THE UNIVERSITY OF TEXAS AT AUSTIN

MITCHELL INSTITUTE TEXAS A&M UNIVERSITY

Vector Fermion Portal Dark Matter

Jiang-Hao Yu

University of Texas at Austin

JHY, PRD 90 (2014) 9095010 [arXiv: 1409.3227]

Mitchell Workshop on Collider and Dark Matter Physics
05/18/2015 - 05/22/2015

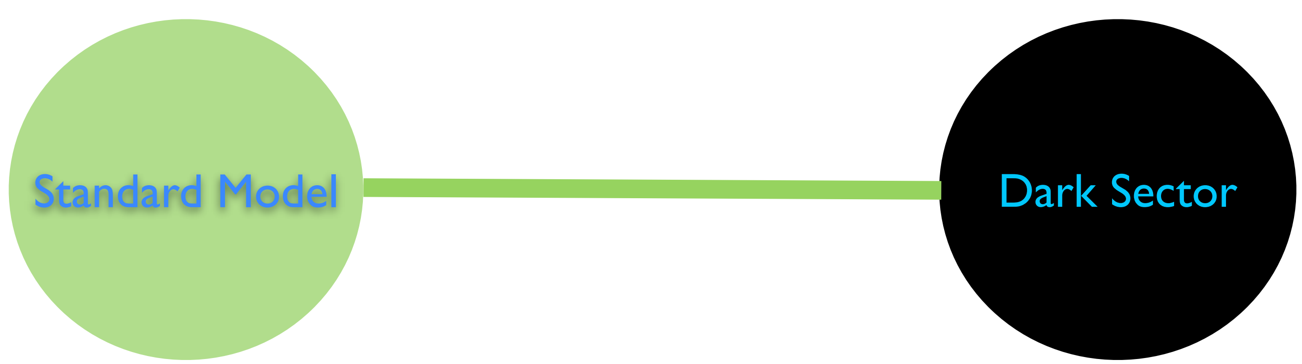
WIMP Dark Matter

- Popular scenario: WIMP (weakly interacting massive particle)
- WIMP naturally lead to correct dark matter abundance

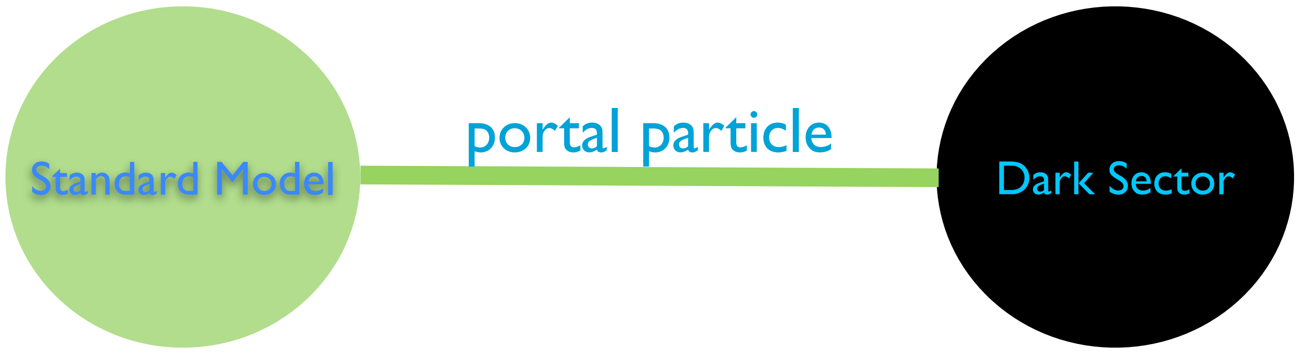
$$\Omega_{\rm dm} \simeq 0.23 \times \left(\frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$

weak scale cross section

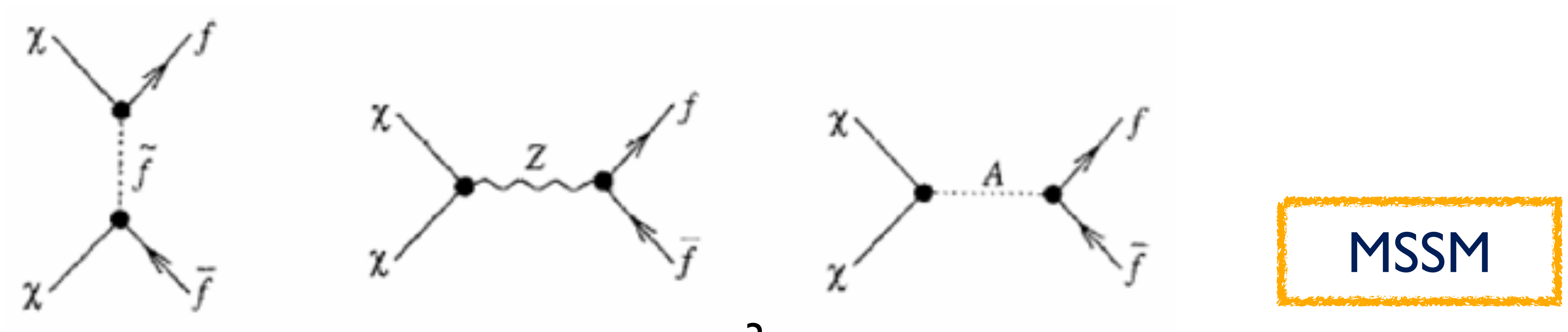
- WIMP: natural ingredient of beyond SM theories
- Popular WIMP scenario: portal to a dark sector (simplified model)



Portal Dark Matter

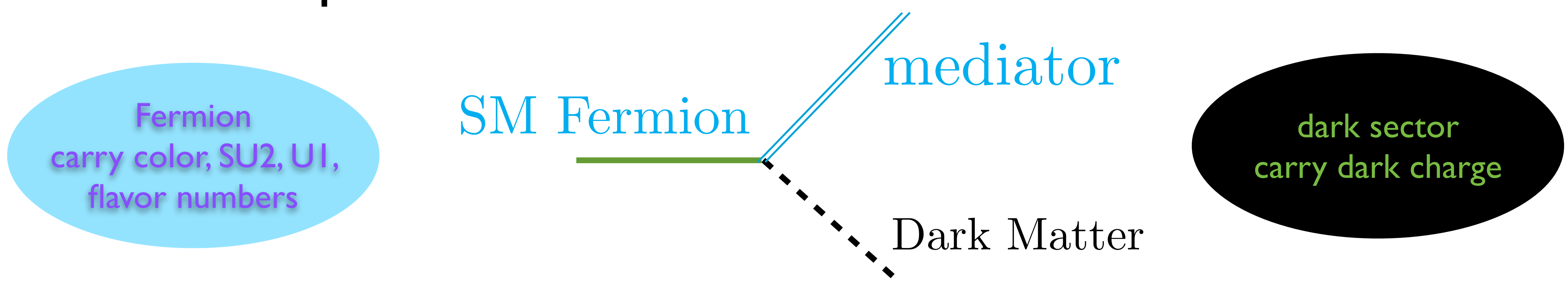


- Portal particle:
  - Z [excluded by SI direct detection, $\gamma^\mu \gamma_5$ SD dominant (OK)]
  - Photon [kinetic mixing, dipole dark matter, ...]
  - Higgs boson [tightly constrained, but still alive]
  - Quark/lepton [main focus in this talk]
  - new particles, such as Z', dilation, etc
- Some theories have several portal particles



Flavor Portal Dark Matter

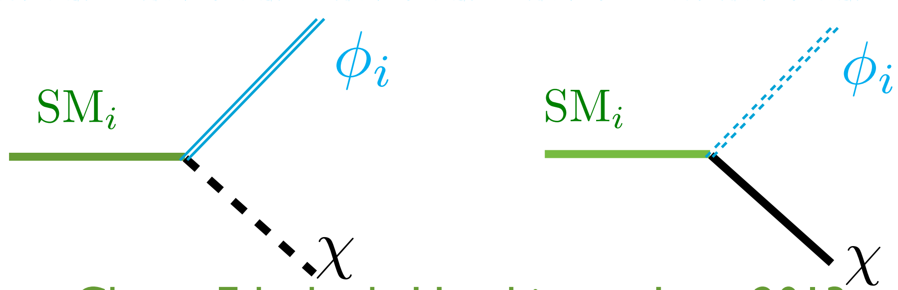
- Model Description



- Model Classification:

  - Fermion Portal Dark Matter

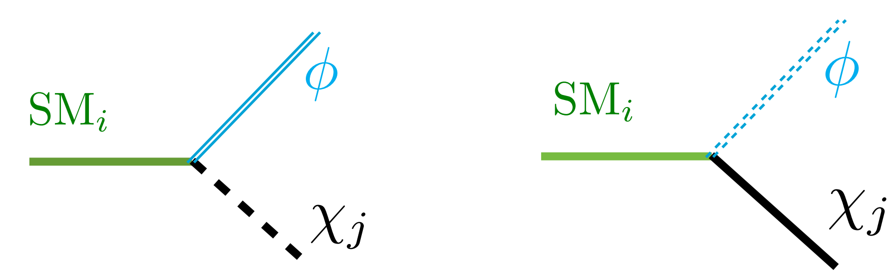
    mediator carries color, hyper charge and flavor numbers, dark matter only carries dark charge



Chang, Edezhath, Hutchinson, Luty, 2013
Bai, Berger 2013
Chang, Edezhath, Hutchinson, Luty, 2014
Bai, Berger 2014
DiFranzo, Nagao, Rajaraman, Tait, 2013
……

  - Flavored Dark Matter

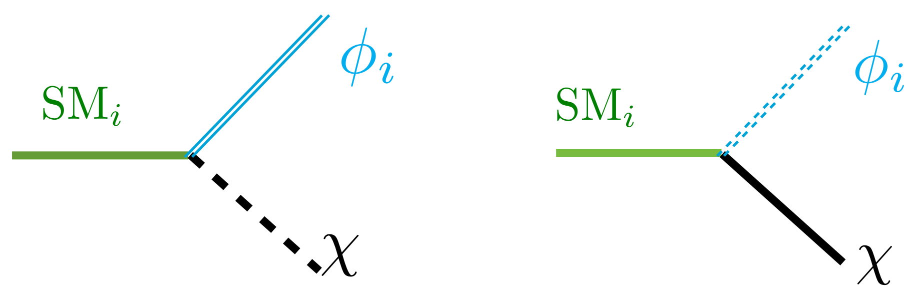
    mediator carries color, hyper charge, dark matter carries dark charge and flavor number



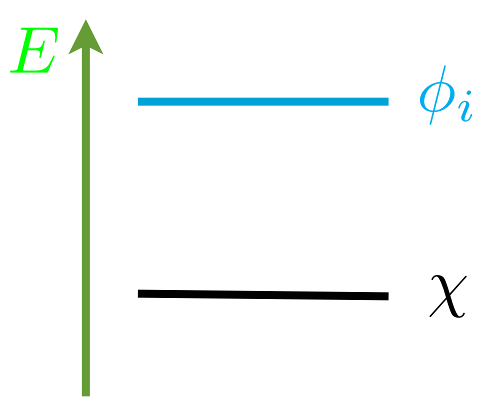
Kile, Soni 2011
Kamenik, Zupan 2011
Batell, Pradler, Spannowsky 2011
Agrawal, Blanchet, Chacko, Kilic 2012
…….

Phenomenology of Flavor Portal Model

Fermion Portal Dark Matter



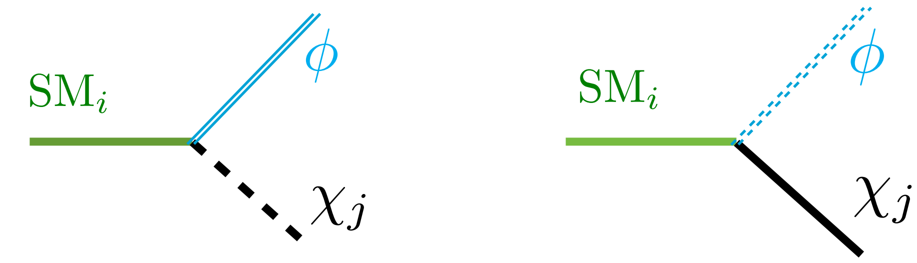
only one dark matter



$$\mathcal{L} \supset \lambda_{ij} l_i^c \chi \phi_j + \mathrm{h.c.}$$

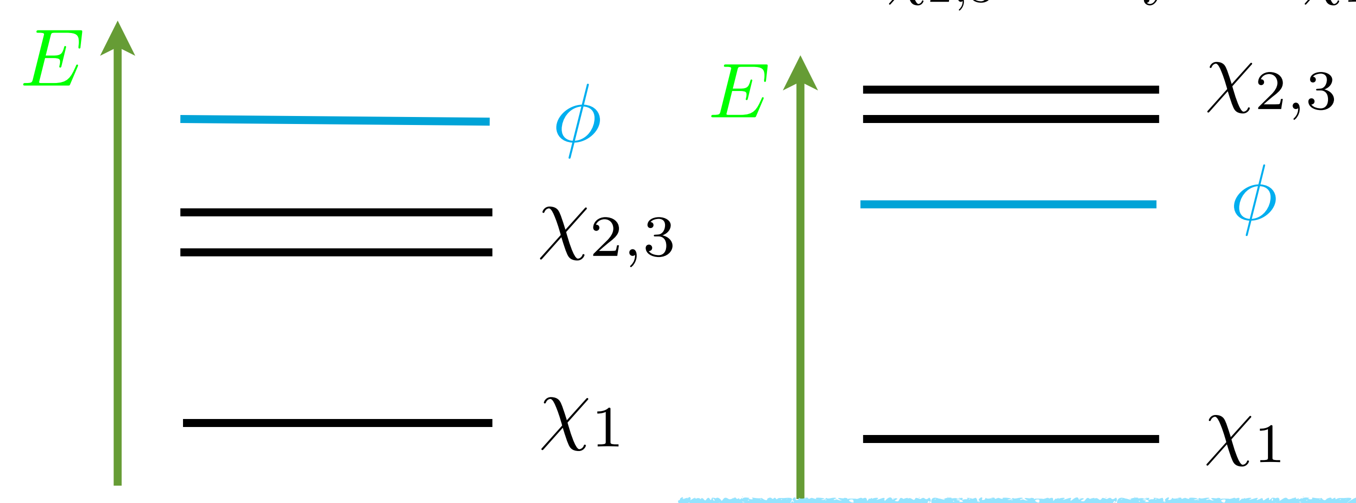
$$\mathcal{L} \supset \lambda_{ij} q_i^c \chi \phi_j + \mathrm{h.c.}$$

Flavored Dark Matter



three copies of dark matter

$\chi_{2,3}$ decays to χ_1



Richer collider signatures!

