ON-SHELL MEDIATORS

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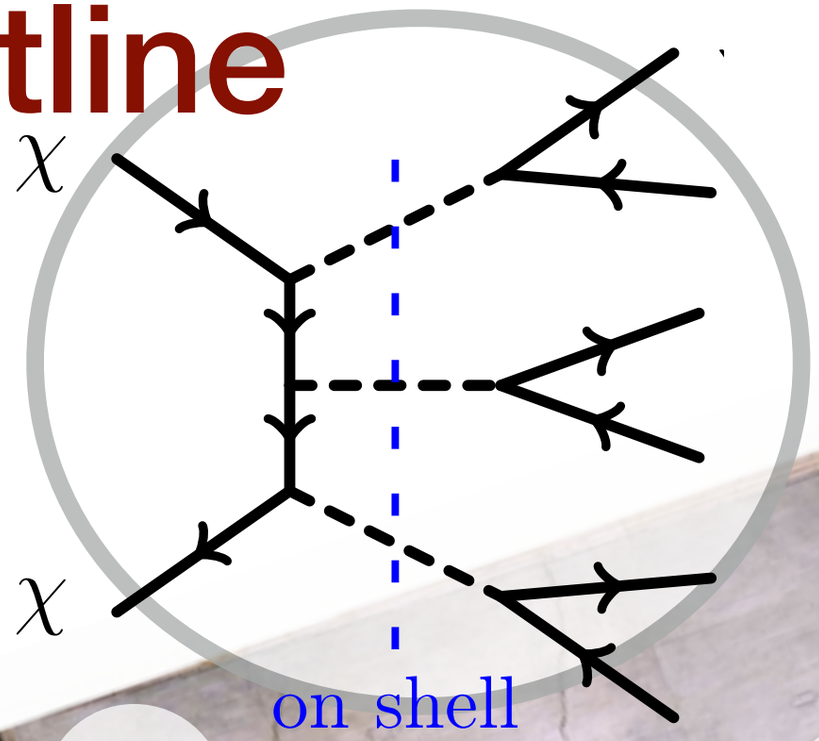
arXiv:1404.6528 (PRD), 1503.05919

