

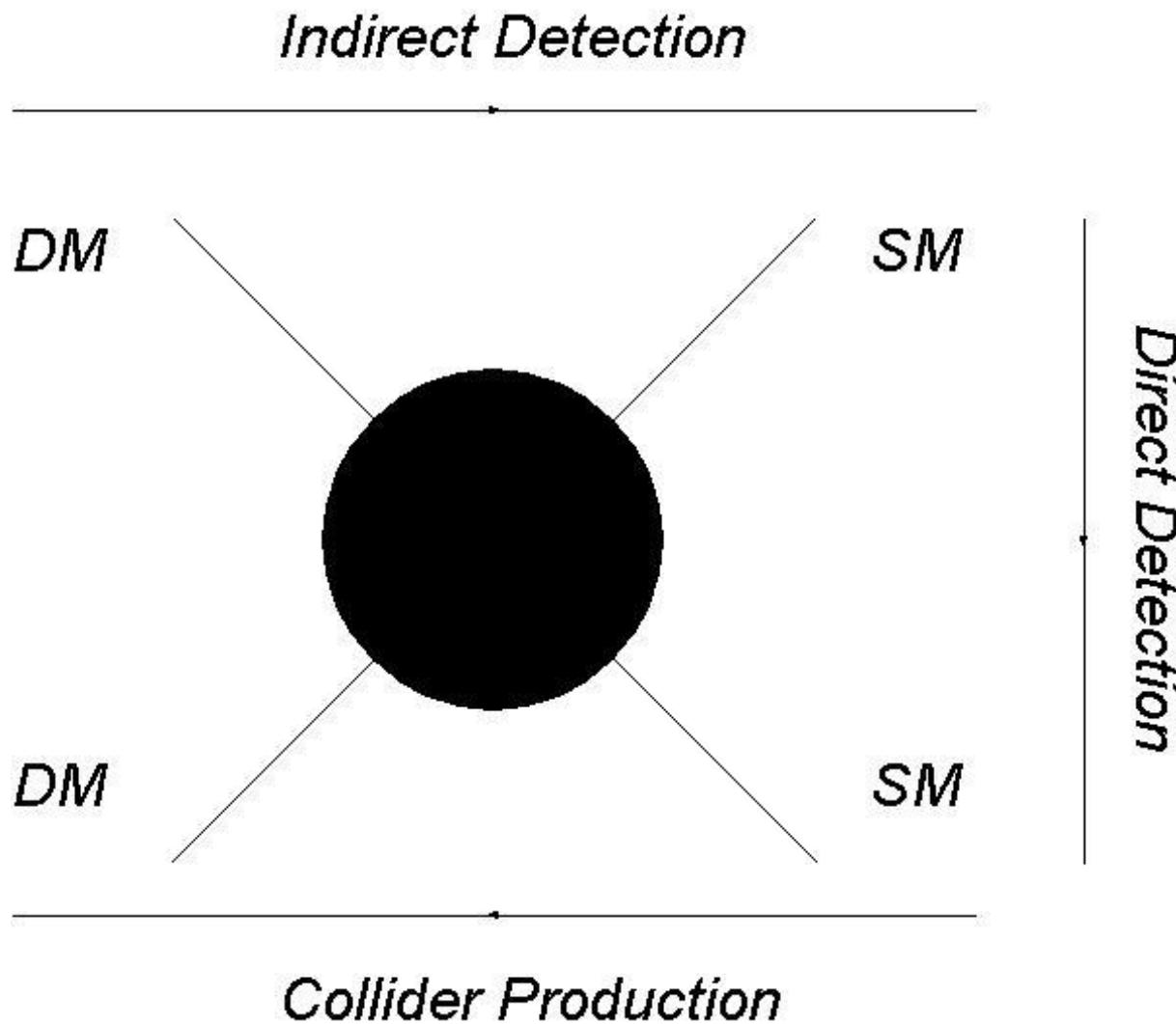


Dark Matter and Complementarity

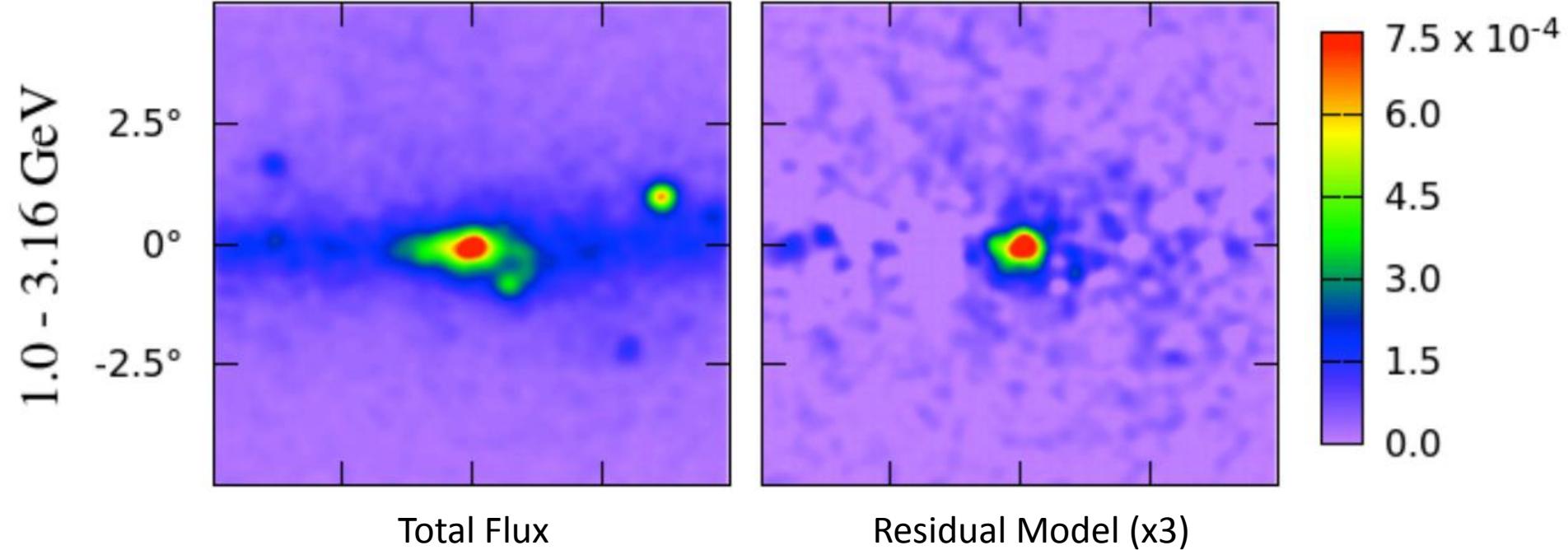
Alexander M. Wijangco
UC Irvine

Work done with:
M. Abdullah, A. DiFranzo, A. Rajaraman,
T. M.P. Tait, P. Tanedo
arXiv:1404.6528 [hep-ph]

What is complementarity?