Kilic, Klimek, Yu, 15

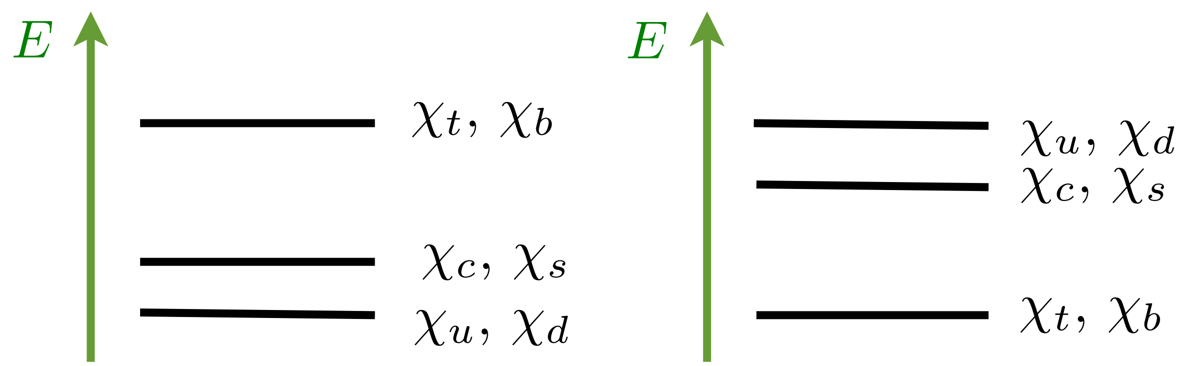
$$\mathcal{L} \supset \lambda_{ij}\, q_i^c\, \chi_j\, \phi + \mathrm{h.c.}$$

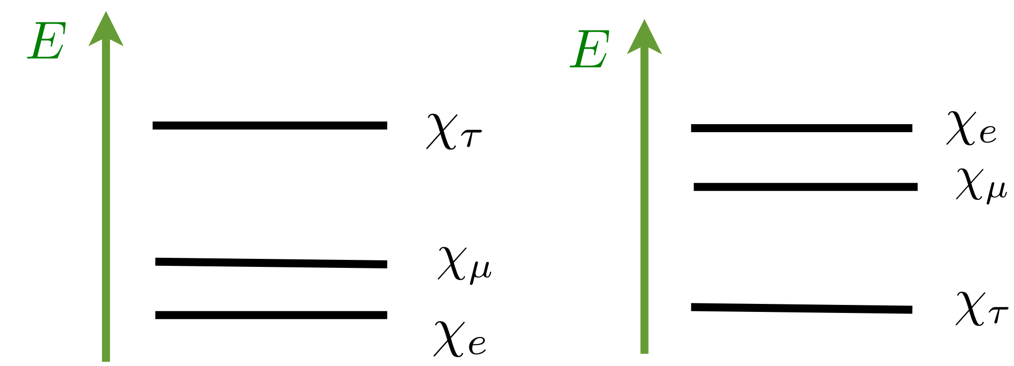
$$\mathcal{L} \supset \lambda_{ij}\, l_i^c\, \chi_j\, \phi + \mathrm{h.c.}$$

small off-diagonal coupling due to flavor violation constraints

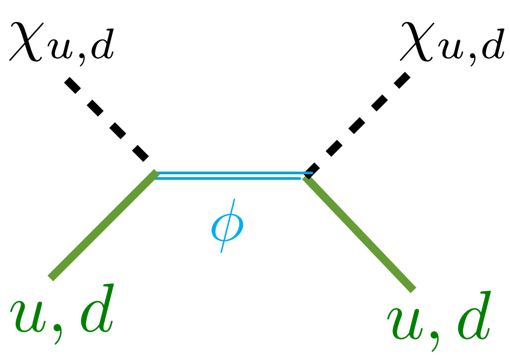
Tau/Top Flavored Dark Matter

- Normal/inverted mass hierarchy under MFV $[m_\chi]_i^{\ j} = (m_0 \mathbb{1} + \Delta m\, y^\dagger y)_i^{\ j}$

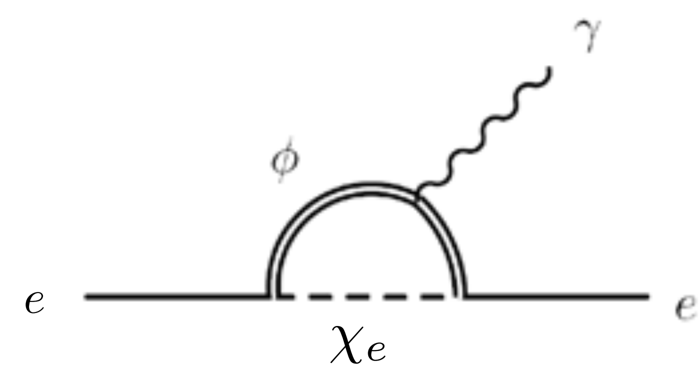




direct detection



g-2



- Tau/top/bottom-flavored dark matter

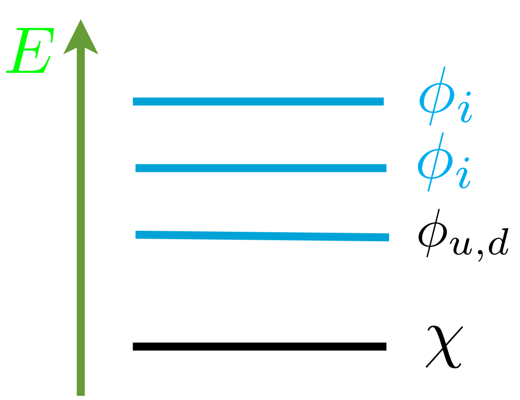
Direct detection, collider constraints seem OK

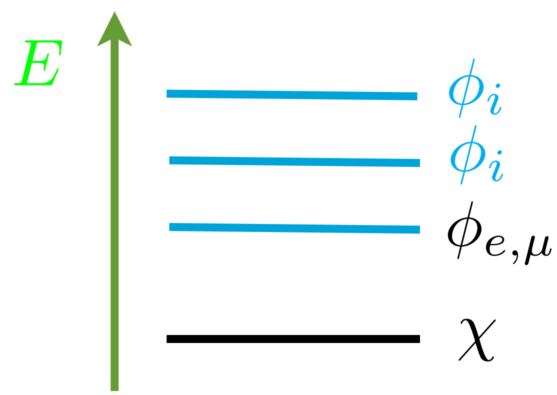
Usually only lightest dark matter is relevant in the relic density/direct detection/indirect detection

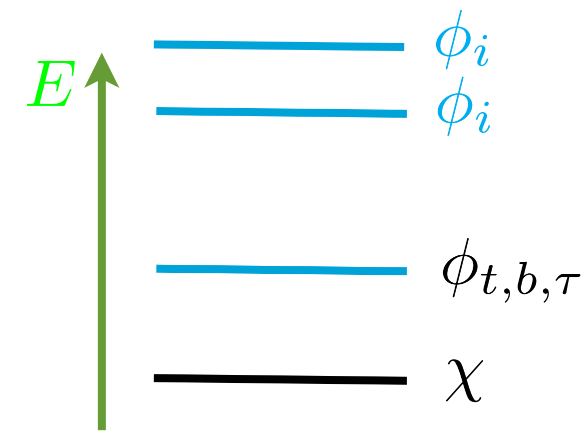
Can Kilic's talk

Fermion Portal Dark Matter

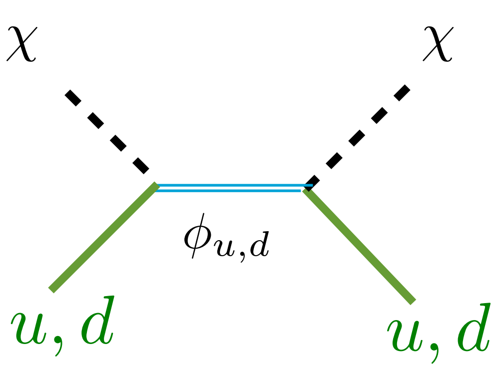
- First two generation portal dark matter highly constrained



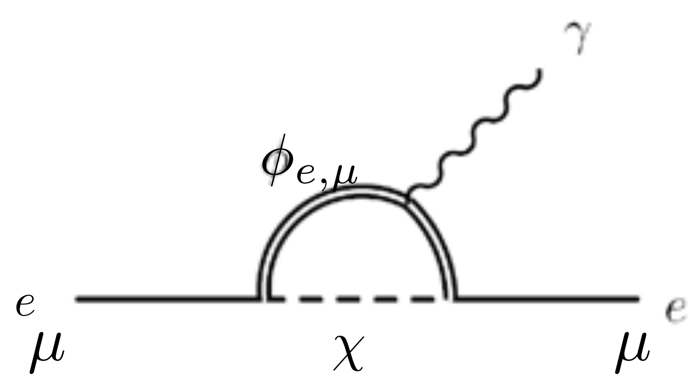




direct detection

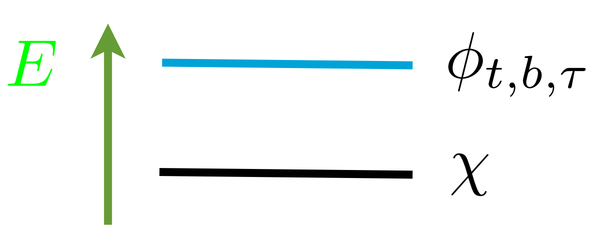


g-2



The mediators for the first two generations are very heavy, or missing

- Third generation portal dark matter

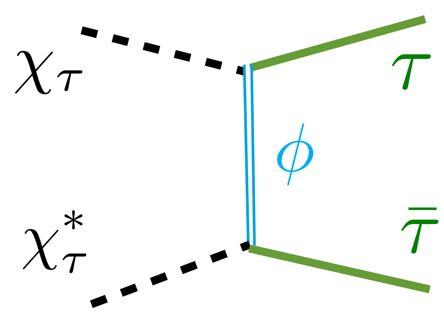


Usually only lightest mediator is relevant in the relic density/direct detection/indirect detection

Why Vector Flavor Portal DM?

- Study the scenario: only the lightest DM (FDM case) or the lightest mediator (fermion portal DM) is relevant

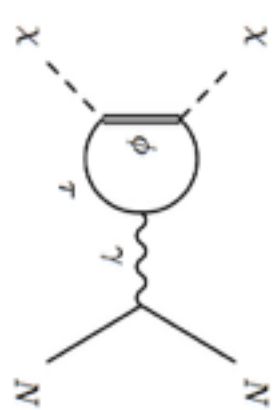
- Scalar dark matter



$$= \frac{\lambda_\phi^4}{16\pi} \frac{m_\tau^2}{(m_\phi^2 + m_\chi^2)^2} + \frac{\lambda_\phi^4}{48\pi} \frac{m_\chi^2}{(m_\phi^2 + m_\chi^2)^2} v^2$$

s-wave suppressed

- Direct Detection: scalar dark matter

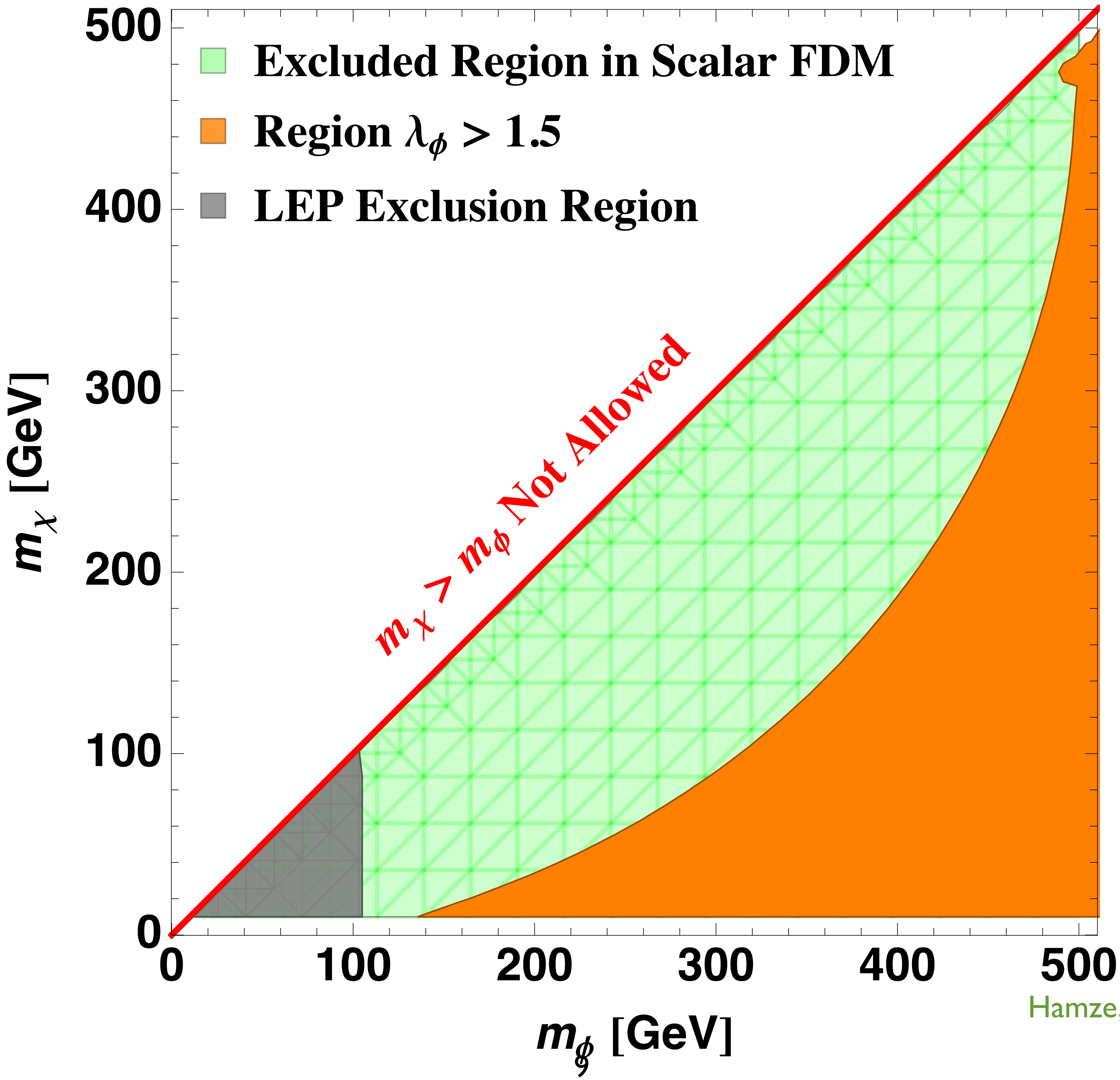


$$= \frac{\lambda_\phi^2 e^2}{32\pi^2 m_\phi^2} \left(1 + \frac{2}{3} \ln \frac{m_\tau^2}{m_\phi^2}\right) \left[\chi^* \overleftrightarrow{\partial}^\mu \chi \overline{N} \gamma_\mu N\right]$$

charge radius

- similarly third generation quark

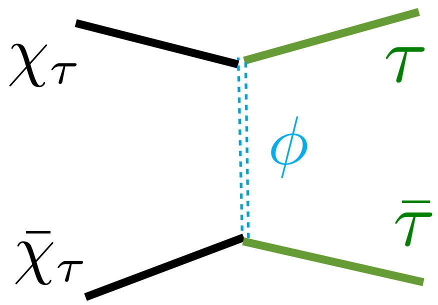
Scalar Portal DM



Hamze, Kilic, Trendafilova, Yu, 2015

Fermion Portal DM

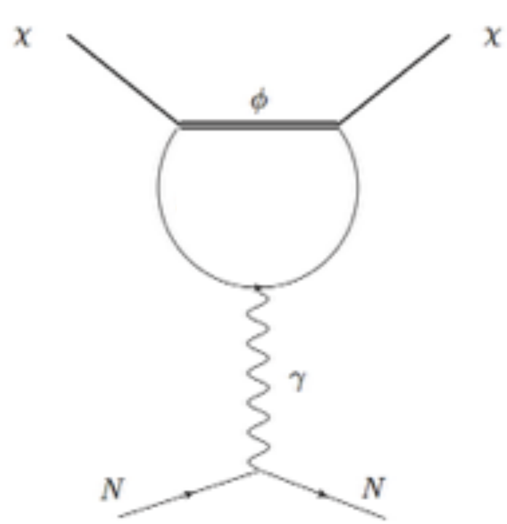
- Fermion dark matter



$$= \frac{\lambda_\phi^4}{32\pi} \frac{m_\chi^2}{(m_\phi^2 + m_\chi^2)^2}$$

s-wave dominant indirect signature!