& Work in Progress with Collaborators

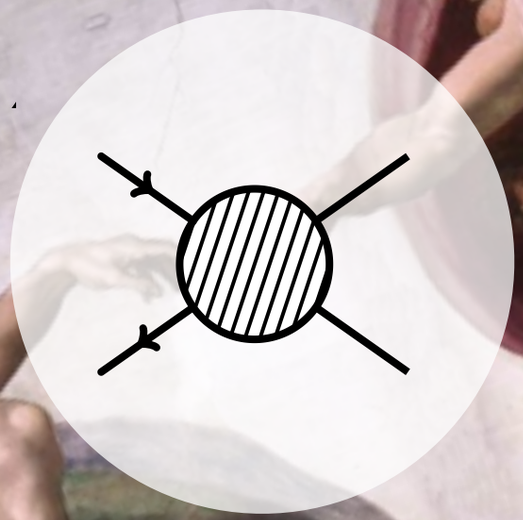
UC Davis HEFTI Seminar, April 2015

Outline

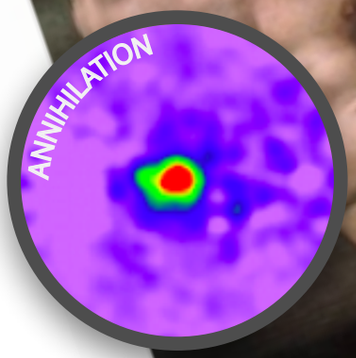


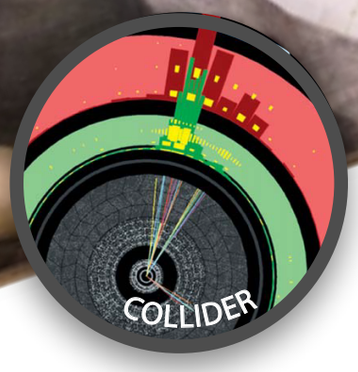
Nature

UV Models



Simplified Models

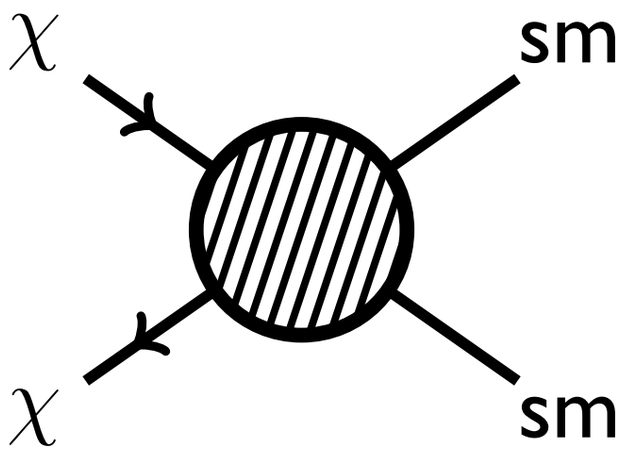




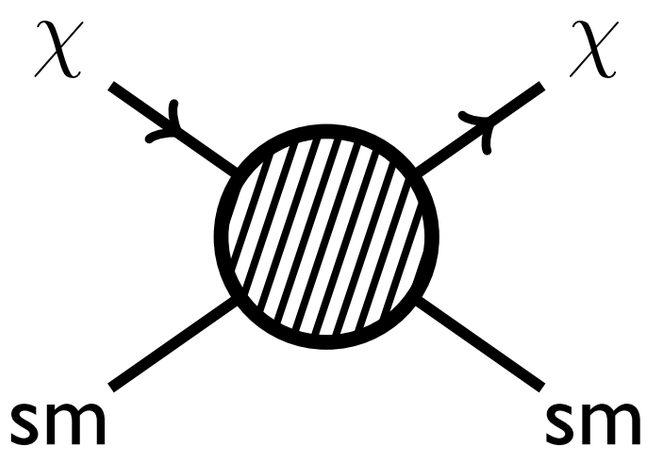
Experiments

Michelangelo Buonarroti,
“Creation of Adam” (1510)