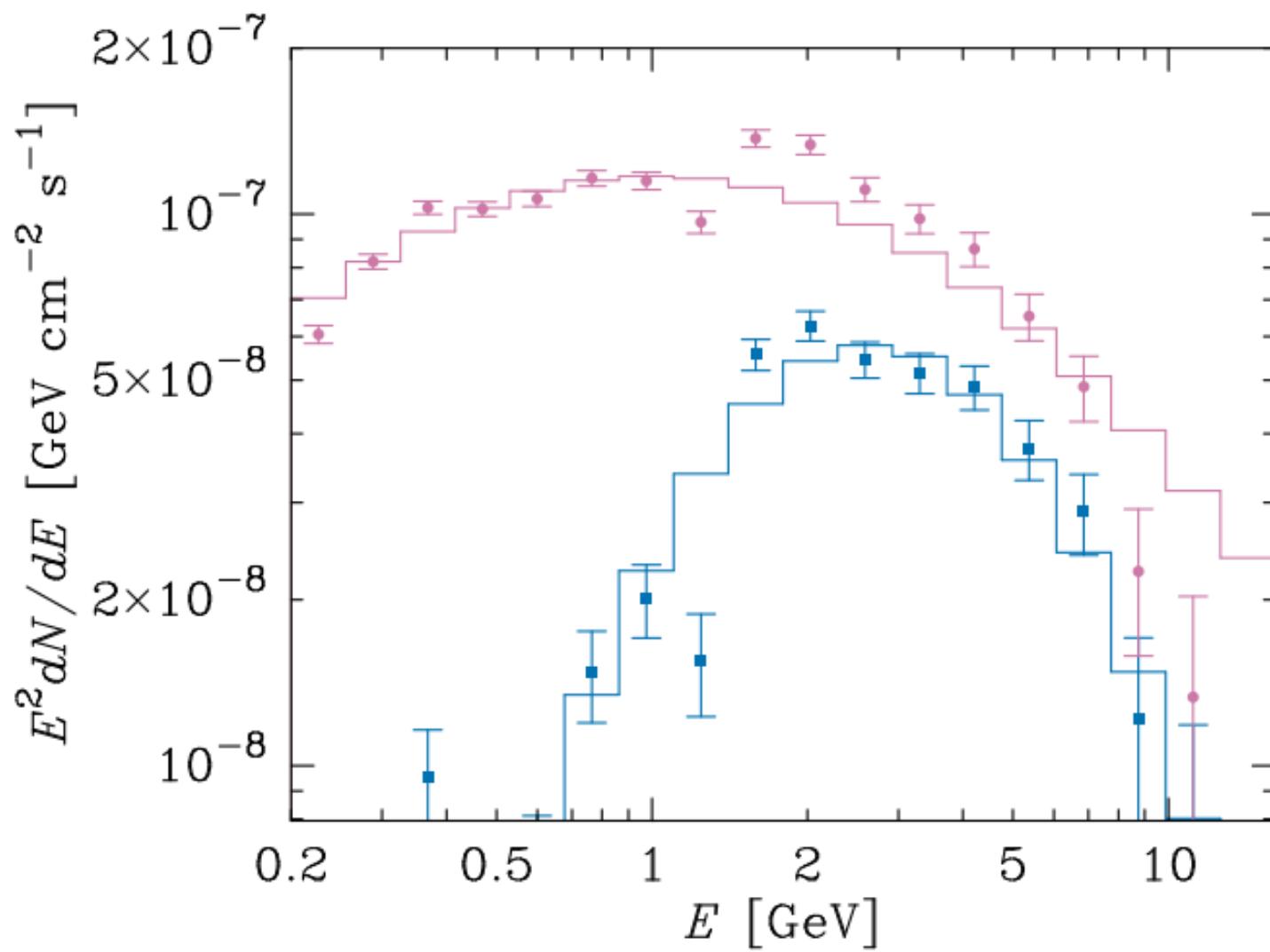


What is the Galactic Center Excess?



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

T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N.L. Rodd and T. R. Slatyer, "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter," arXiv:1402.6703 [astro-ph.HE]



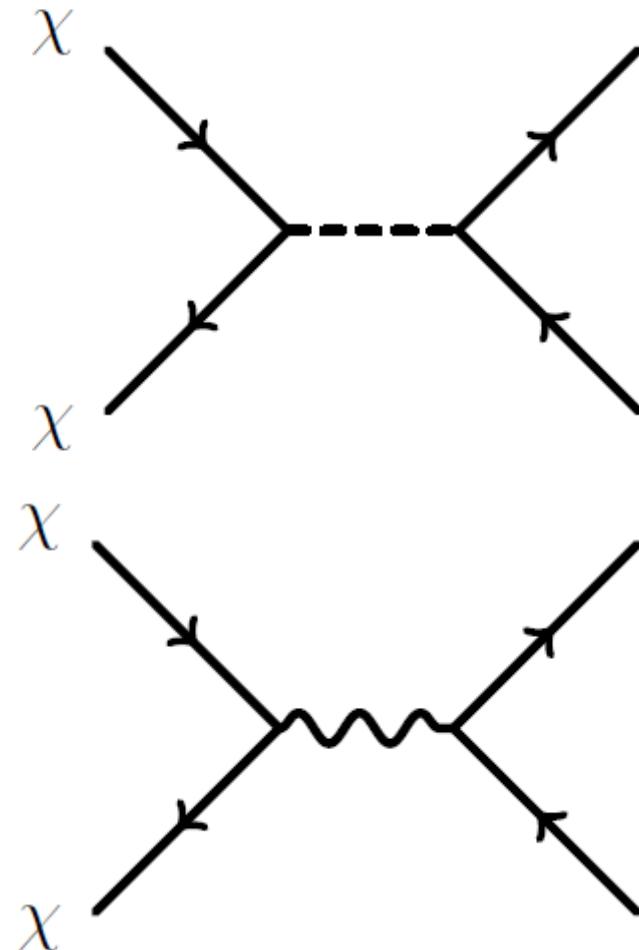
$$\sigma v = 5.1 \times 10^{-26} \text{ cm}^3/\text{s}$$

Particle Physics Models for the Galactic Center

- Inputs from the galactic center:
 - Value of σv is suggestive of thermal WIMP
 - S-wave DM annihilation
 - Annihilation should produce τ or b particles
 - The resulting τ or b should have a particular energy to reproduce the observed spectrum

Two Body Annihilation

- Two WIMPs meet and become a pair of SM particles
- Both resulting particles have the energy of the WIMP mass in the center of mass frame
- Since WIMPs are non relativistic, that frame is typically the galactic frame



Two Body Annihilation has been extensively explored

- Effective Interactions
 - A. Alves *et al.* arXiv:1403.5027 [hep-ph]
- Simplified Models
 - A. Berlin *et al.* arXiv:1404.0022 [hep-ph]
 - C. Boehm *et al.* arXiv:1401.6458 [hep-ph]
 - E. Izaguirre *et al.* arXiv:1404.2018 [hep-ph]
 - P. Agrawal *et al.* arXiv:1404.1373 [hep-ph]
- UV Models
 - S. Ipek *et al.* arXiv:1404.3716 [hep-ph]

Effective Operators

$$\frac{m_q}{M_*^3} \bar{\chi}\chi \bar{q}q \quad (\text{D1})$$

$$\frac{m_q}{M_*^3} \bar{\chi}\gamma^5\chi \bar{q}q \quad (\text{D2})$$

$$\frac{m_q}{M_*^3} \bar{\chi}\chi \bar{q}\gamma^5 q \quad (\text{D3})$$

$$\frac{m_q}{M_*^3} \bar{\chi}\gamma^5\chi \bar{q}\gamma^5 q \quad (\text{D4})$$

$$\frac{1}{M_*^2} \bar{\chi}\gamma^\mu\chi \bar{q}\gamma_\mu q \quad (\text{D5})$$

$$\frac{1}{M_*^2} \bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu q \quad (\text{D6})$$

$$\frac{1}{M_*^2} \bar{\chi}\gamma^\mu\chi \bar{q}\gamma_m u\gamma^5 q \quad (\text{D7})$$

$$\frac{1}{M_*^2} \bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu\gamma^5 q \quad (\text{D8})$$

$$\frac{1}{M_*^2} \bar{\chi}\sigma^{\mu\nu}\chi \bar{q}\sigma_{\mu\nu} q \quad (\text{D9})$$

$$\frac{1}{M_*^2} \epsilon^{\mu\nu\alpha\beta} \bar{\chi}\sigma_{\mu\nu}\chi \bar{q}\sigma_{\alpha\beta} q \quad (\text{D10})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi}\chi \left(G_{\mu\nu}^a\right)^2 \quad (\text{D11})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi}\gamma^5\chi \left(G_{\mu\nu}^a\right)^2 \quad (\text{D12})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi}\chi G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \quad (\text{D13})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi}\gamma^5\chi G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \quad (\text{D14})$$