- Direct Detection



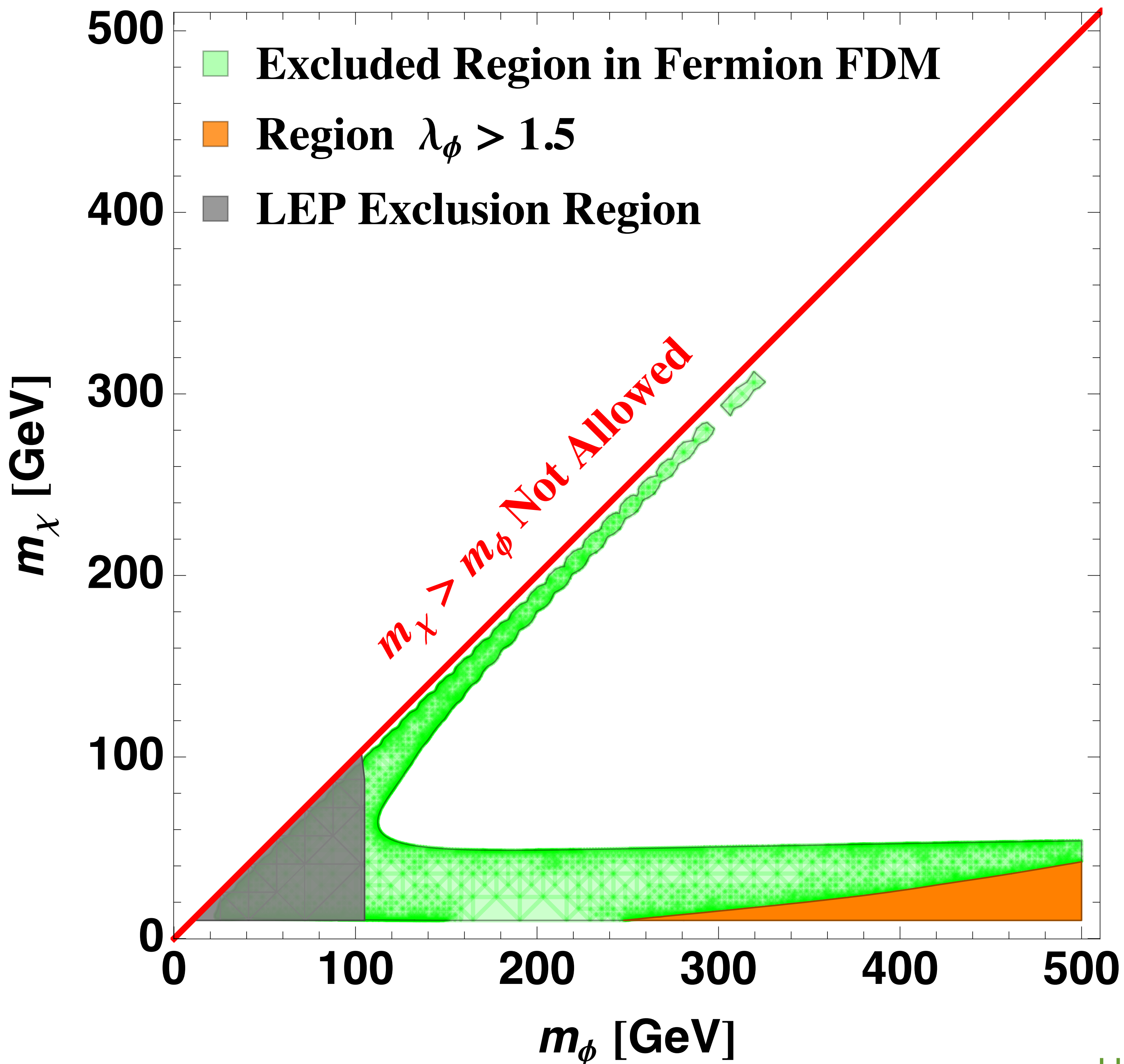
$$= c_\gamma^N \overline{\chi} \gamma^\mu \chi \overline{N} \gamma_\mu N + c_Q^N \overline{\chi} i \sigma^{\alpha\mu} \frac{k_\alpha}{k^2} \chi \overline{N} K_\mu N + c_\mu^N \overline{\chi} i \sigma^{\alpha\mu} \frac{k_\alpha}{k^2} \chi \overline{N} i \sigma^{\beta\mu} k_\beta N$$

charge radius

Magnetic dipole moment

Hamze, Kilic, Trendafilova, Yu, 2015

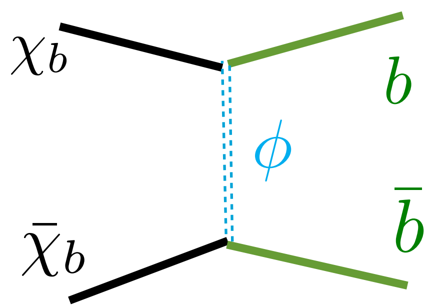
Fermion Portal DM



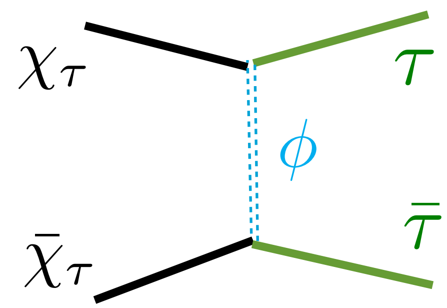
Hamze, Kilic, Trendafilova, Yu, 2015

Bottom Portal DM

- Relic density

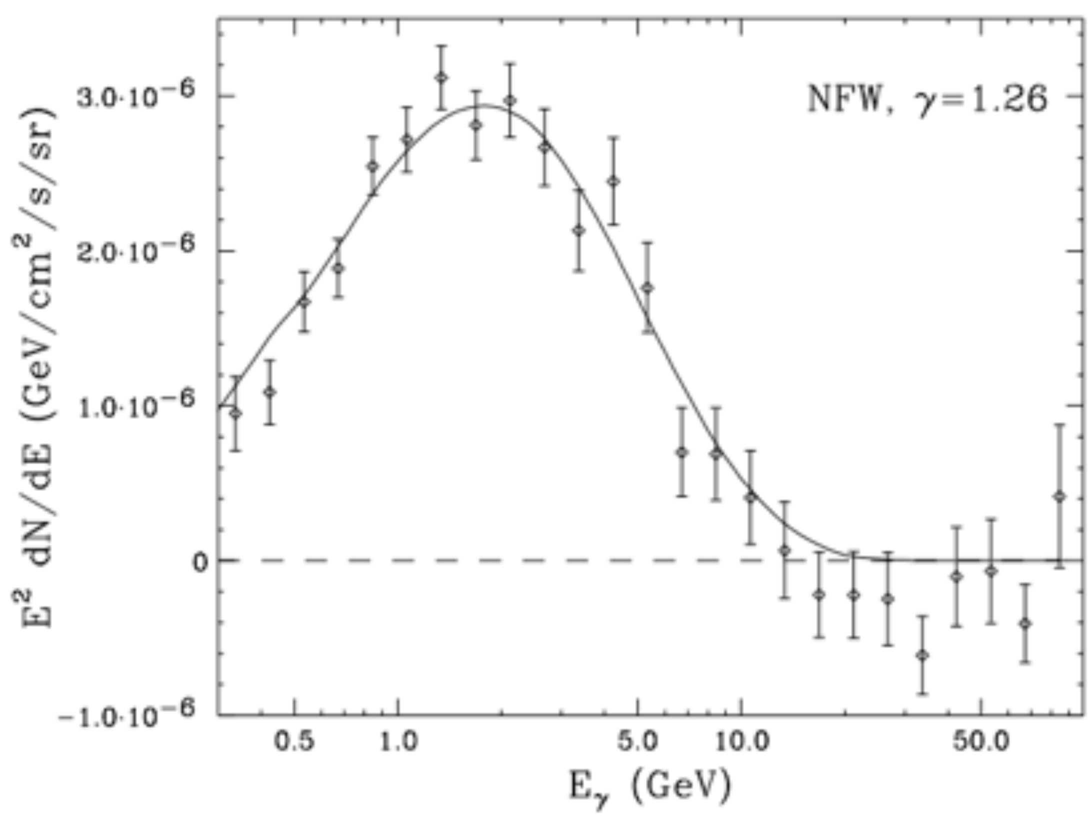


$\simeq 3\times$



$$\simeq 3\times \frac{\lambda_\phi^4}{32\pi}\frac{m_\chi^2}{(m_\phi^2+m_\chi^2)^2}$$

- indirect detection signature: Galactic Center GeV excess



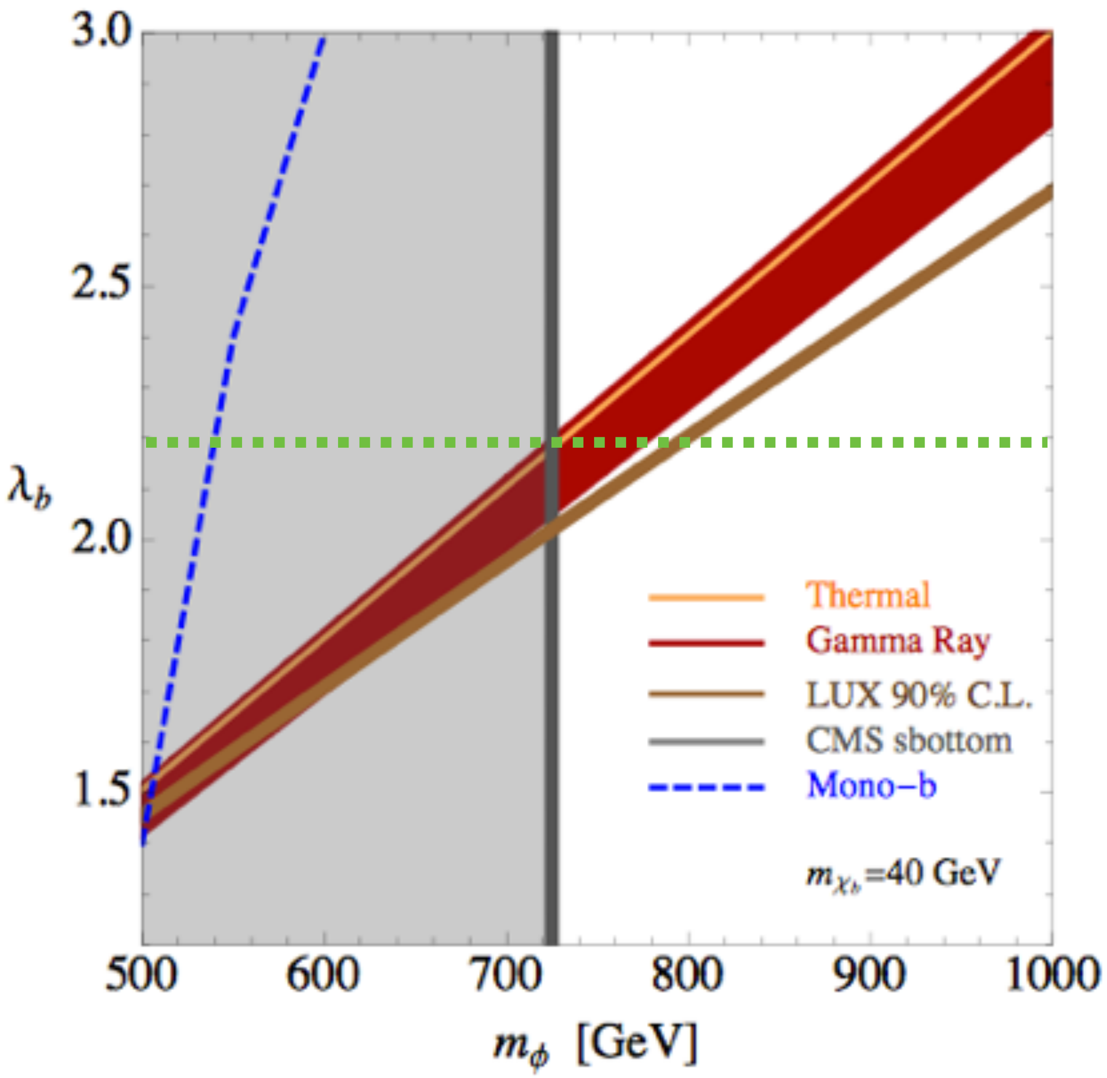
favor bb, tautau

Can bottom portal DM explain GeV excess?

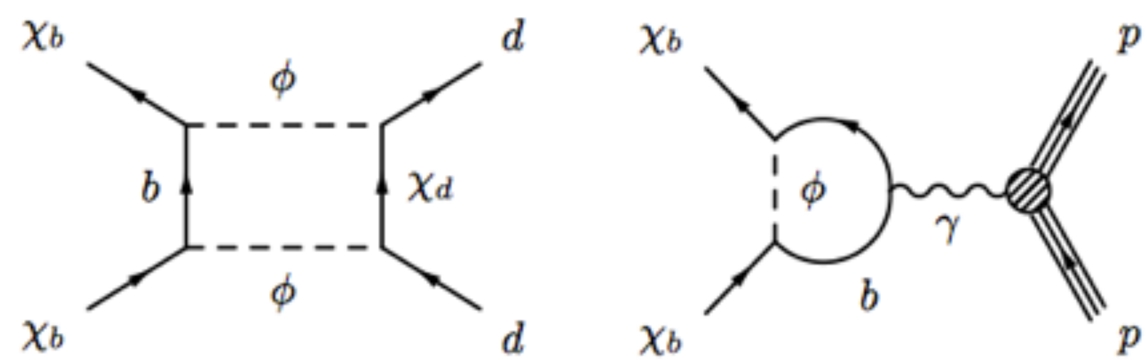
Abazajian+ 2014
Daylan+2014

Bottom-FDM meets GeV Excess

- In the context of flavored dark matter



Agrawal, Batell, Hooper, Lin, 14'



direct detection cancellation between diagrams

bb final state (antiproton data)

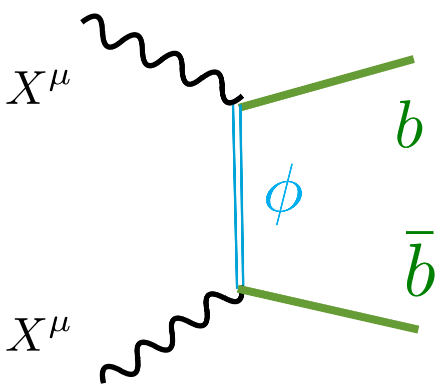
- Large coupling is allowed.

Too large coupling: non-perturbative!

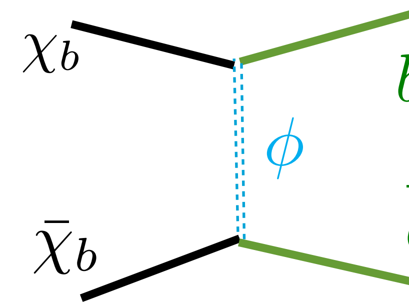
FDM / Fermion-portal DM could not explain GeV excess?