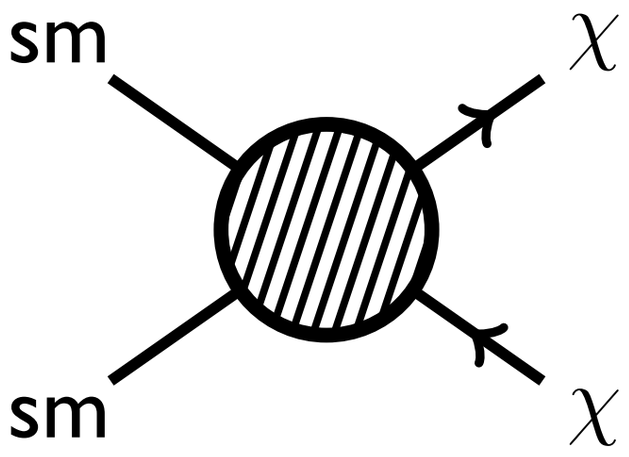
Conventional View of DM Interactions



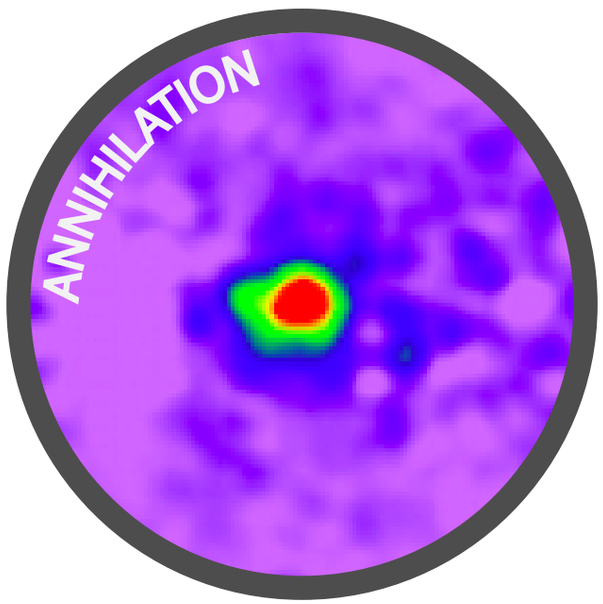
Indirect

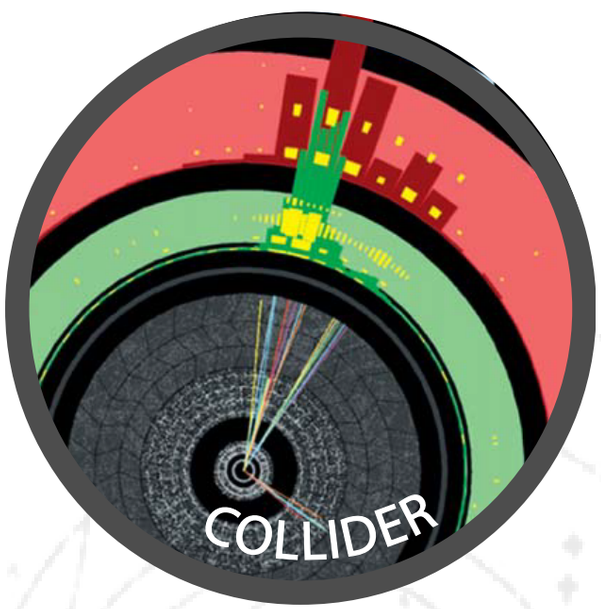


Direct



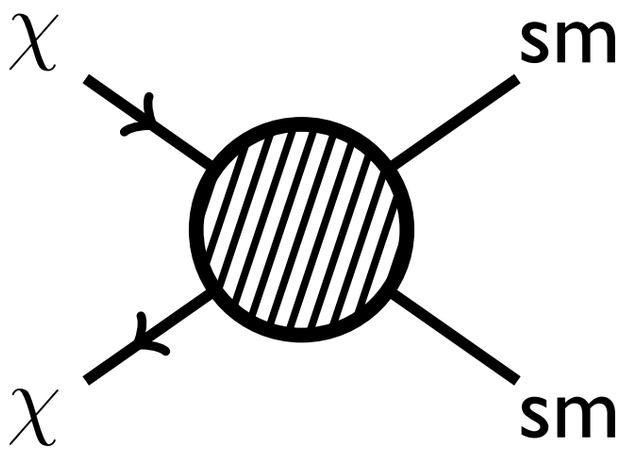