Effective Operators

$$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q \quad (\text{D1})$$

$$\frac{m_q}{M_*^3} \bar{\chi} \gamma^5 \chi \bar{q} q \quad (\text{D2})$$

$$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} \gamma^5 q \quad (\text{D3})$$

$$\frac{m_q}{M_*^3} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q \quad (\text{D4})$$

$$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \quad (\text{D5})$$

$$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu q \quad (\text{D6})$$

$$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_m u \gamma^5 q \quad (\text{D7})$$

$$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q \quad (\text{D8})$$

$$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \quad (\text{D9})$$

$$\frac{1}{M_*^2} \epsilon^{\mu\nu\alpha\beta} \bar{\chi} \sigma_{\mu\nu} \chi \bar{q} \sigma_{\alpha\beta} q \quad (\text{D10})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi} \chi (G_{\mu\nu}^a)^2 \quad (\text{D11})$$

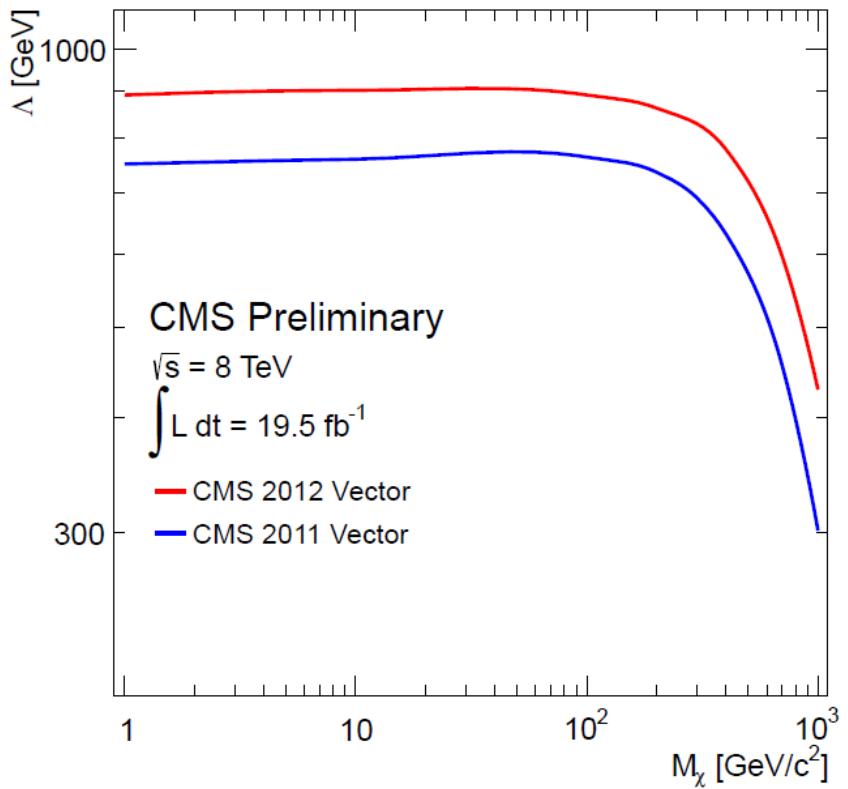
$$\frac{\alpha_s}{4M_*^3} \bar{\chi} \gamma^5 \chi (C_{\mu\nu}^a)^2 \quad (\text{D12})$$

$$\frac{\alpha_s}{4M_*^3} \bar{\chi} \chi G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \quad (\text{D13})$$

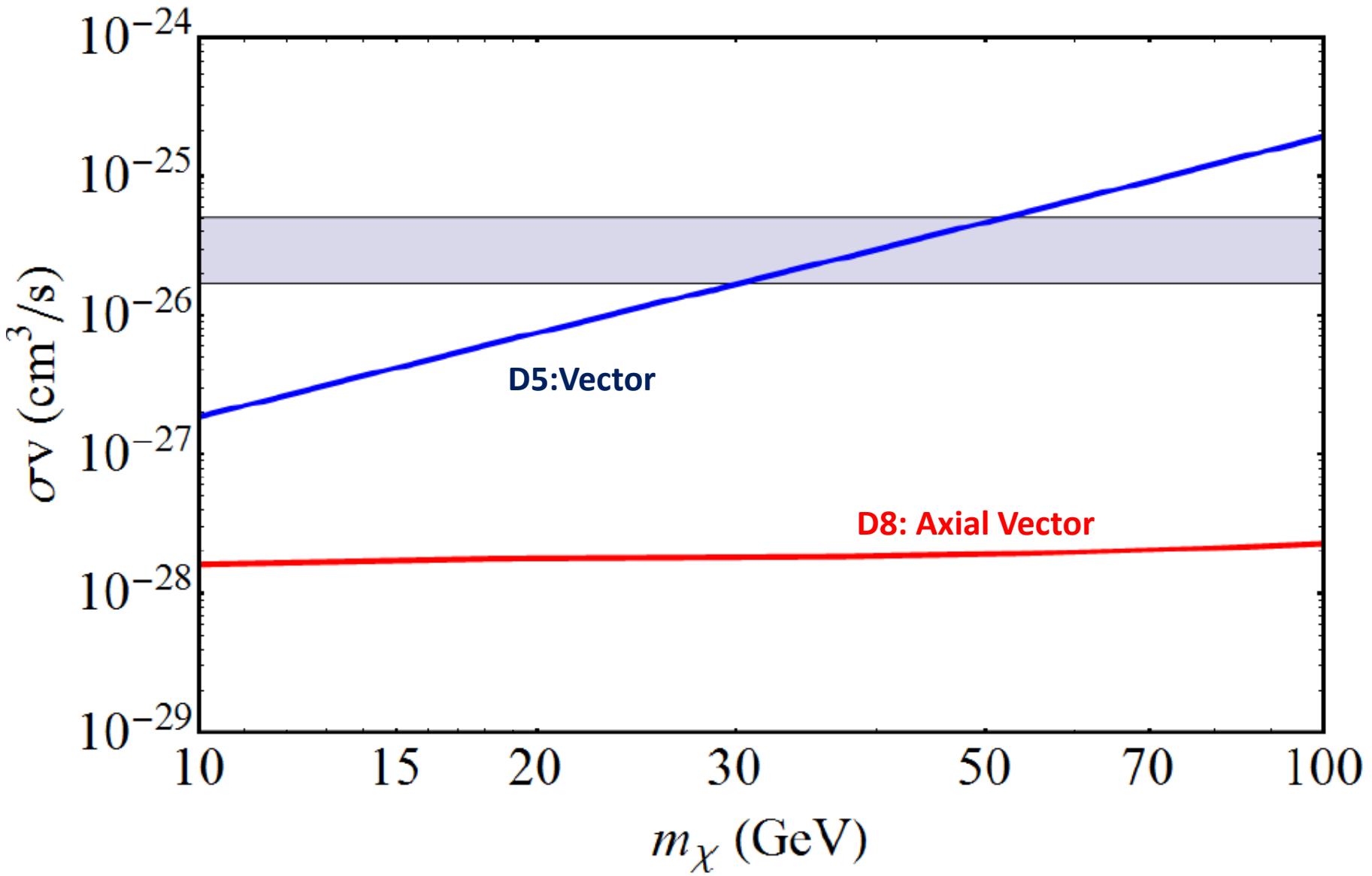
$$\frac{\alpha_s}{4M_*^3} \bar{\chi} \gamma^5 \chi C_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \quad (\text{D14})$$

CMS Monojet Search

- Attempt to produce a WIMP pair via quark annihilation
- Detectable events occur when the pair is recoiling off QCD ISR, resulting in a single jet and MET