Vector Dark Matter

- Larger thermal cross section



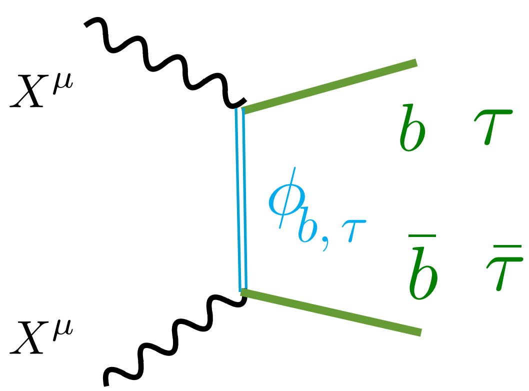
$$= \frac{2N_c\lambda_\phi^4}{9\pi}\frac{m_\chi^2}{(m_\phi^2+m_\chi^2)^2} \gg$$

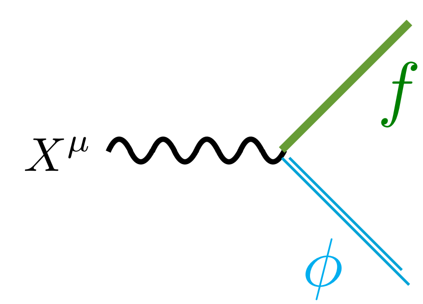


- Vector dark matter: fermion-portal

To avoid anti-proton constraint, both b and tau final states

Need model building (extend gauge group)





Model Building

- SU(2) x U(1) x U(1) with T-parity

	$SU(2)_L$	$U(1)_1$	$U(1)_2$
H	2	$\frac{Y}{\sqrt{2}}$	$\frac{Y}{\sqrt{2}}$
Φ	1	$\frac{Y}{\sqrt{2}}$	$-\frac{Y}{\sqrt{2}}$
Q_L	2	$\frac{Y}{\sqrt{2}}$	$\frac{Y}{\sqrt{2}}$
b_{1R}	1	Y_1	Y_2
b_{2R}	1	Y_2	Y_1
t_{1R}	1	Y_1	Y_2
t_{2R}	1	Y_2	Y_1

$$D^\mu H = \partial^\mu H + ig_2 \frac{\tau^a}{2} W^{a\mu} H + i\frac{g'}{2}(B_1^\mu + B_2^\mu) H$$

$$D^\mu \Phi = \partial^\mu \Phi + i\frac{g'}{2}(B_1^\mu - B_2^\mu)\Phi$$

generate masses

$$D^\mu \psi_1 = \left[\partial^\mu + ig'(Y_1 B_1^\mu + Y_2 B_2^\mu)\right]\psi_1,$$
$$D^\mu \psi_2 = \left[\partial_\mu + ig'(Y_2 B_1^\mu + Y_1 B_2^\mu)\right]\psi_2.$$

new couplings

$$Y_{\rm SM} = \frac{Y_1 + Y_2}{\sqrt{2}}$$

T-parity

$$B^\mu = \frac{1}{\sqrt{2}}(B_1^\mu + B_2^\mu) \qquad X^\mu = \frac{1}{\sqrt{2}}(B_1^\mu - B_2^\mu)$$

$$B_1^\mu \leftrightarrow B_2^\mu \qquad B^\mu \leftrightarrow B^\mu \qquad X^\mu \leftrightarrow -X^\mu$$

$$f_R = \frac{1}{\sqrt{2}}(\psi_1 - \psi_2) \qquad \phi_R = \frac{1}{\sqrt{2}}(\psi_1 + \psi_2)$$

$$\psi_1 \leftrightarrow -\psi_2 \qquad f_R \leftrightarrow f_R \qquad \phi_R \leftrightarrow -\phi_R$$

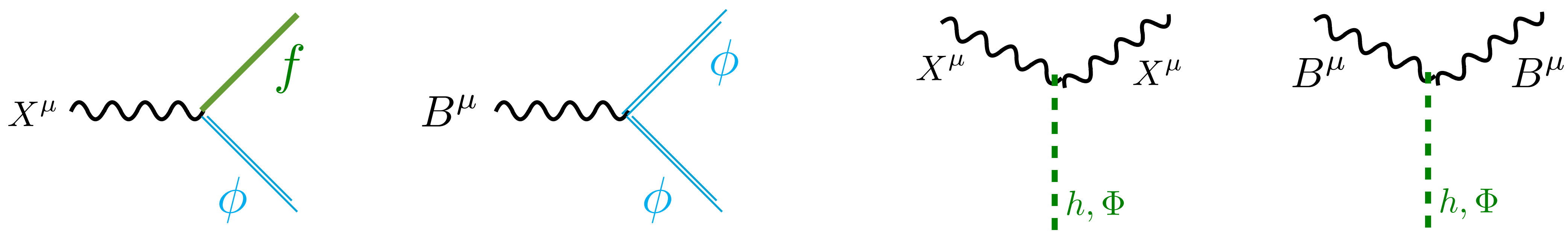
generate couplings

$$\mathcal{L} = \overline{\psi}_1 i\gamma_\mu D^\mu \psi_1 + \overline{\psi}_2 i\gamma^\mu D^\mu \psi_2$$

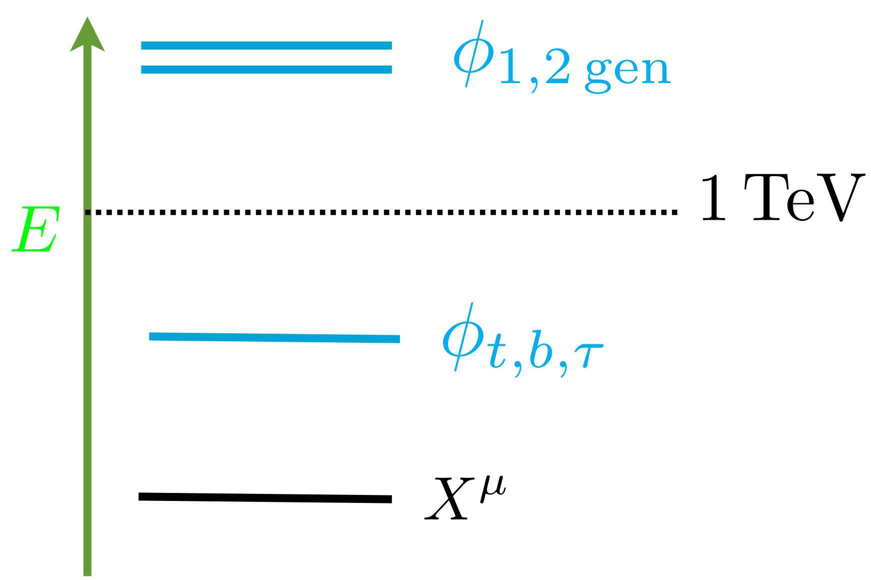
$$\mathcal{L} \supset \overline{f}_R i\gamma_\mu \left[\partial^\mu + ig'YB^\mu\right] f_R + \overline{\phi}_R i\gamma_\mu \left[\partial^\mu + ig'YB^\mu\right]\phi_R + \overline{\phi}_R i\gamma_\mu \left[ig'Y'X^\mu\right] f_R + \overline{f}_R i\gamma_\mu \left[ig'Y'X^\mu\right]\phi_R$$

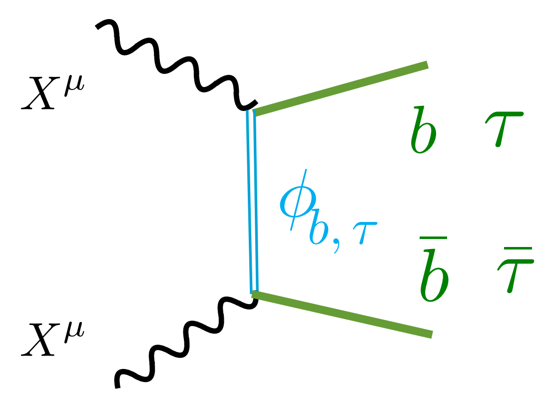
Vector Fermion-Portal Dark Matter

- New couplings



- Mass spectrum (Split)



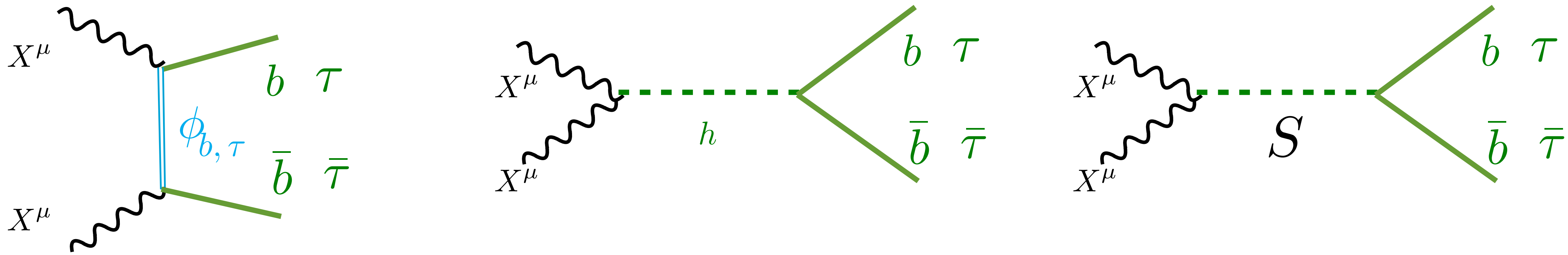


$$\sim \frac{m_X^2}{(m_\phi^2 + m_X^2)^2}$$

Third generation final states dominant

mX ~ GeV - 100 GeV, no tt final state for 3rd generation favored coupling

Relic Abundance

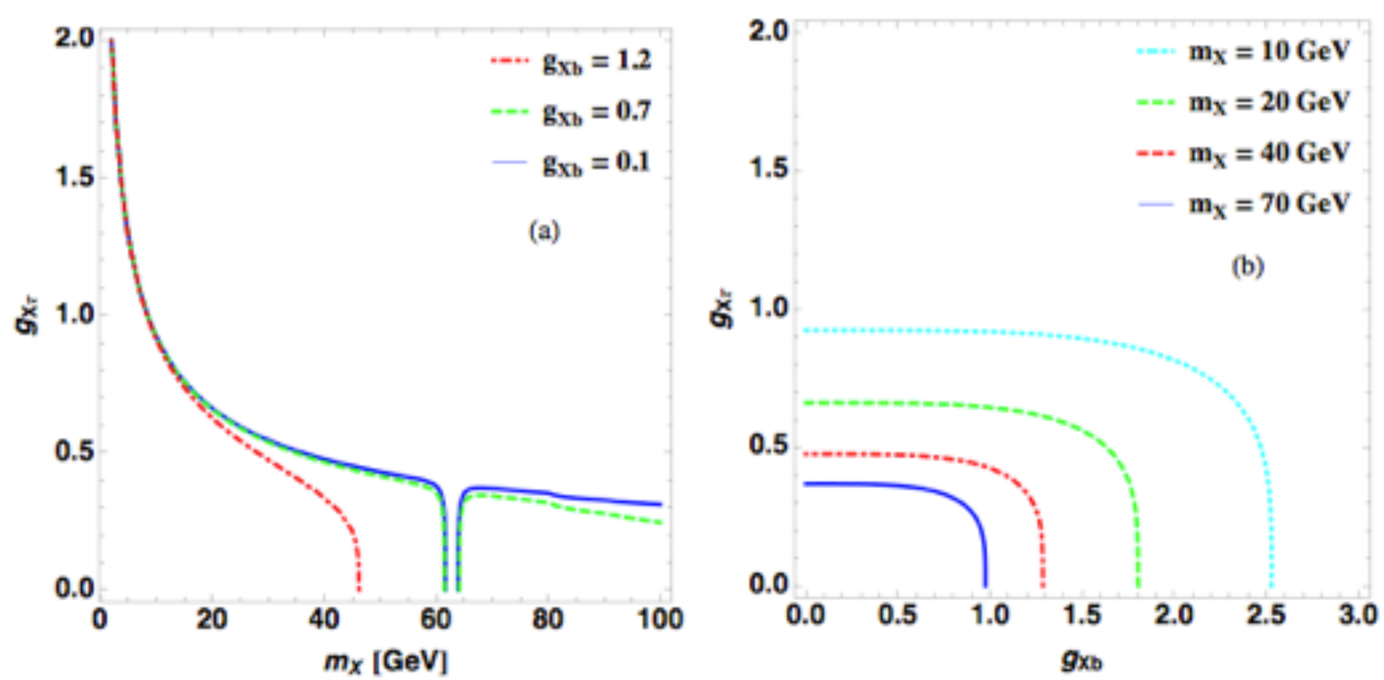


$$(\sigma v)_{\text{t-channel}} = \frac{2N_c g_X^4}{9\pi} \frac{m_X^2}{(m_X^2 + m_F^2)^2},$$

$$(\sigma v)_{\text{s-channel}} = \frac{N_c m_f^2}{12\pi v^2} \frac{g_\phi^2 c_\varphi^2 s_\varphi^2 m_X^2 (m_S^2 - m_h^2)^2}{(4m_X^2 - m_h^2)^2 (4m_X^2 - m_S^2)}$$

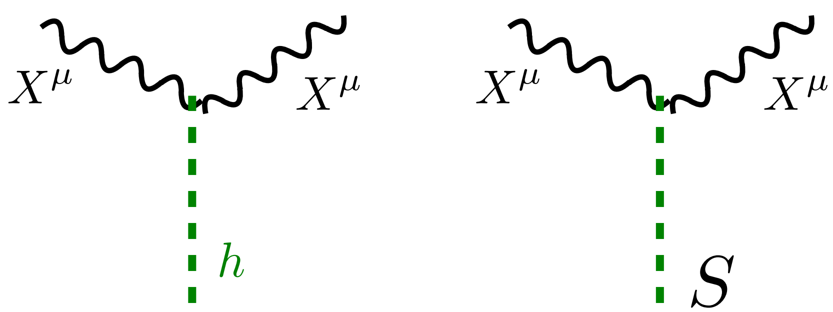
dominant contribution

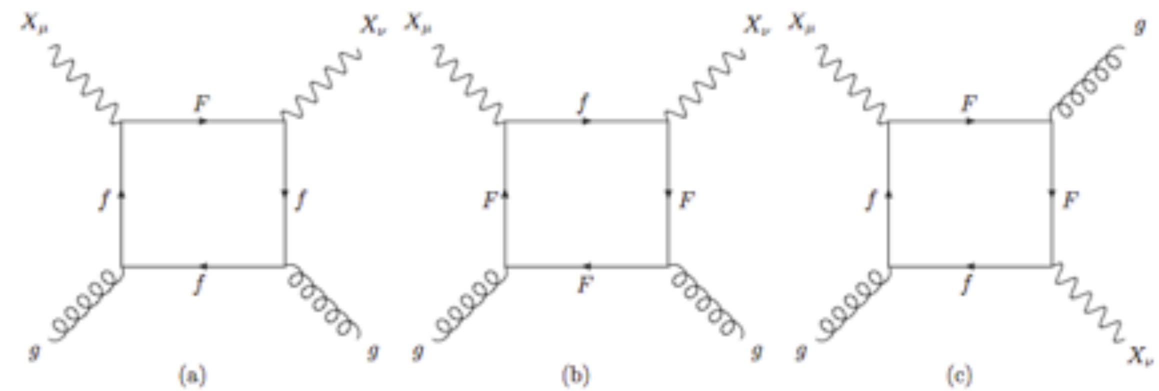
s-wave suppressed



Direct Detection

- Spin-independent





$$\mathcal{L} = g_\phi c_\varphi s_\varphi m_X \frac{m_q}{v} \left(\frac{1}{m_h^2} - \frac{1}{m_S^2} \right) X_\mu X^\mu \bar{q} q \, .$$

$$\mathcal{L} = b_g X^\rho X_\rho G^{a\mu\nu} G^a_{\mu\nu} ,$$

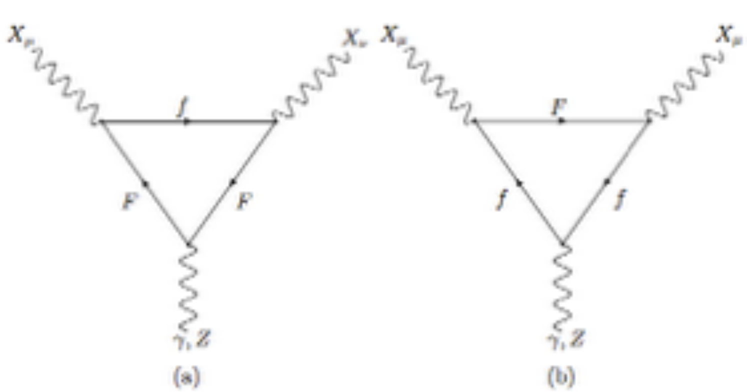
$$\mathcal{C}_N = \frac{g_\phi c_\varphi s_\varphi}{2} \frac{m_N}{v} \left(1 - \frac{7}{9} f_{TG}^{(N)} \right) \left(\frac{1}{m_h^2} - \frac{1}{m_S^2} \right) - \frac{g_X^2}{108} f_{TG}^{(N)} \frac{m_N}{m_X} \frac{3m_F^2 - 2m_X^2}{(m_F^2 - m_X^2)^2} ,$$