Collider



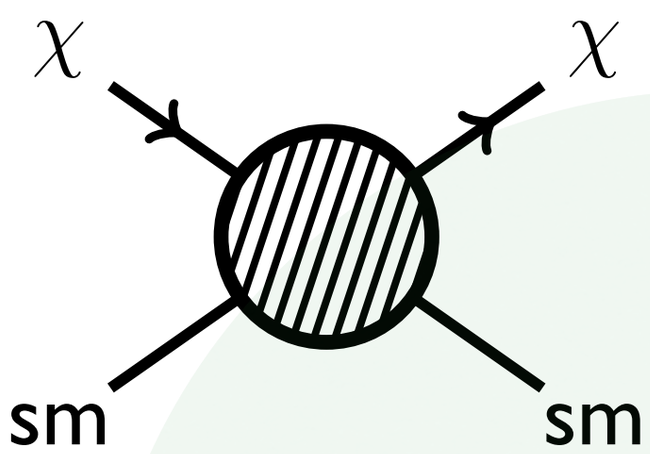


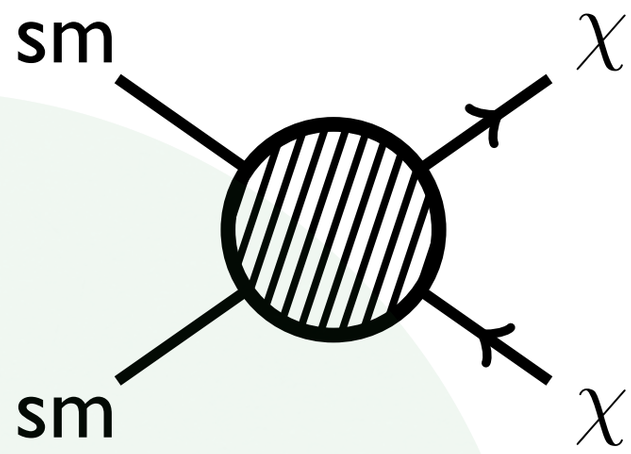
Exceptions: SIMP Miracle (1402.5143), DMdm (1312.2618), Boosted Dark Matter (1405.7370), …