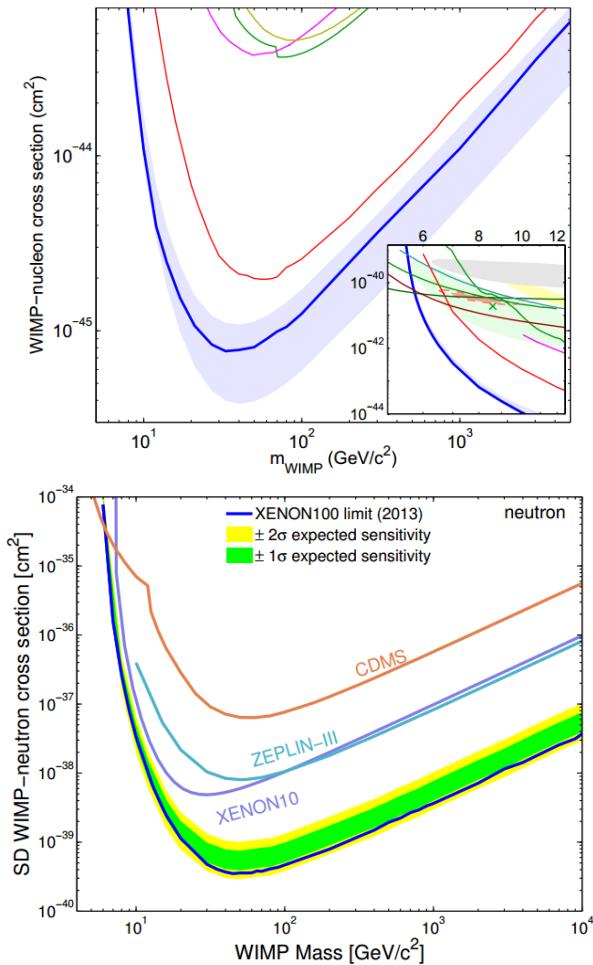


Bounds on Heavy Physics from Colliders



Direct Detection Nucleon Scattering

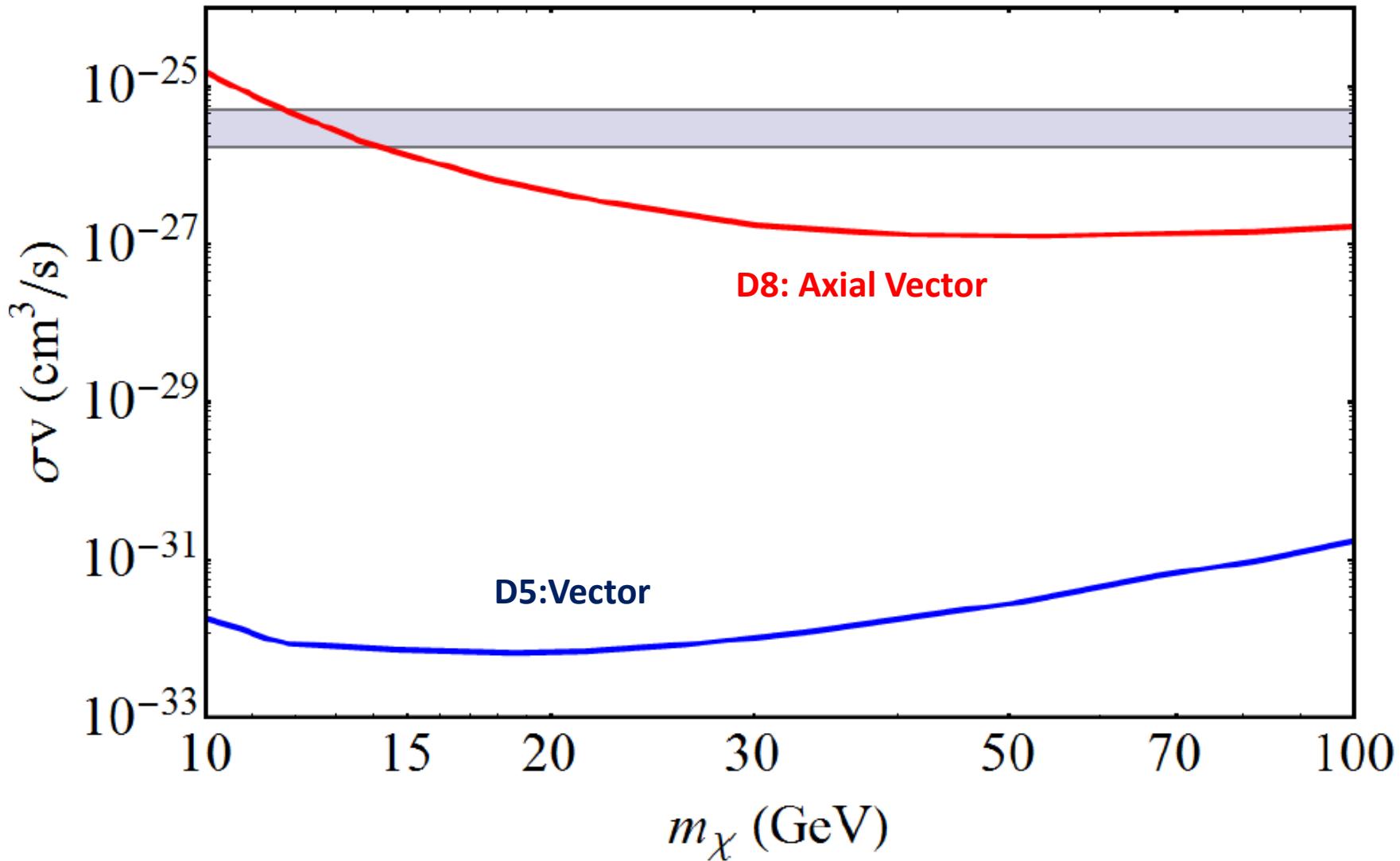
- Attempt to observe WIMP nucleon scattering
- This scattering may or may not be independent of the nucleus spin



D. S. Akerib *et al.* LUX Collaboration, “First results from the LUX dark matter experiment at the Sanford Underground Research Facility,” arXiv:1310.8214 [astro-ph.CO].

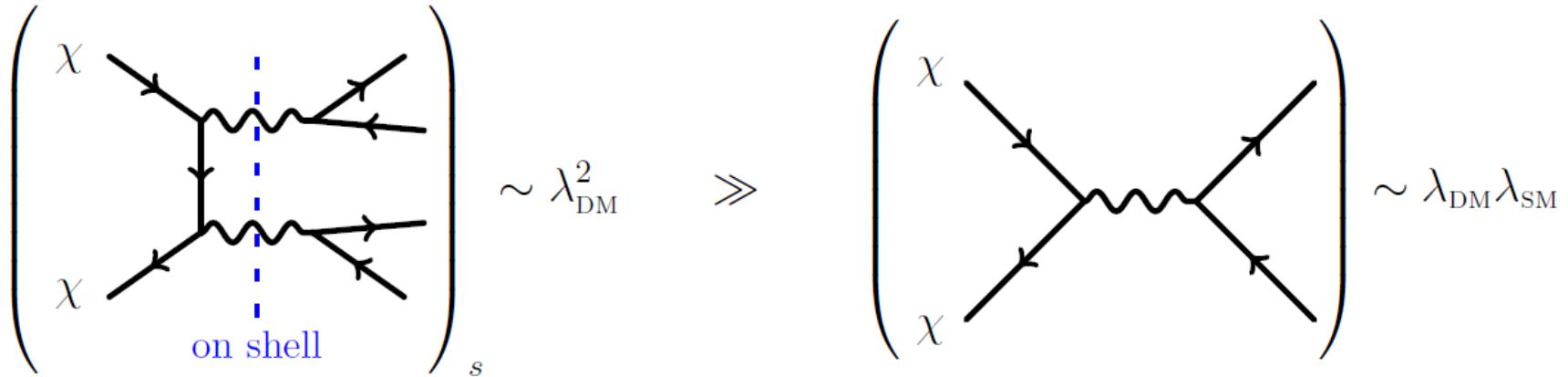
E. Aprile *et al.* XENON100 Collaboration, “Limits on spin-dependent WIMP-nucleon cross sections from 225 live days of XENON100 data,” Phys. Rev. Lett. **111**, no. 2, 021301 (2013) [arXiv:1301.6620 [astro-ph.CO]]