Suppression

$$\sigma_N^{\rm SI} = \frac{\mu_N^2}{\pi} \mathcal{C}_N^2 ,$$

$$\sigma_N^{\rm SD} = \frac{16 \mu_N^2}{\pi} \mathcal{A}_N^2 .$$

- Spin-dependent



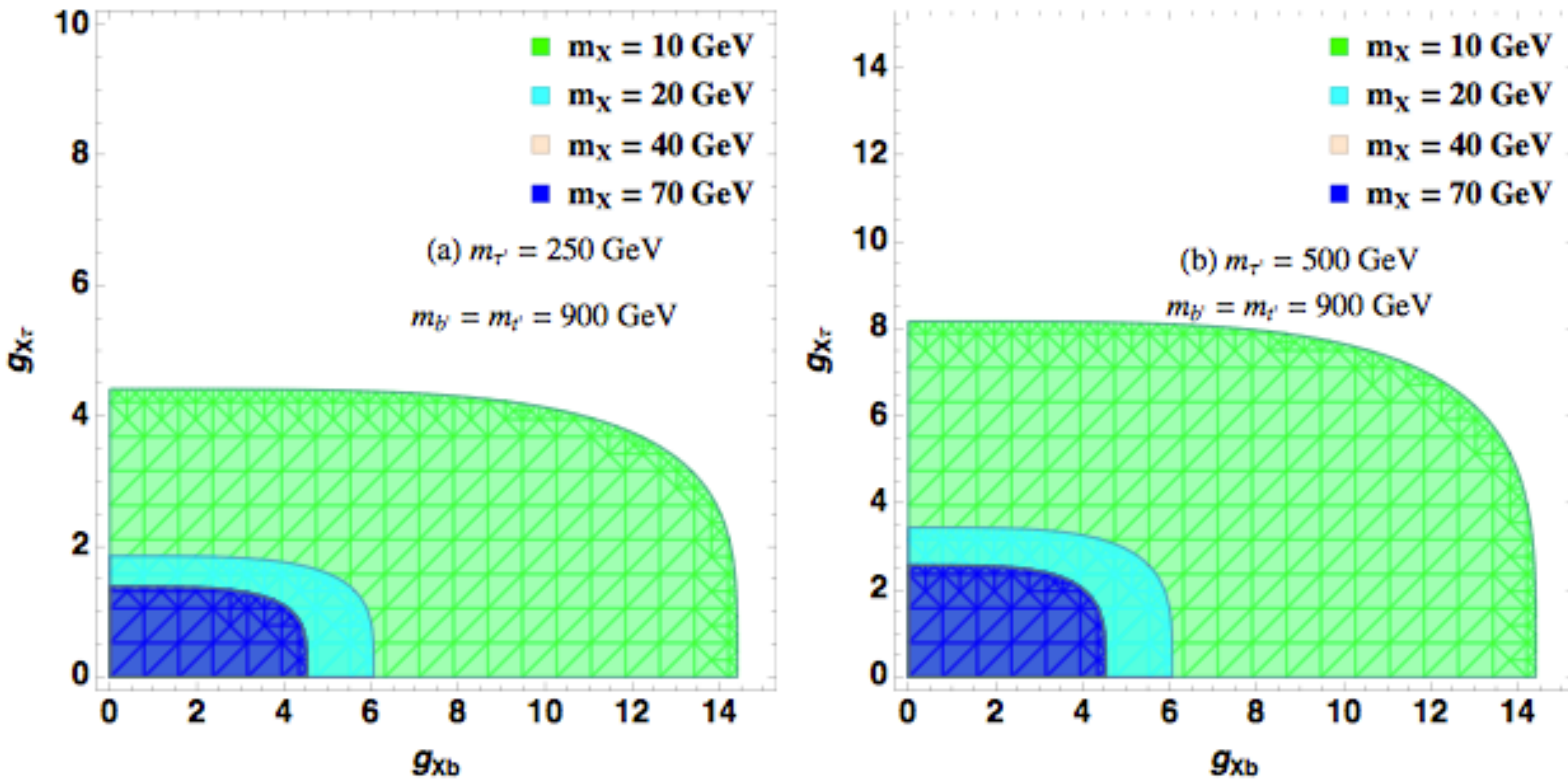
$$\mathcal{L} = d_X \epsilon^{\mu\nu\rho\sigma} \left(X_\mu \partial_\nu X_\rho \right) \bar{q} \gamma_\sigma \gamma_5 q \, ,$$

$$\mathcal{A}_N = e d_X \sum_q \Delta_q^N ,$$

$$d_X \simeq N_c \frac{e Q g_X^2}{\pi^2} \left(\frac{(m_F^6 - m_f^6)}{3(m_F^2 - m_f^2)^4} \log \frac{m_F}{m_f} - \frac{m_F^2 + m_f^2}{4(m_F^2 - m_f^2)^2} \right)$$

Only SD

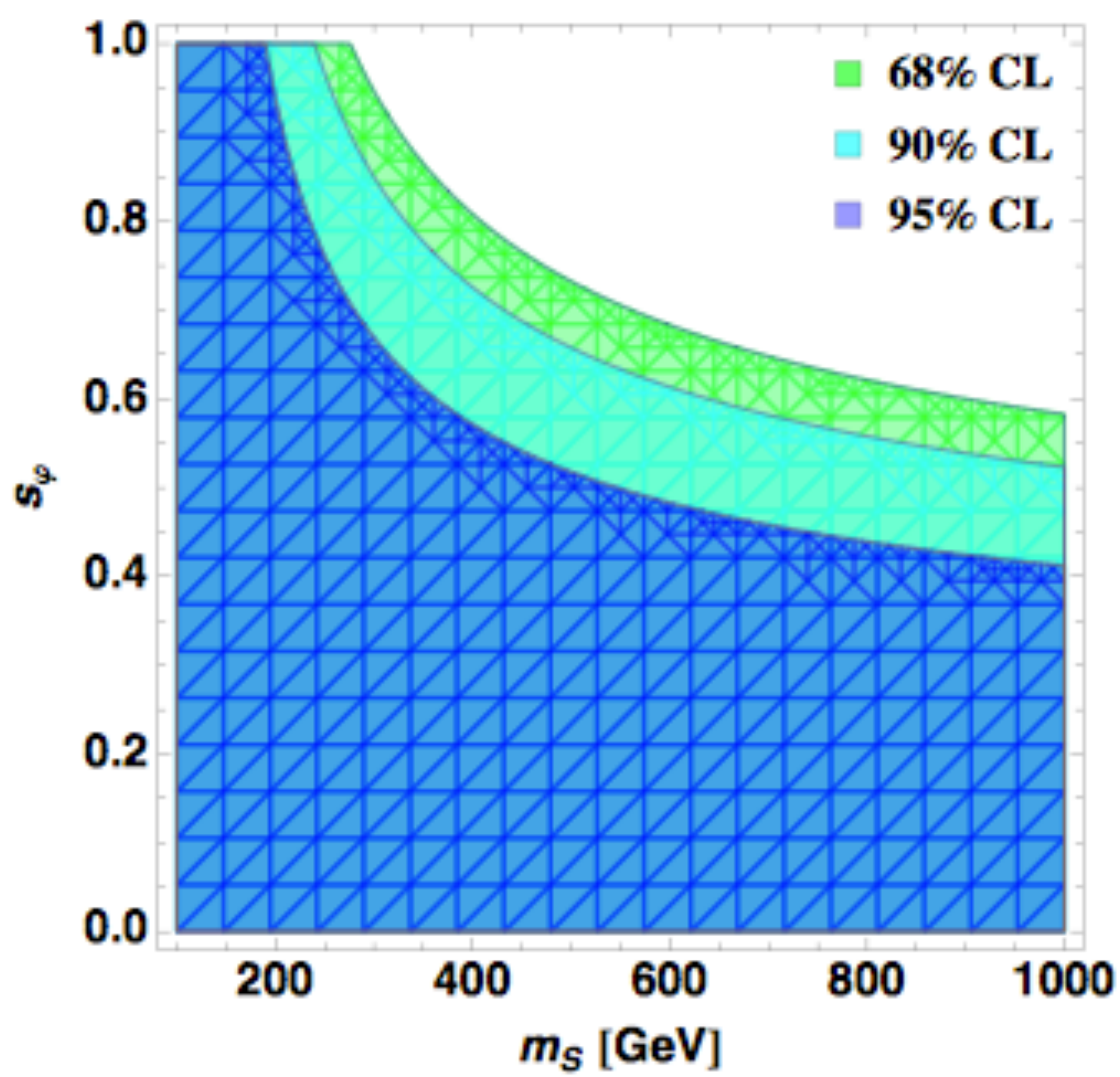
Direct Detection



Precision Constraints

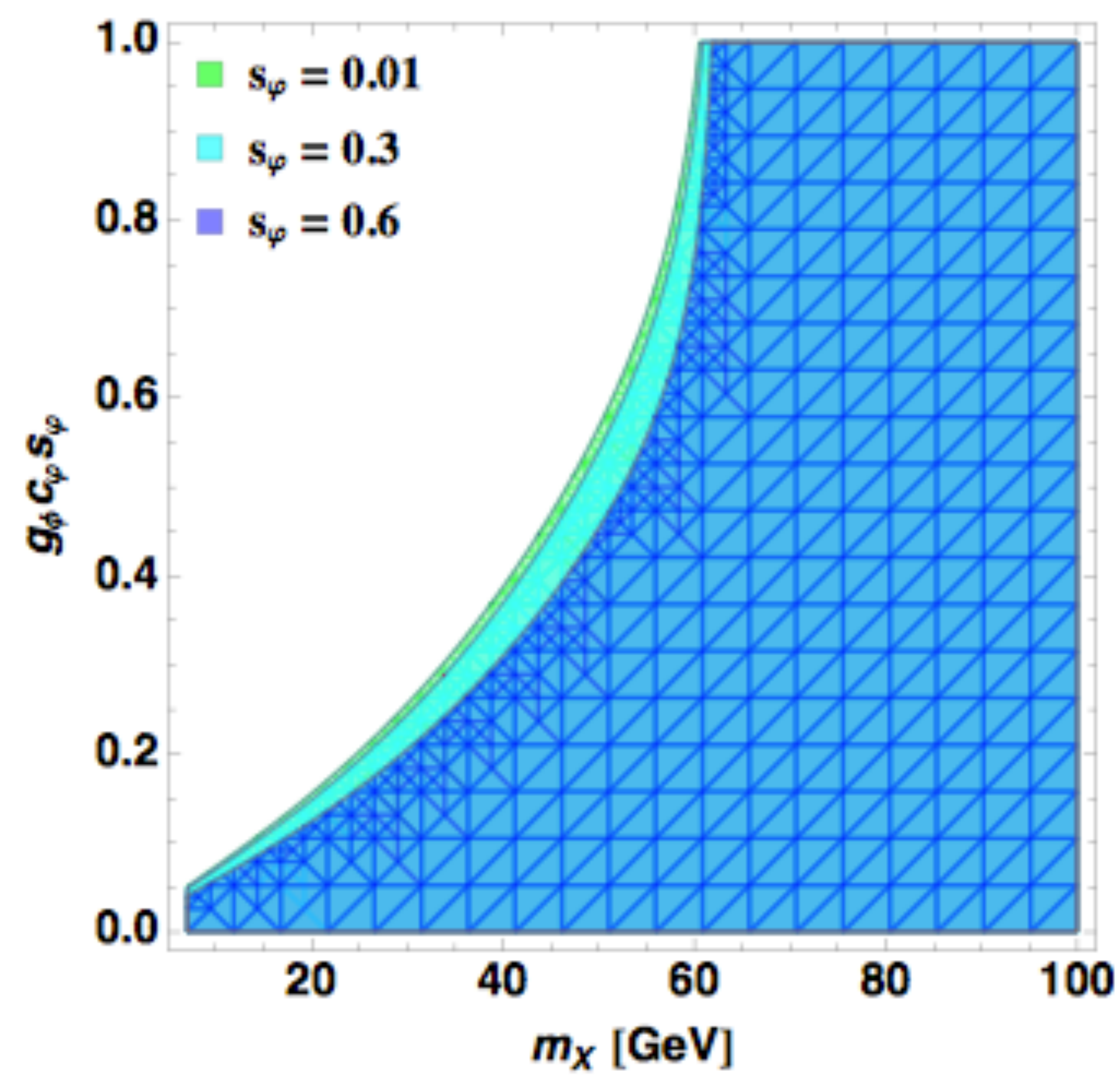
- S, T parameters

$$\Delta T = s_\varphi^2 \left[T_s(m_S^2) - T_s(m_h^2) \right]$$
$$\Delta S = s_\varphi^2 \left[S_s(m_S^2) - S_s(m_h^2) \right]$$



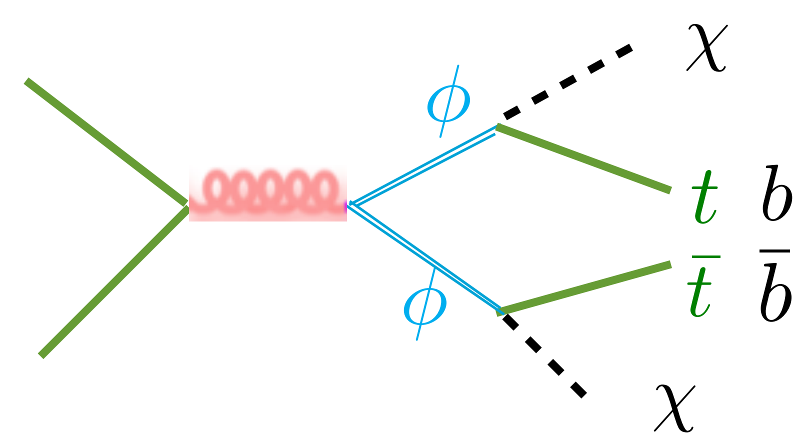
- Higgs invisible decay

$$\Gamma_h^{\rm inv} = \frac{g_{XXh}^2}{64\pi} \frac{m_h^3}{m_X^4} \left(1 - \frac{4m_X^2}{m_h^2} + \frac{12 m_X^4}{m_h^4}\right) \left(1 - \frac{4m_X^2}{m_h^2}\right)^{1/2} \quad (29)$$