Conventional View of DM Interactions



Indirect



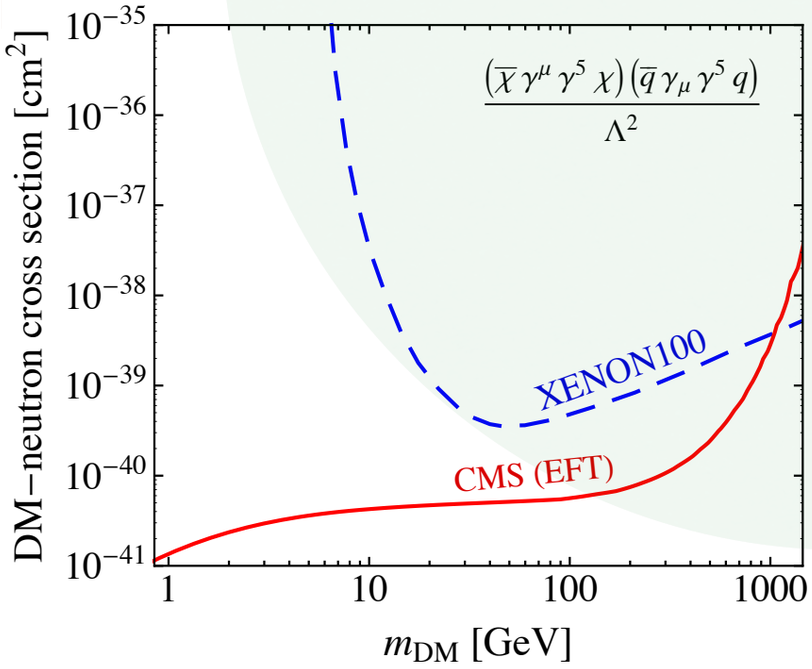


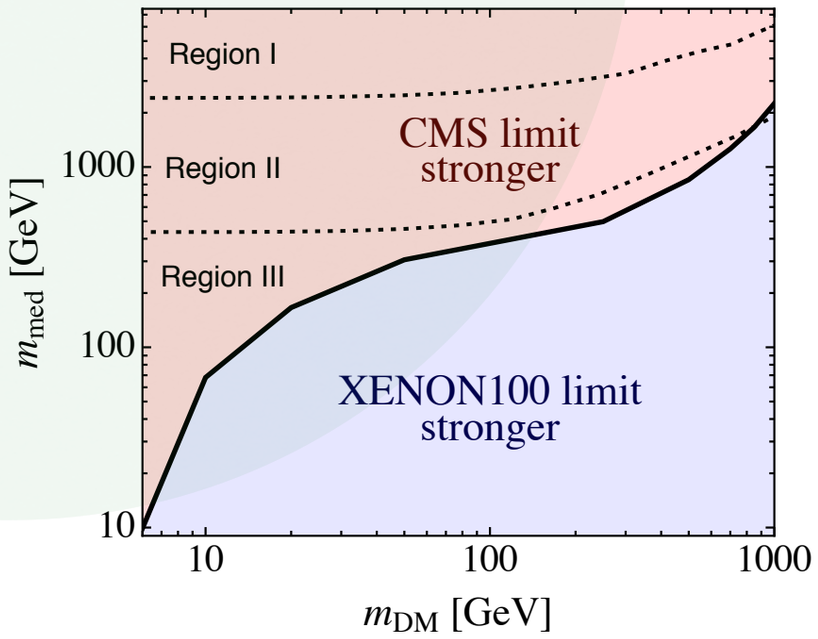
Direct

Collider

Mono-SM

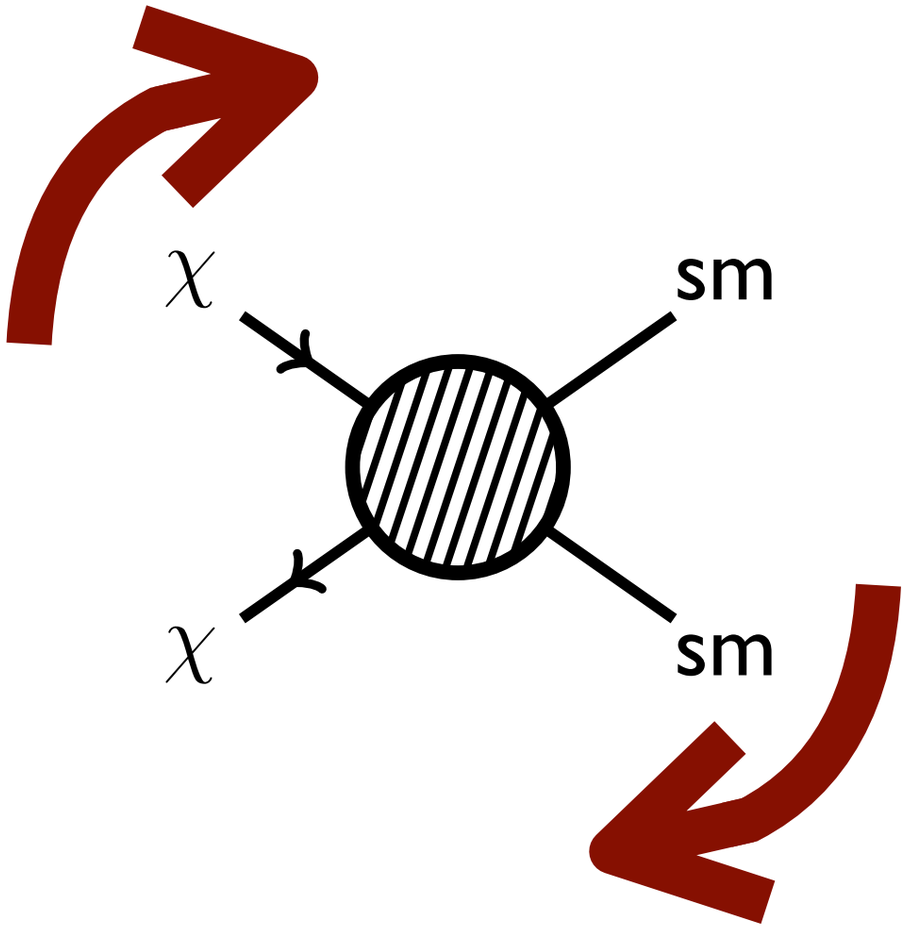