Bounds from Direct Detection

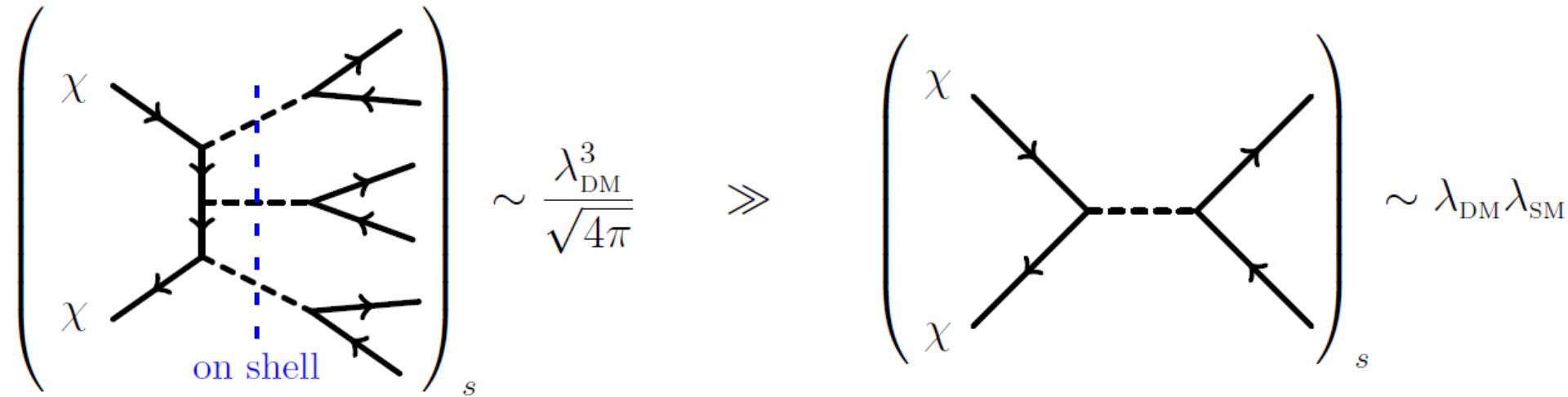


Solution: On-shell mediators

$$\mathcal{L}_{int} = \lambda_{DM} V^\mu \bar{\chi} \gamma_\mu (\gamma^5) \chi + \lambda_{SM} V^\mu \bar{q} \gamma_\mu (\gamma^5) q$$



$$\mathcal{L}_{int} = \lambda_{DM} \phi \bar{\chi} \gamma^5 \chi + \lambda_{SM} \phi \bar{q}_L (\gamma^5) q_R + H.C.$$



- Inputs from the galactic center:
 - Value of σv is suggestive of thermal WIMP
 - S-wave DM annihilation
 - Annihilation should produce τ or b particles
 - The resulting τ or b should have a particular energy
- Do on-shell mediators satisfy:
 - Allows for WIMPs
 - 2 vectors or 3 pseudoscalars
 - Resulting particles controlled by mediator couplings
 - Can get 40 GeV b quarks

Parameter space for the galactic center

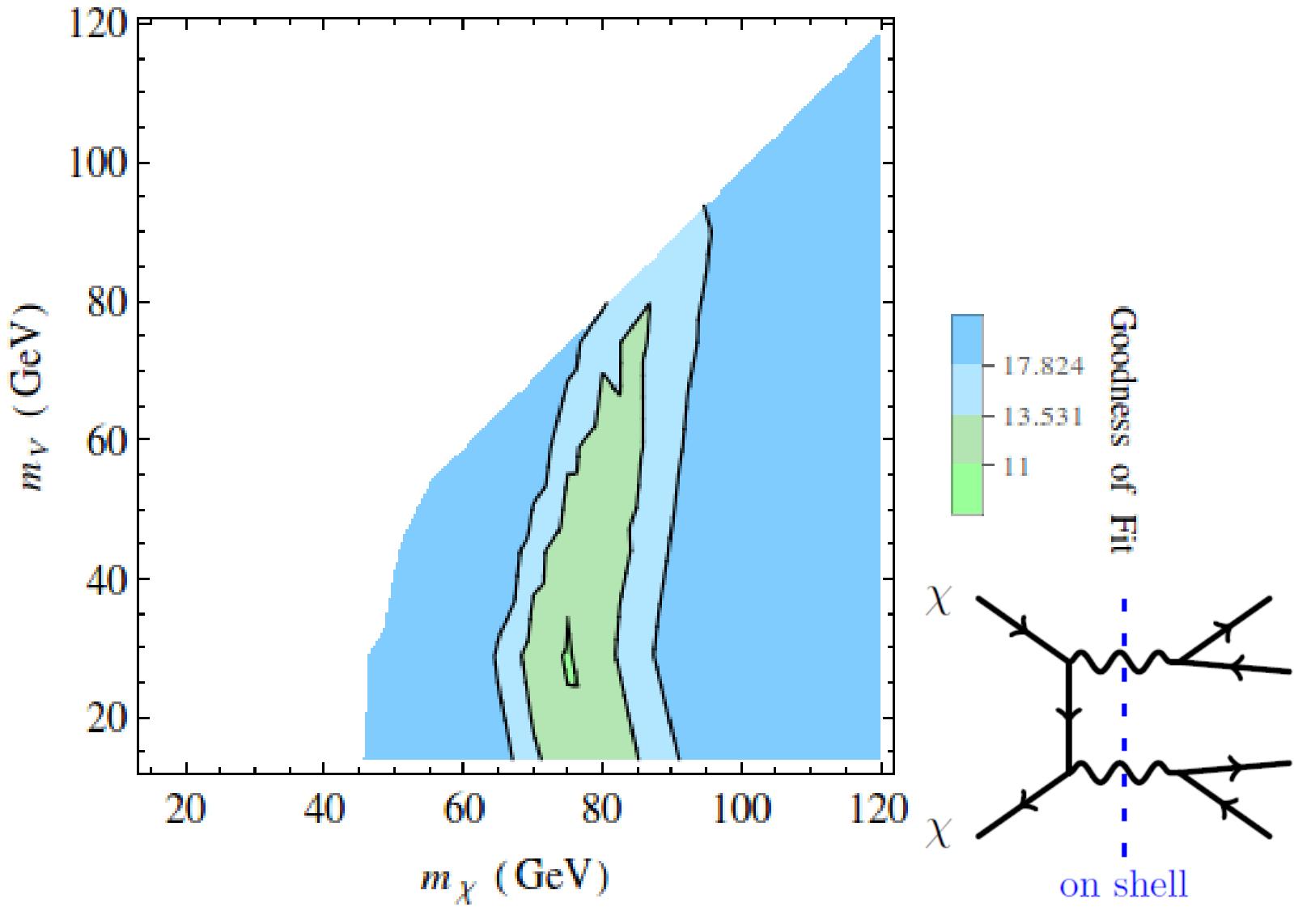
The relevant parameters are:

- WIMP mass: controls shape of the spectrum
- Mediator mass: controls shape of the spectrum
- DM Coupling: affects normalization

Since this fit is heavily dependent on the shape, we impose a 20% error on all residuals.