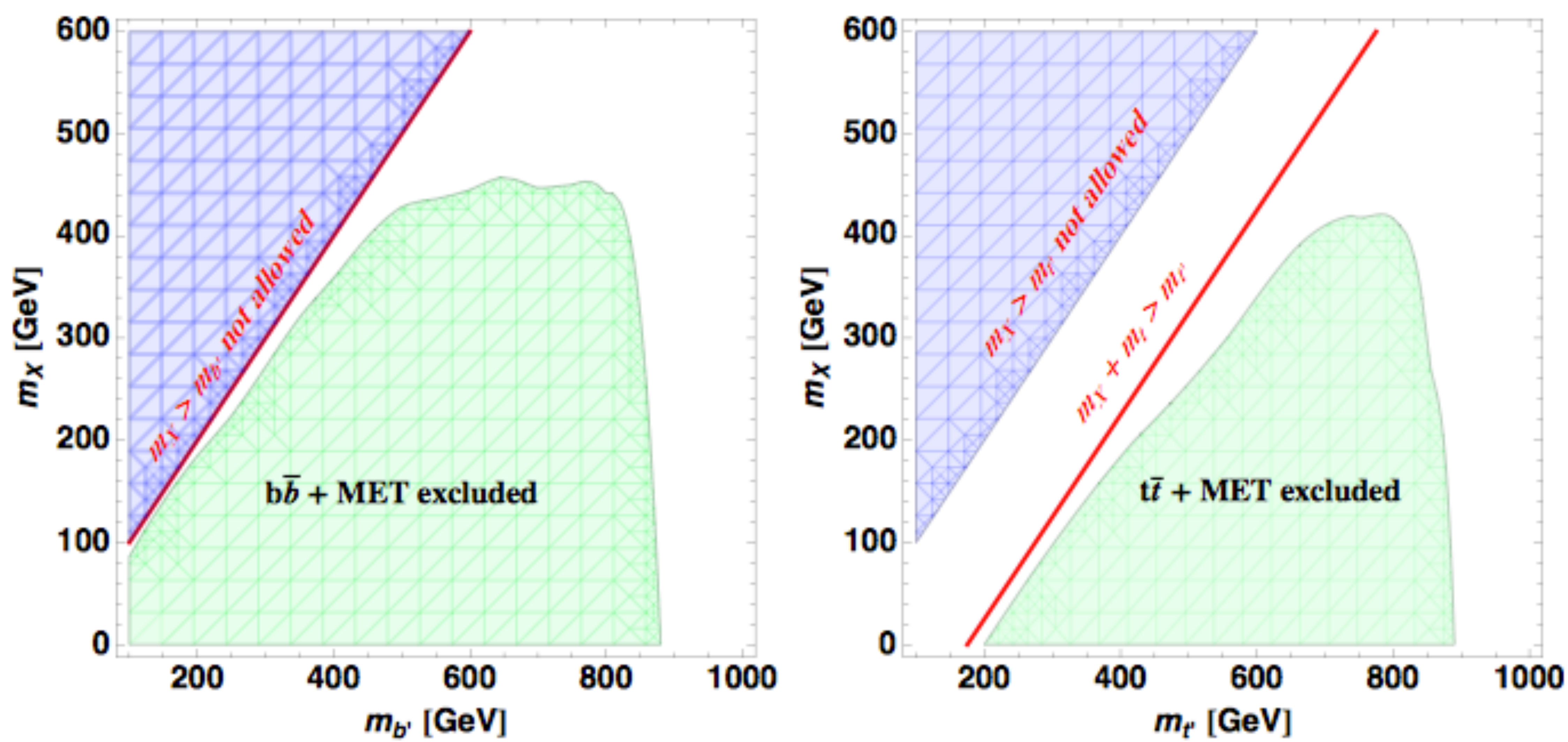


Collider Searches

- t/b pair + missing energy
- Mono-b/t searches



top pair + MET
bottom pair + MET
tau pair + MET



Photon Energy Flux

- Photon Flux

$$\frac{d\Phi^\gamma}{dE_\gamma} = \frac{1}{8\pi m_X^2}\langle\sigma v\rangle \frac{dN^\gamma}{dE_\gamma} \times \int_{\Delta\Omega} J(\psi) d\Omega$$

astrophysics (halo profile)

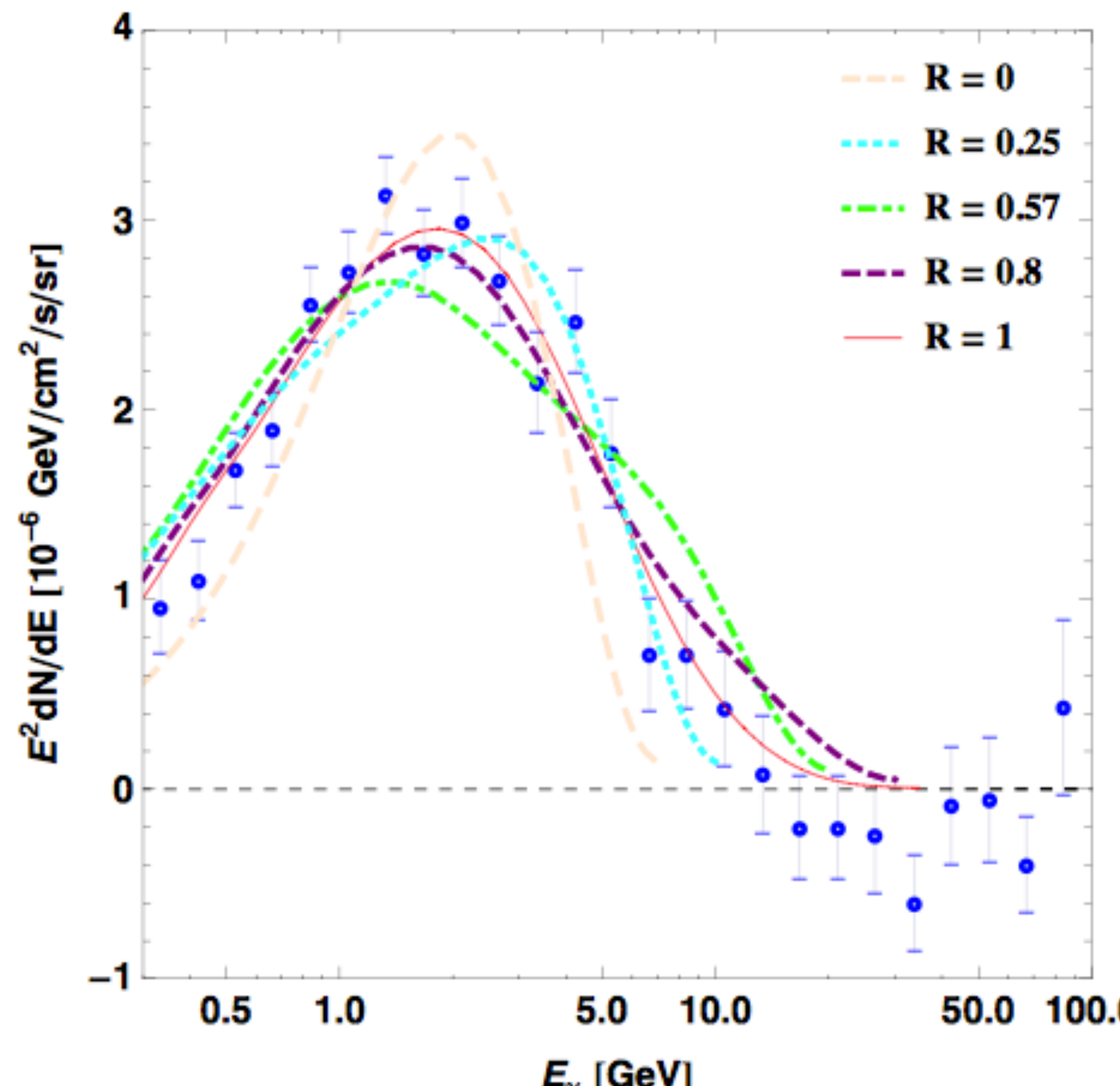
$$J(\psi) = \int_{\text{l.o.s.}} [\rho(r(s,\psi))]^2 ds$$

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

Particle Physics (photon spectrum)

$$\frac{dN^\gamma}{dE_\gamma} = R\,\frac{dN^\gamma_{b\bar{b}}}{dE_\gamma} + (1-R)\,\frac{dN^\gamma_{\tau\bar{\tau}}}{dE_\gamma}.$$

