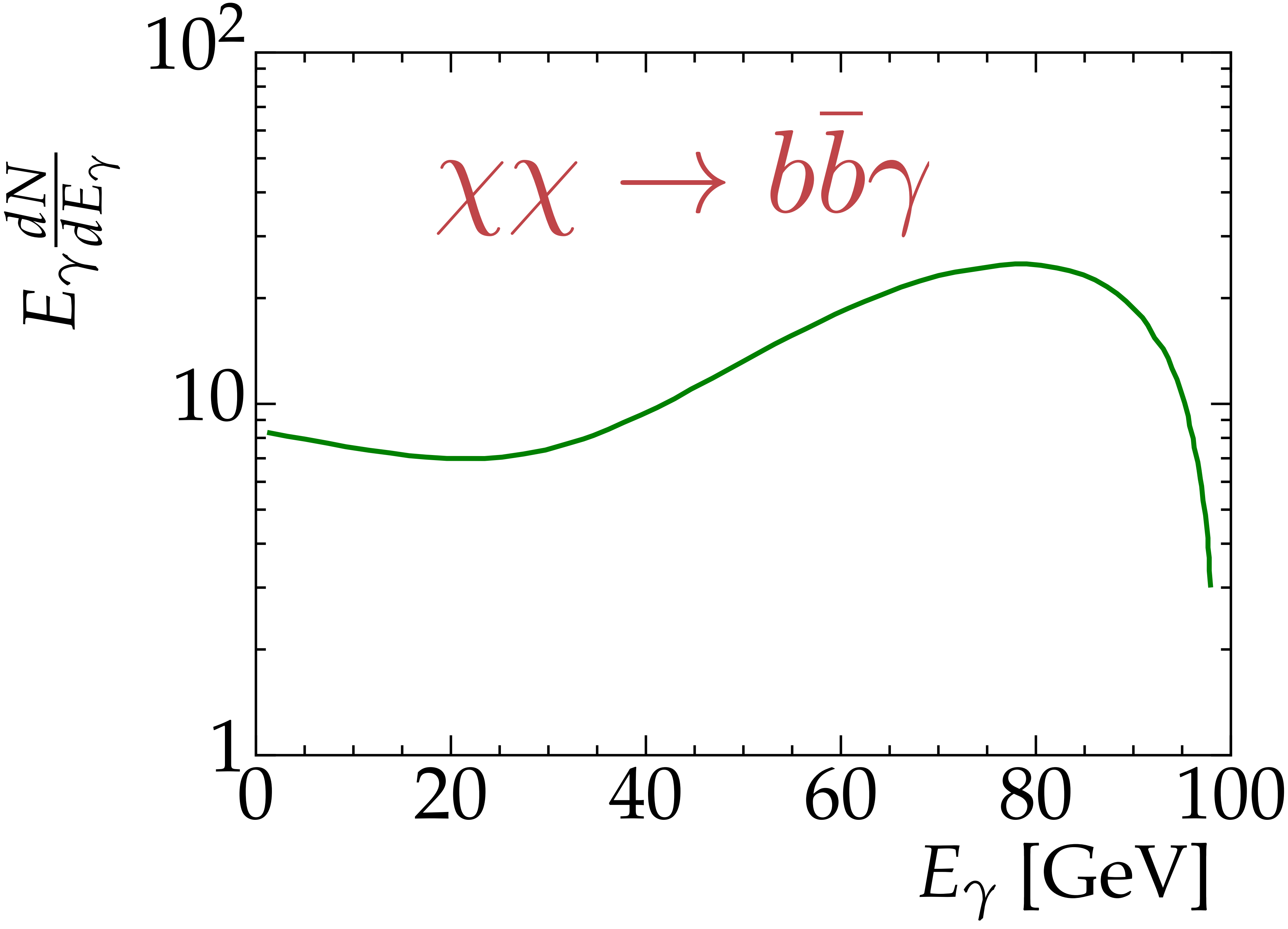
Conclusions

* Electroweak bremsstrahlung lifts the helicity suppression of DM annihilation to fermions.
* dim-8 operator encodes this effect in EFT framework.
* In spite of higher dimensionality of dim-8 operator, it does not suffer any suppression from DM relative velocity.
* Annihilation cross- section from dim 8 operator to the dim 6 operator is always larger at all dark matter mass scales > 1 TeV.
* Cancellation in the 2-body cross-section between dim 6 and dim 8 for $\Lambda/m_\chi \simeq 1.4$
* Bounds on the γ-ray flux and relic density translates into stringent bound on the EFT scale.
* For high mass DM (> 200 GeV), relic density provides the strongest bound on Λ.

Thank You!!

Photon Energy Spectrum

$d_6 = 1$, $d_8 = 1$, $v = 10^{-3}$, $M_{DM} = 100$ GeV, $\Lambda = 1$ TeV



Photon Energy Spectrum

$d_6 = 1$, $d_8 = 1$, $v = 10^{-3}$, $M_{DM} = 100$ GeV, $\Lambda = 1$ TeV