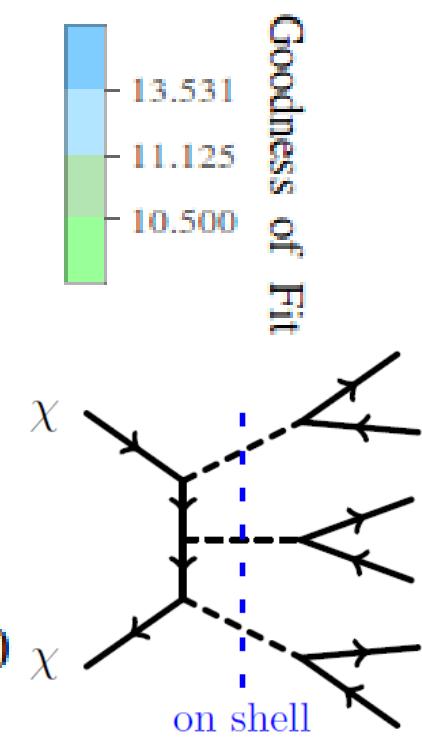
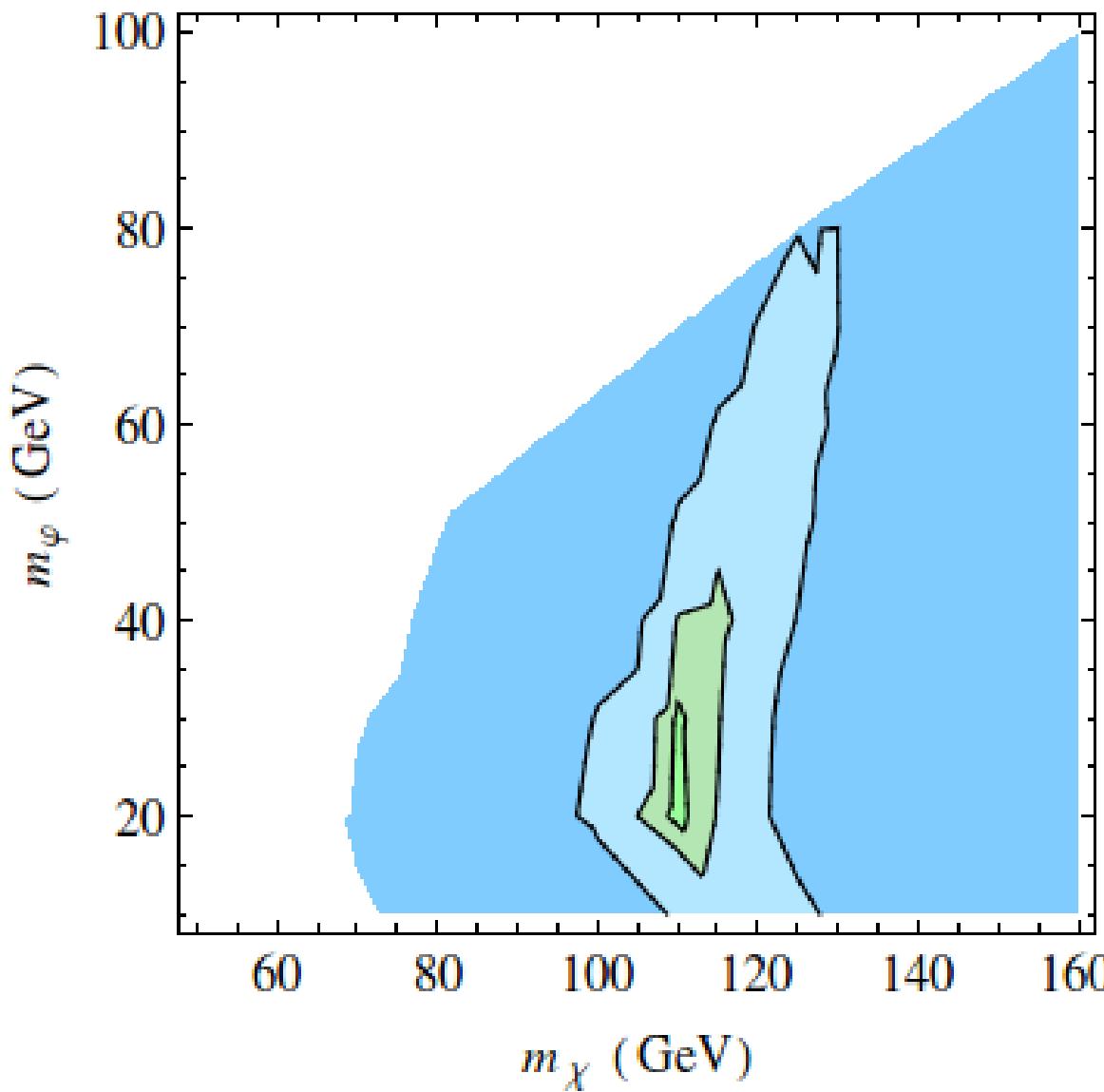
$$\text{goodness of fit} = \sum_i \left(\frac{\log D_i - \log (\lambda_{\text{DM}}^{2n} S_i)}{\log(0.2D_i)} \right)^2$$