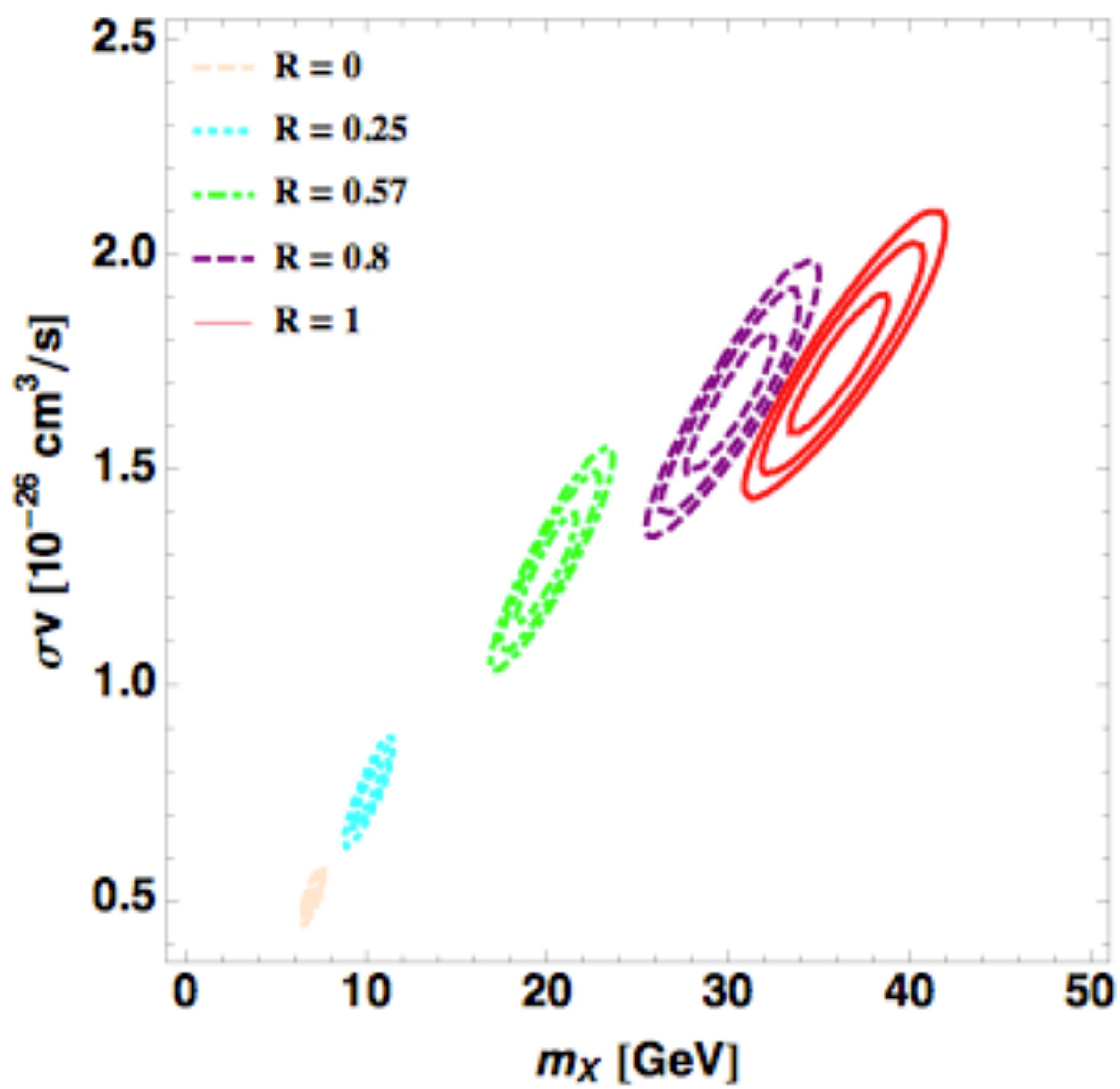
R: determined by model parameters



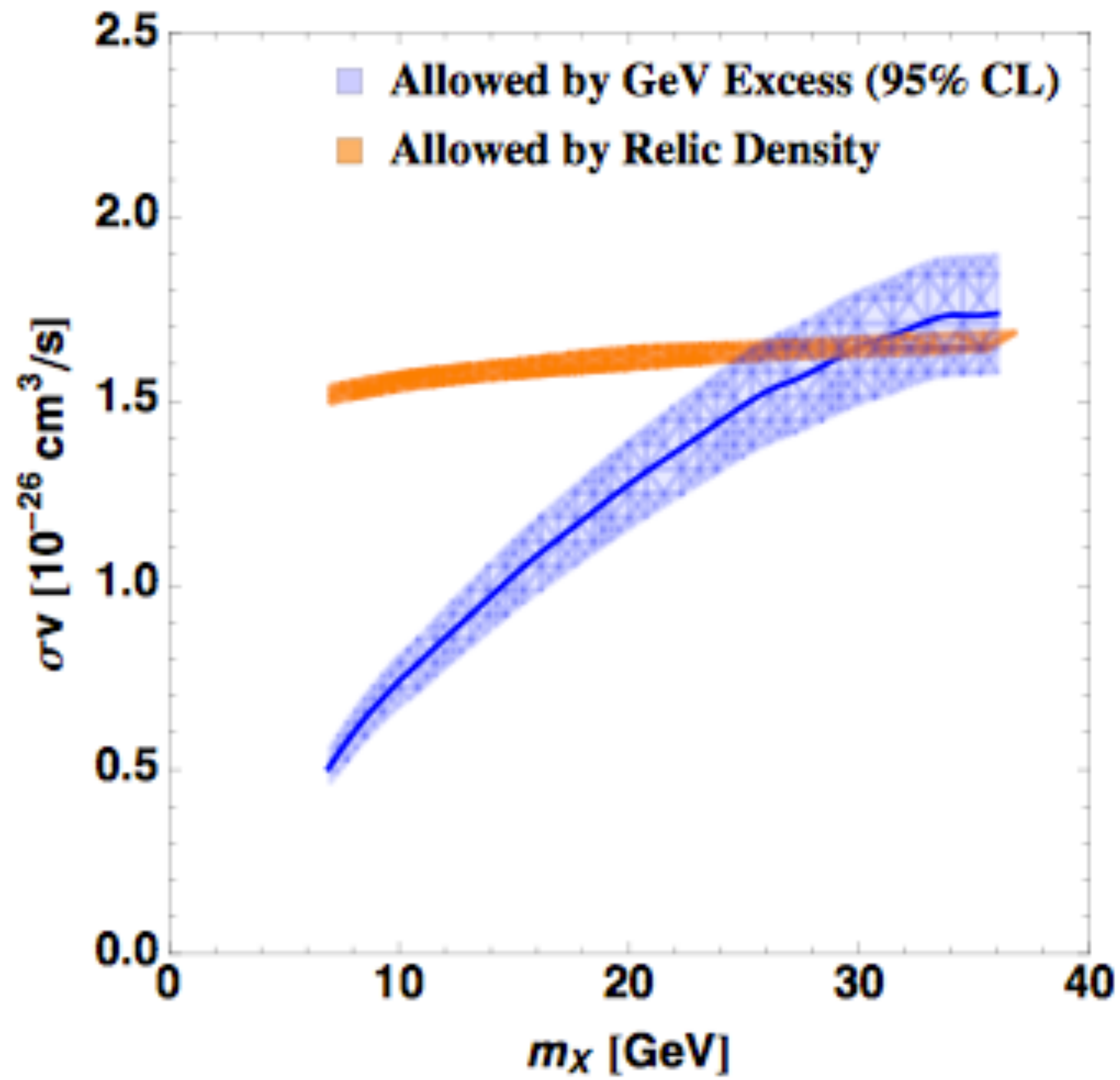
Data taken from Daylan+2014

Explain GeV Excess

Best Fit

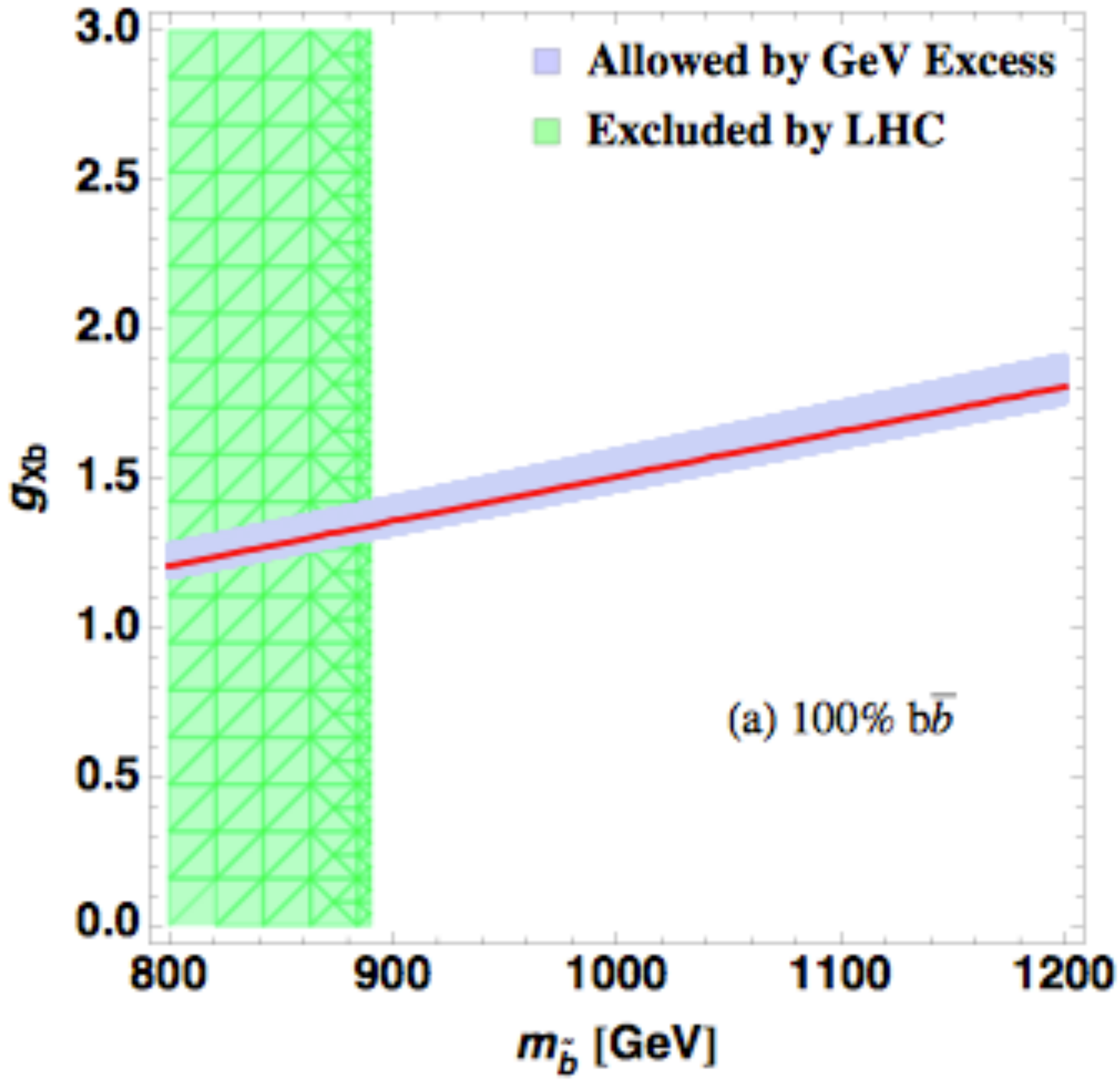


Parameter Scan

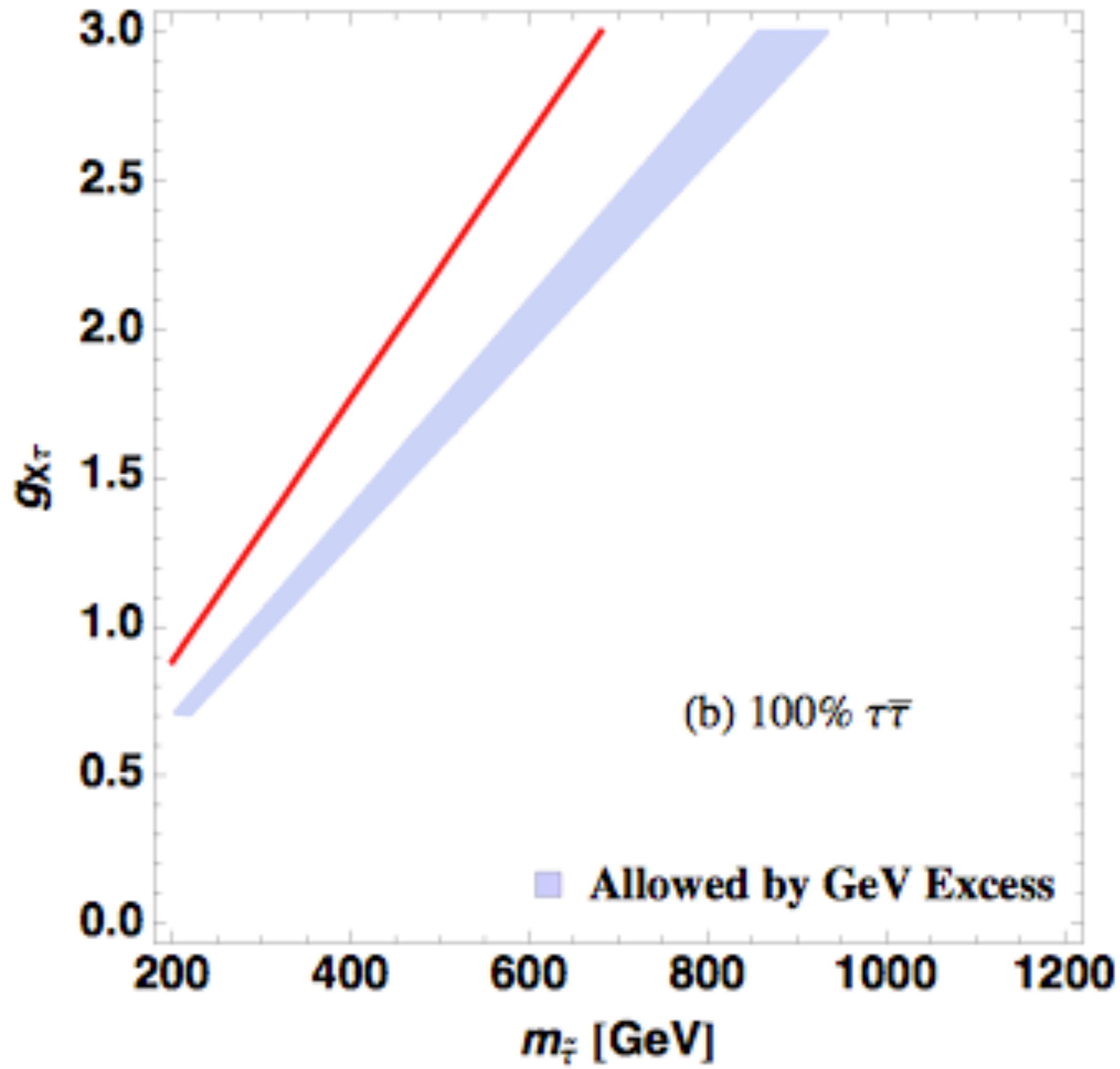


Explain GeV Excess

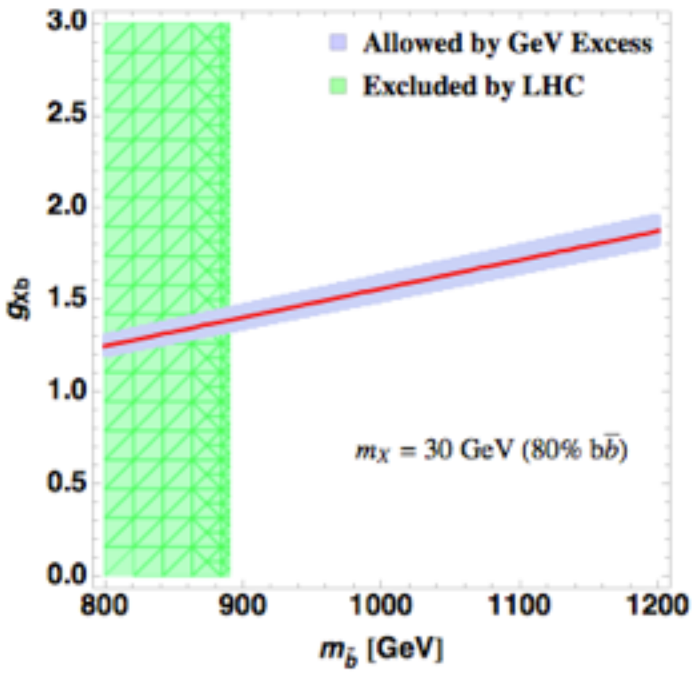
bb OK

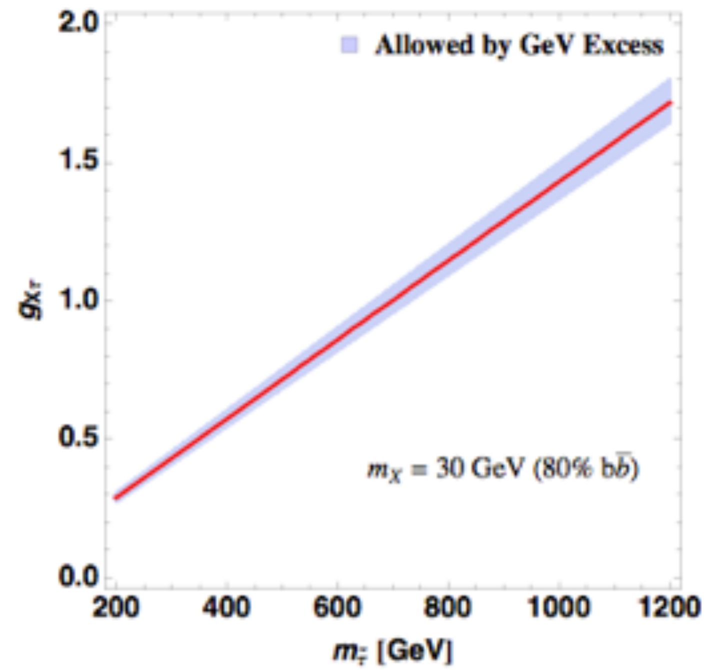


Pure tautau doesn't work

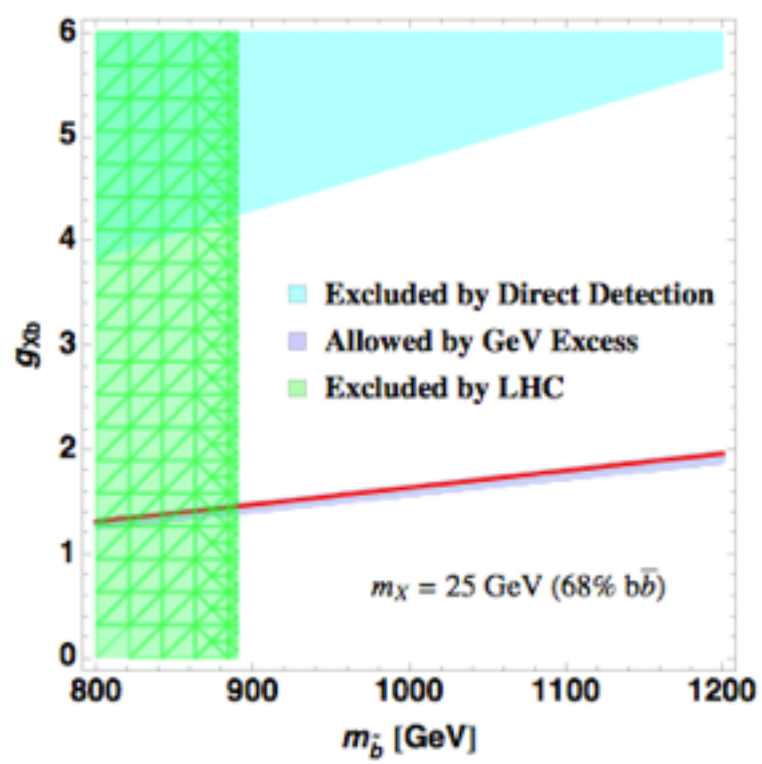


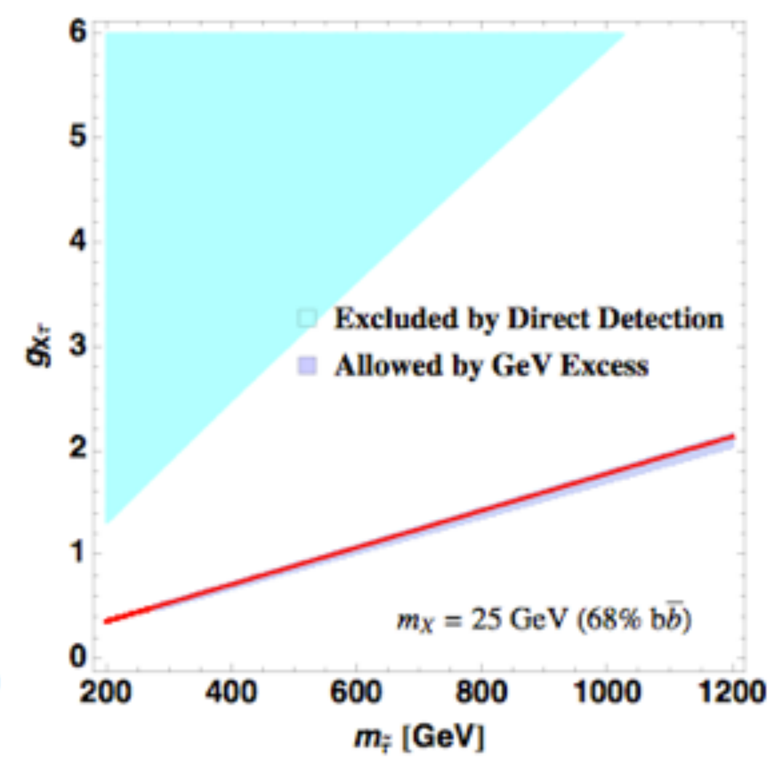
Explain GeV Excess





Mixed bb and tautau is fine (not excluded by antiproton data)





Summary

- As a simplified model, flavor portal dark matter has many interesting features.

- Scalar flavor portal DM is ruled out; fermion flavor portal DM is ok, but hard to explain GeV excess

- Vector fermion-portal dark matter could explain Galactic Center GeV excess.

- Direct detection constraints are weak due to the weak constraints on SD cross section

- A SU(2) x U(1) x U(1) model with T-parity could generate Vector fermion-portal dark matter

Thank You

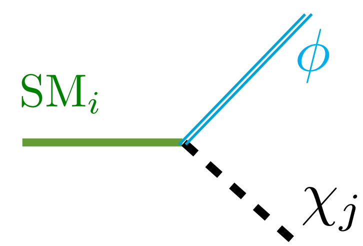
BackUp Slides

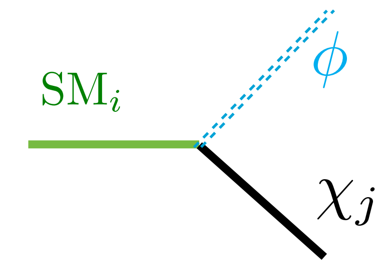
Flavored Dark Matter

- Flavored dark matter (FDM)

SM = Q, u, d: quark FDM
SM = L, e: lepton FDM

consider quark/lepton singlet

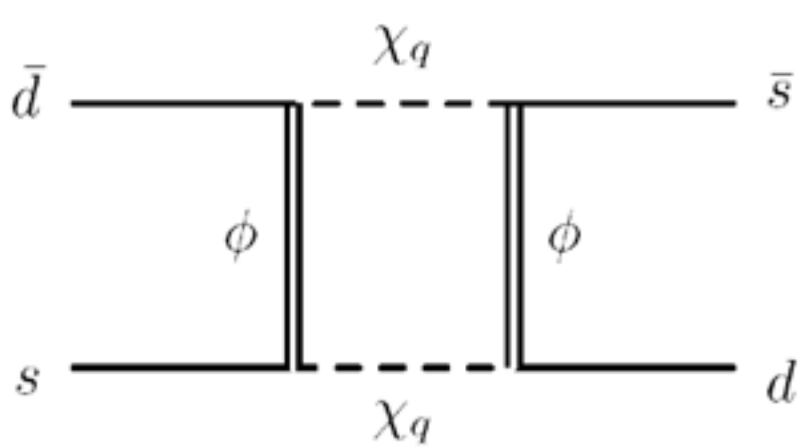




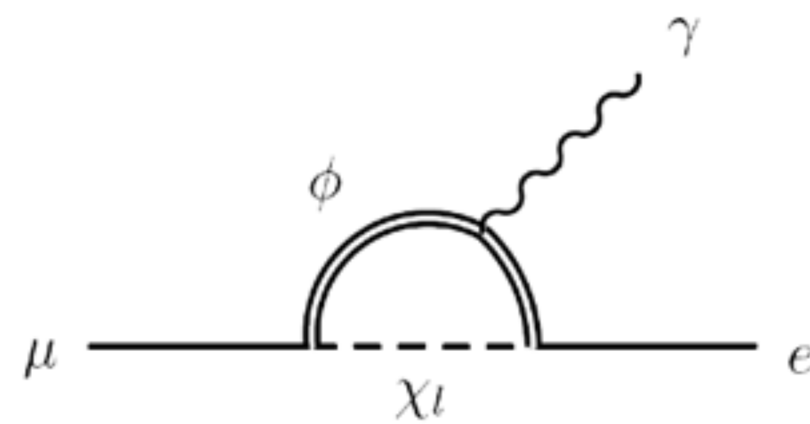
$$\mathcal{L} \supset \lambda_{ij}\, q_i^c\, \chi_j\, \phi + \mathrm{h.c.}$$

$$\mathcal{L} \supset \lambda_{ij}\, l_i^c\, \chi_j\, \phi + \mathrm{h.c.}$$

- Flavor violating processes



Assume minimal flavor violation (MFV) to avoid flavor problem



complex scalar χ + Dirac mediator ϕ

$$\lambda_{ij} = [\alpha I + \beta y^\dagger y]_{ij}, \quad \alpha \gg \beta$$

Can Kilic's talk

Yukawa Terms

$$\mathcal{L} \supset \overline{Q_1} H_1 \psi_1 + \overline{Q_2} H_2 \psi_2 + h.c.$$

	$SU(2)_L$	$U(1)_1$	$U(1)_2$
H_1	2	$\frac{Y}{\sqrt{2}}$	0
H_2	2	0	$\frac{Y}{\sqrt{2}}$
ϕ	1	$\frac{Y}{\sqrt{2}}$	$-\frac{Y}{\sqrt{2}}$
Q_{1L}	2	$\frac{Y_1}{\sqrt{2}}$	$\frac{Y_2}{\sqrt{2}}$
Q_{2L}	2	$\frac{Y_2}{\sqrt{2}}$	$\frac{Y_1}{\sqrt{2}}$
b_{1R}	1	Y_1	Y_2
b_{2R}	1	Y_2	Y_1
t_{1R}	1	Y_1	Y_2
t_{2R}	1	Y_2	Y_1

$$B^\mu = \frac{1}{\sqrt{2}}(B_1^\mu + B_2^\mu),$$
$$X^\mu = \frac{1}{\sqrt{2}}(B_1^\mu - B_2^\mu),$$
$$H = \frac{1}{\sqrt{2}}(H_1 + H_2),$$
$$S = \frac{1}{\sqrt{2}}(H_1 - H_2),$$

$$H_1 \leftrightarrow H_2 \text{ and } B_1^\mu \leftrightarrow B_2^\mu$$

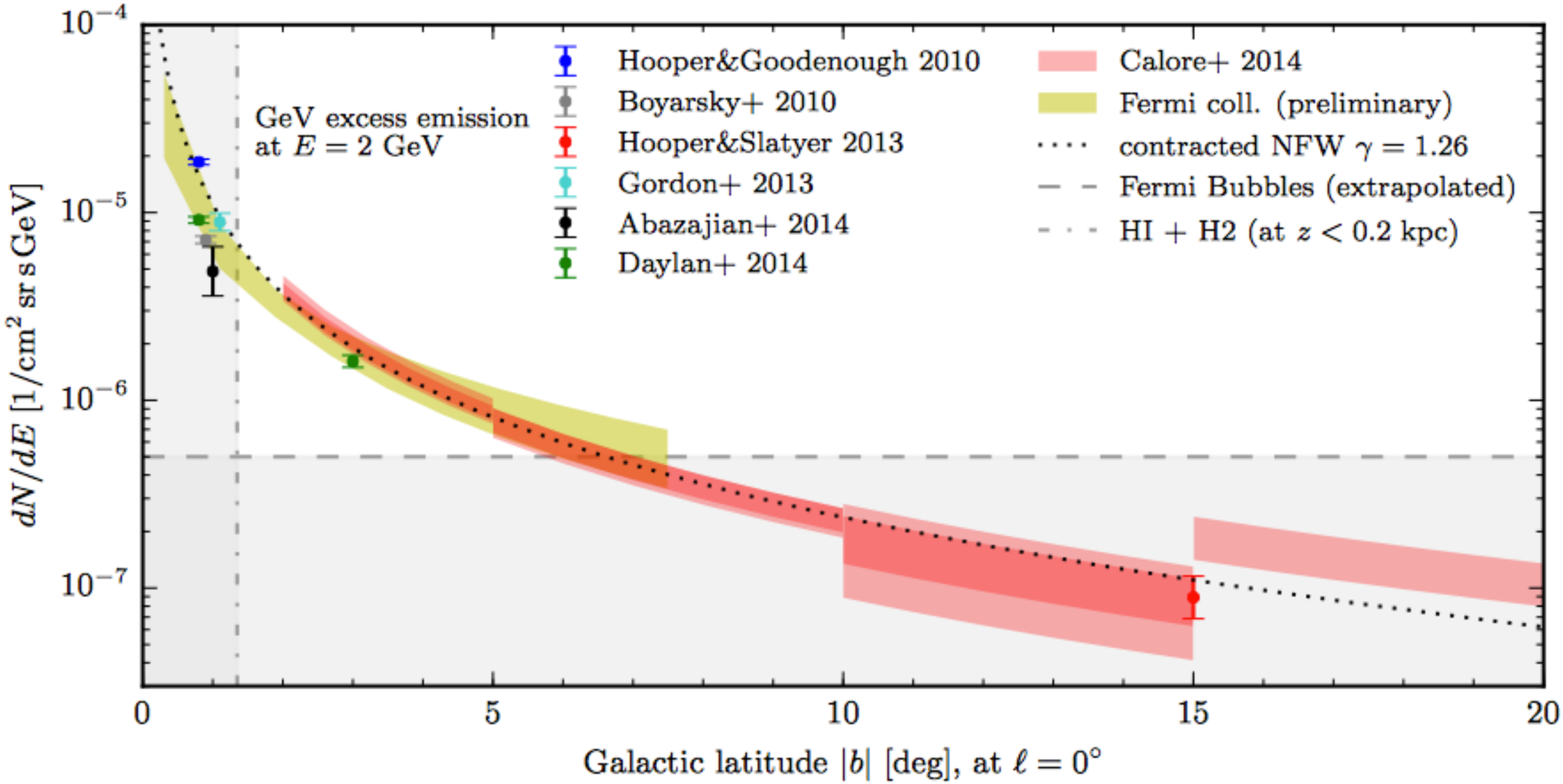
$$f_R = \frac{1}{\sqrt{2}}(\psi_1 - \psi_2),$$
$$F_R = \frac{1}{\sqrt{2}}(\psi_1 + \psi_2).$$
$$Q_L = \frac{1}{\sqrt{2}}(Q_1 - Q_2),$$
$$Q'_L = \frac{1}{\sqrt{2}}(Q_1 + Q_2).$$

$$\psi_1 \leftrightarrow -\psi_2 \text{ and } Q_1 \leftrightarrow -Q_2$$

No anomaly

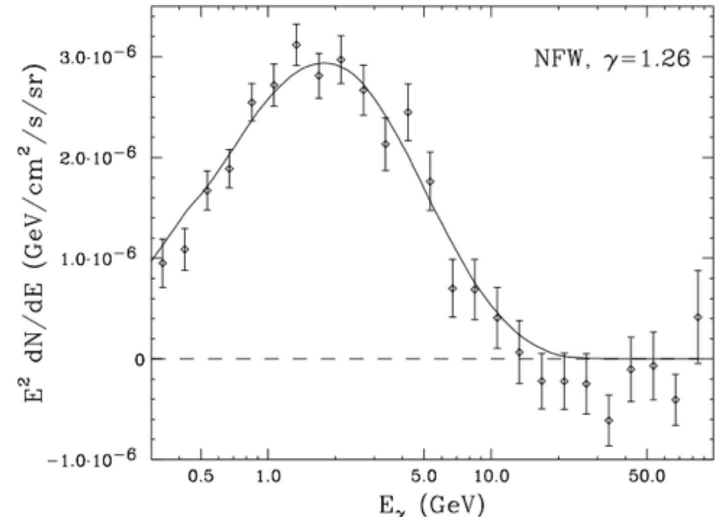
$$\mathcal{L} \supset \overline{Q}_L H f_R + \overline{Q'}_L H F_R + \overline{Q'}_L S f_R + \overline{Q}_L S F_R + h.c.$$

Galactic Center and Inner Galaxy



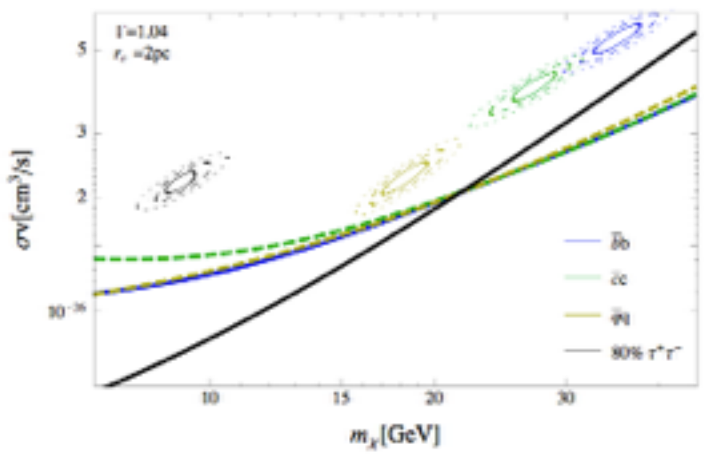
Calore, Cholis, Weniger 2014

Dark Matter Explanations on 2014



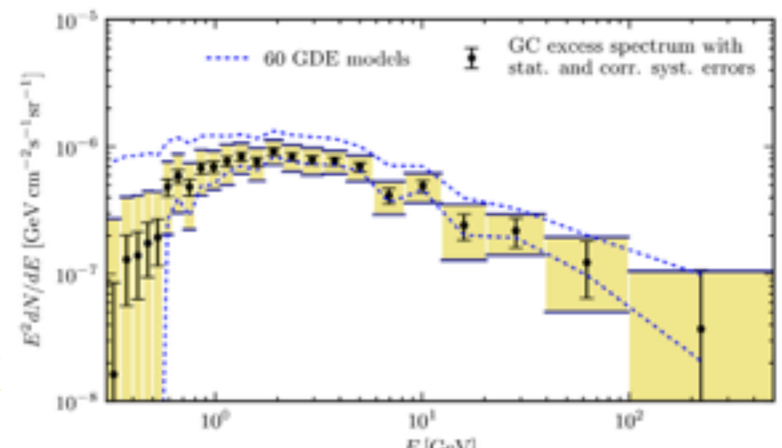
02/2014: favor bb, tautau

Abazajian+ 2014
Daylan+2014



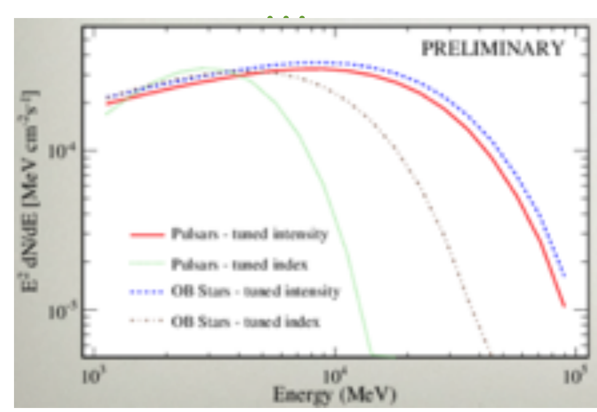
06/2014 bb (antiproton)

Bringmann, Vollmann, Weniger, 14'



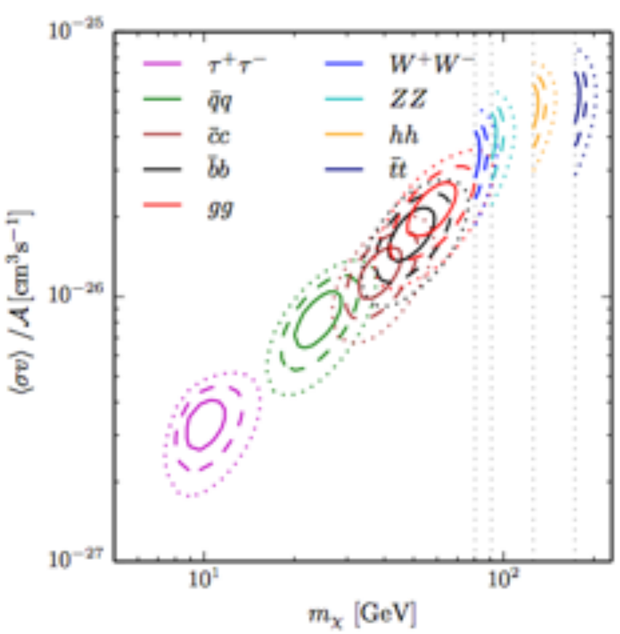
09/2014 harder Tail

Calore, Cholis, Weniger 2014



10/2014 Fermi-LAT

Murgia for Fermi-LAT 2014



11/2014: favor bb,hh,VV, tt

Calore+ 2014
Agrawal+ 2014

Personal view