Significance of Fit for 4 b Spectra – Vector

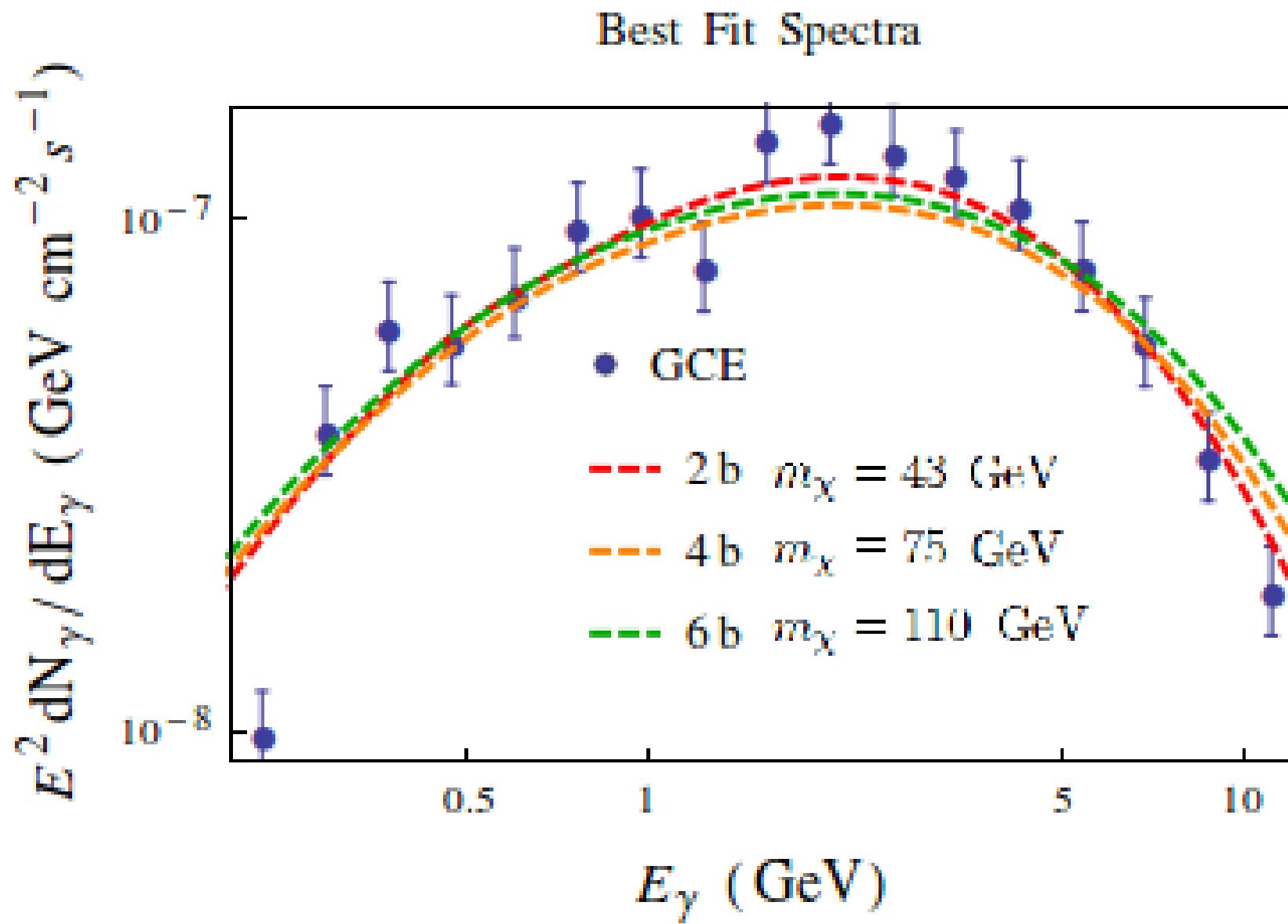


$$\lambda_{\text{DM}} \sim 0.27 - 0.44$$

Significance of Fit for 6 b Spectra – PseudoScalar



$$\lambda_{\text{DM}} \sim 1.1 - 1.4$$



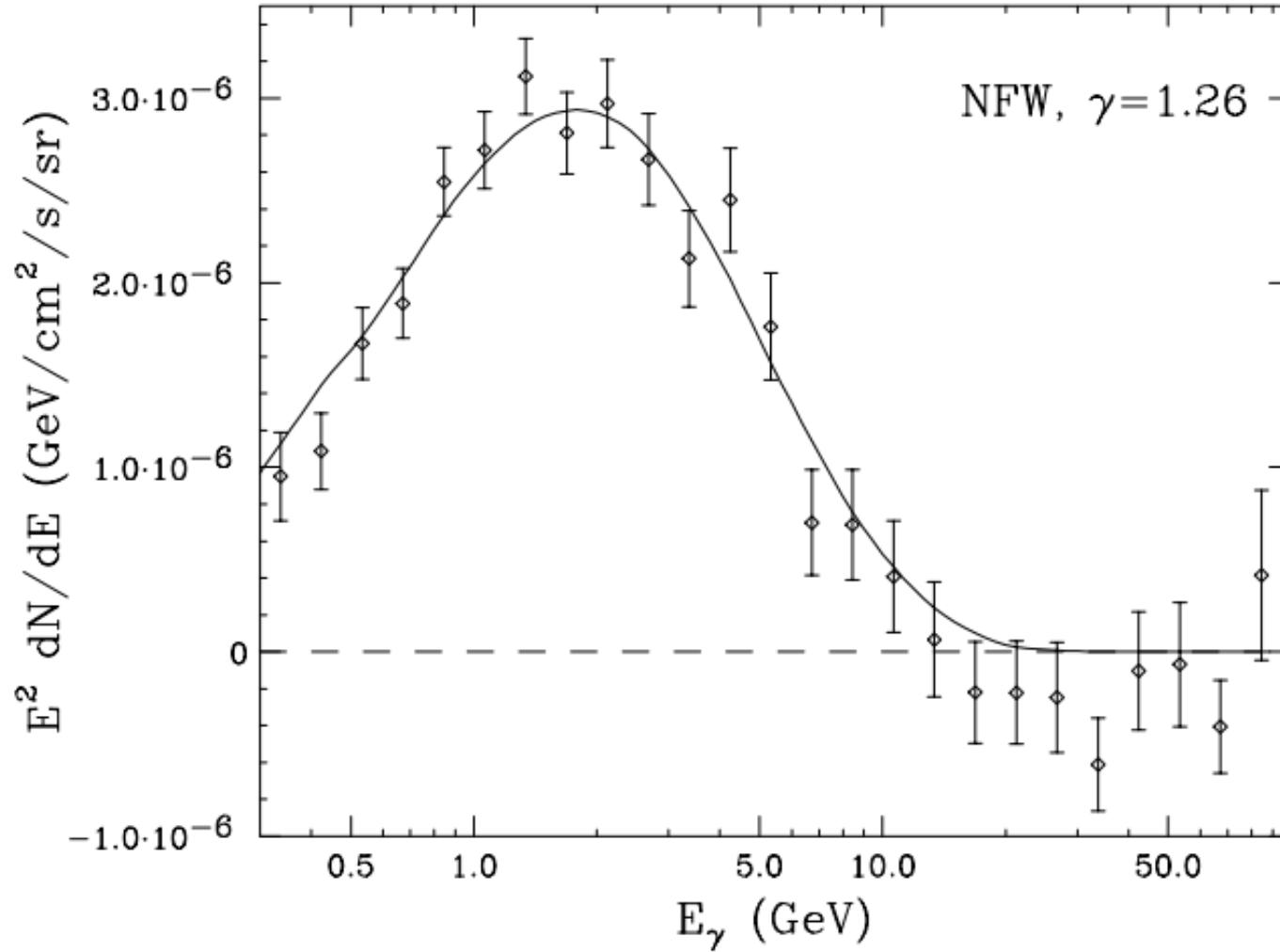
Other On-shell mediator scenarios

- C. Boehm, M. J. Dolan and C. McCabe
arXiv:1404.4977 [hep-ph]
- P. Ko, W.-I. Park and Y. Tang
arXiv:1404.5257[hep-ph]
- A. Martin, J. Shelton and J. Unwin
arXiv:1405.0272 [hep-ph]

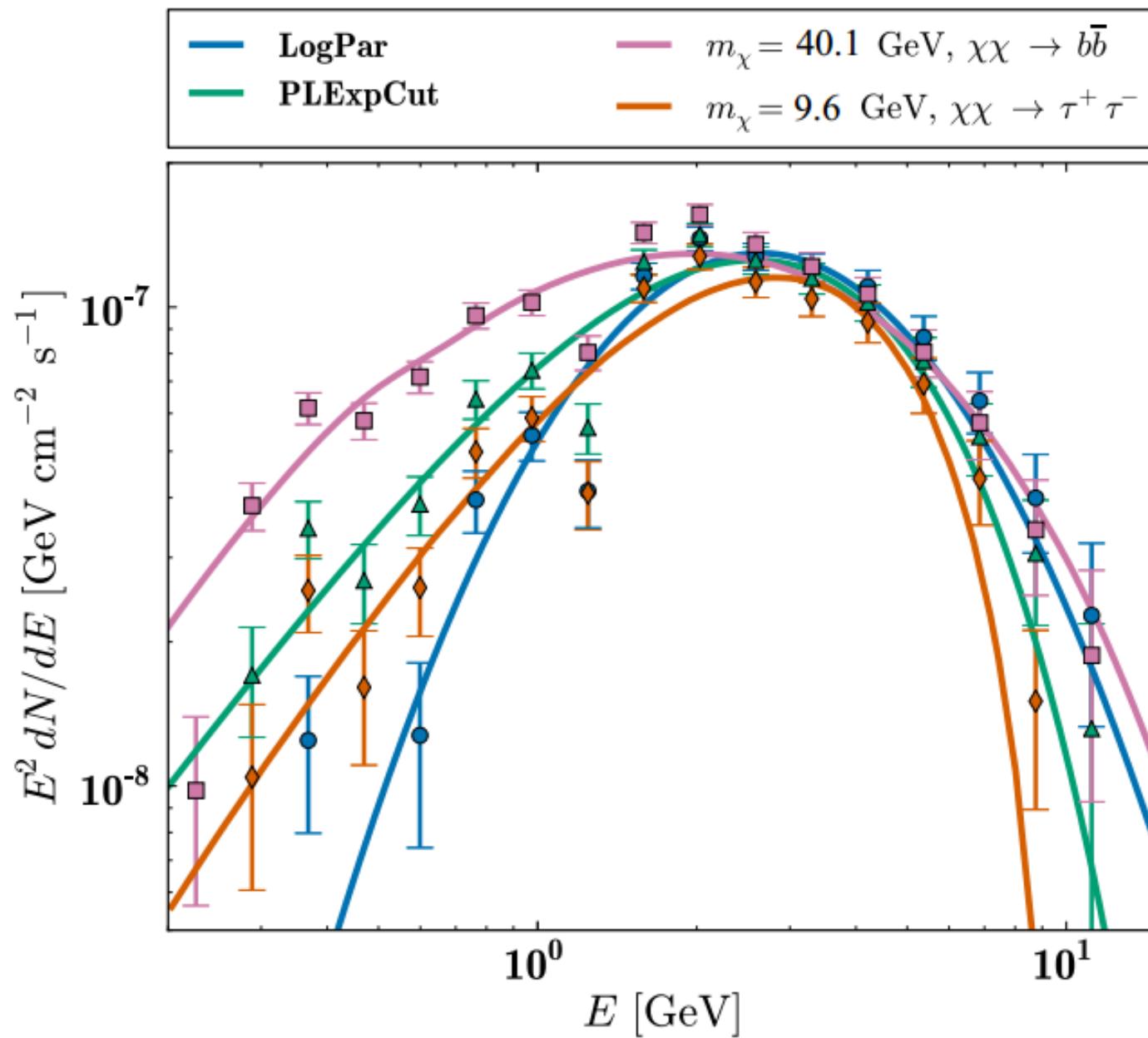
Conclusions

- On-shell mediators can be used to model the galactic center excess
 - WIMP mass 30-110 GeV
 - Excess can be explained with large amounts of freedom with regard to the standard model coupling

Backup Slides

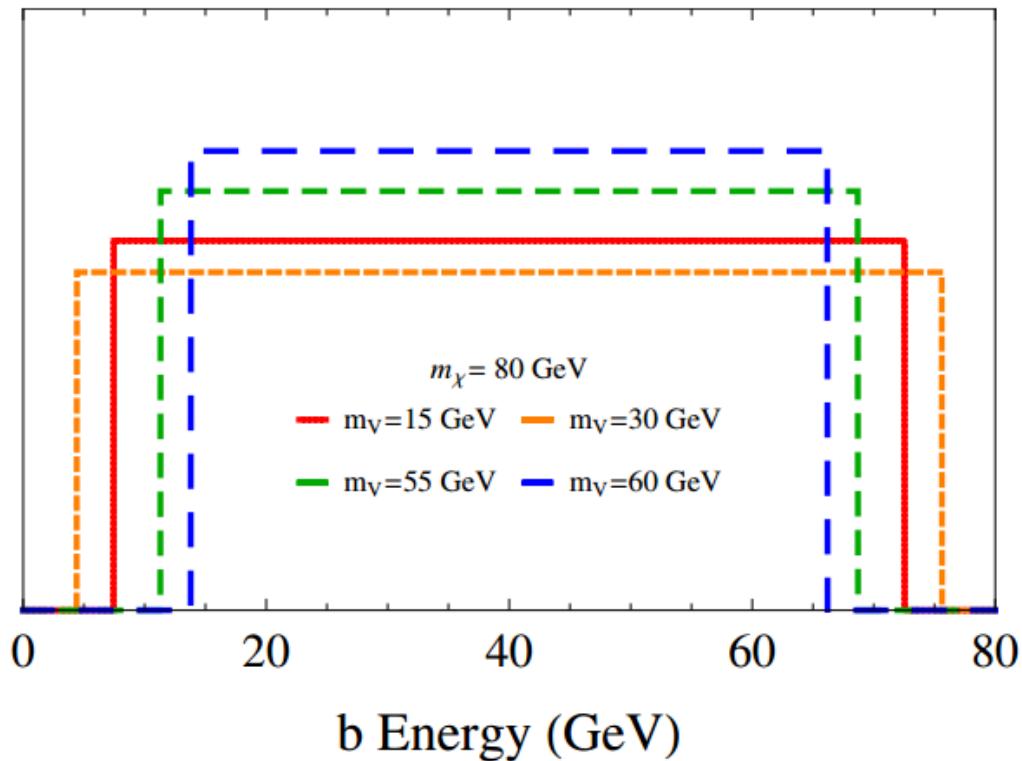


$$\sigma v = 1.7 \times 10^{-26} \text{ cm}^3/\text{s}$$



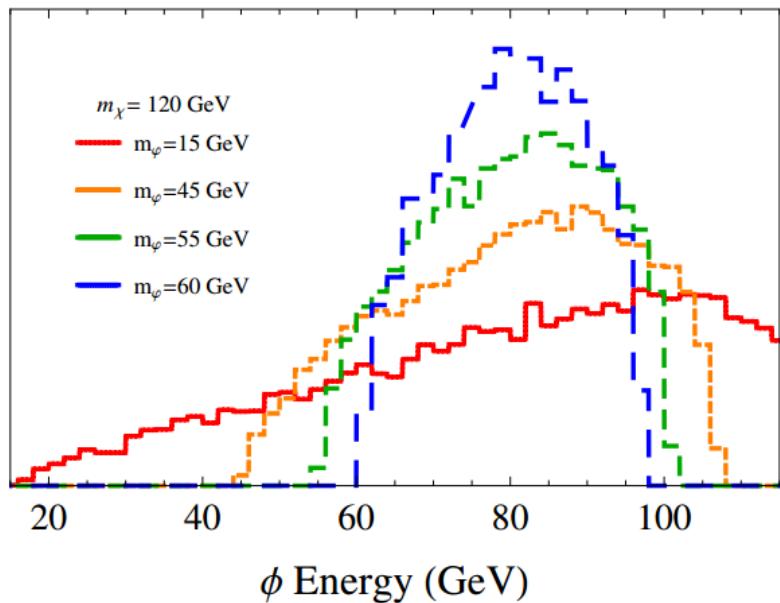
K. N. Abazajian, N. Canac, S. Horiuchi and M. Kaplinghat, “Astrophysical and Dark Matter Interpretations of Extended Gamma Ray Emission from the Galactic Center,” arXiv:1402.4090 [astro-ph.HE].

Spin 1 Mediator

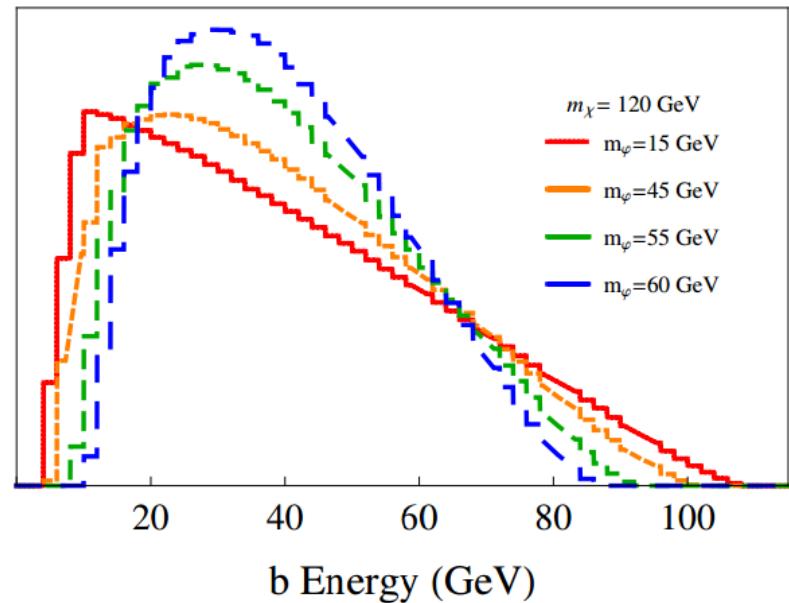


$$\chi\bar{\chi} \rightarrow VV \rightarrow 4b$$

Spin 0 Mediator



$$\chi\bar{\chi} \rightarrow 3\varphi$$



$$\chi\bar{\chi} \rightarrow 3\varphi \rightarrow 6b$$