Mediators Important



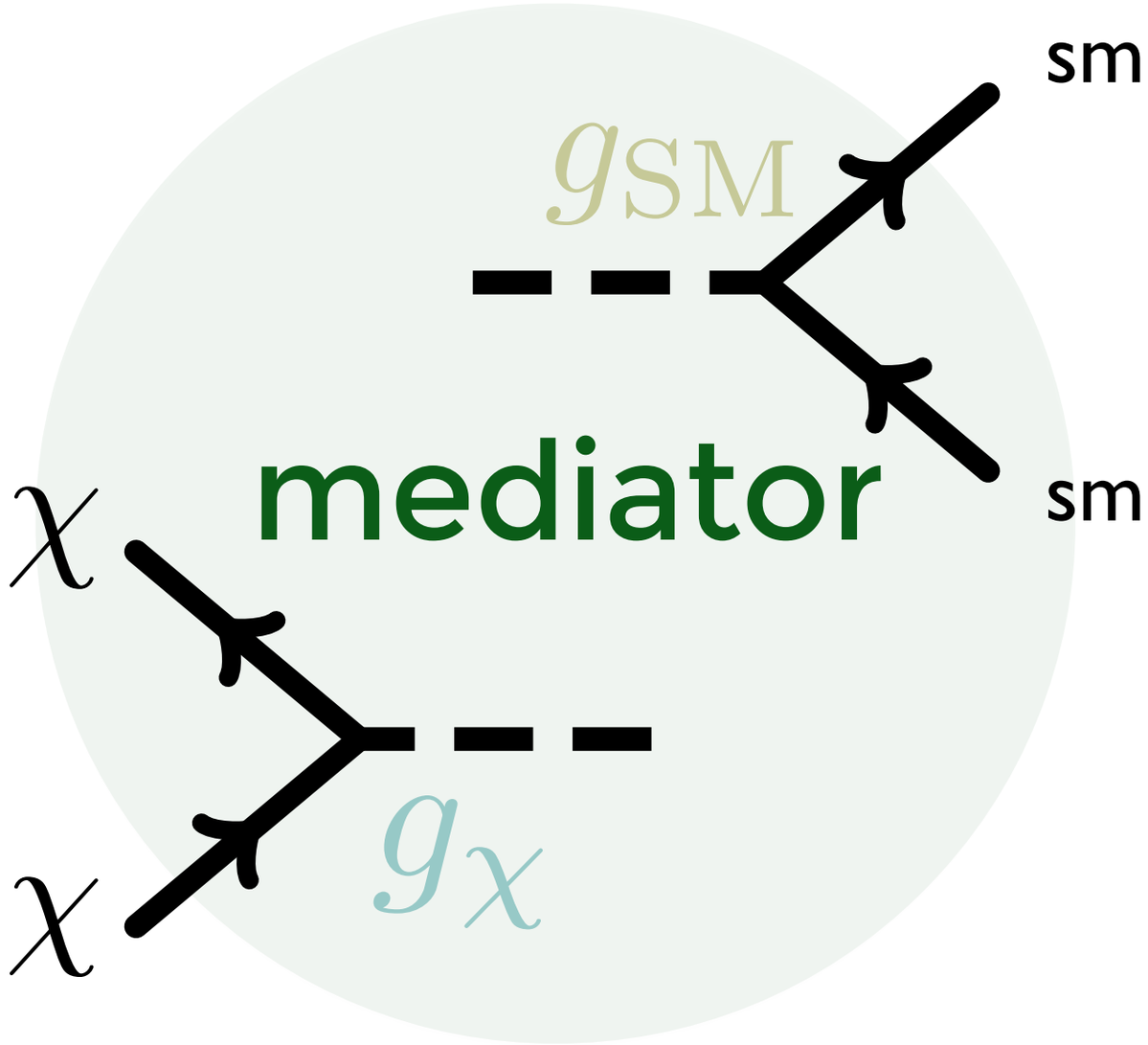


Buchmueller et al. 1308.6799; see also Shepherd 1111.2359, etc…

Simplified Models



rather than this…

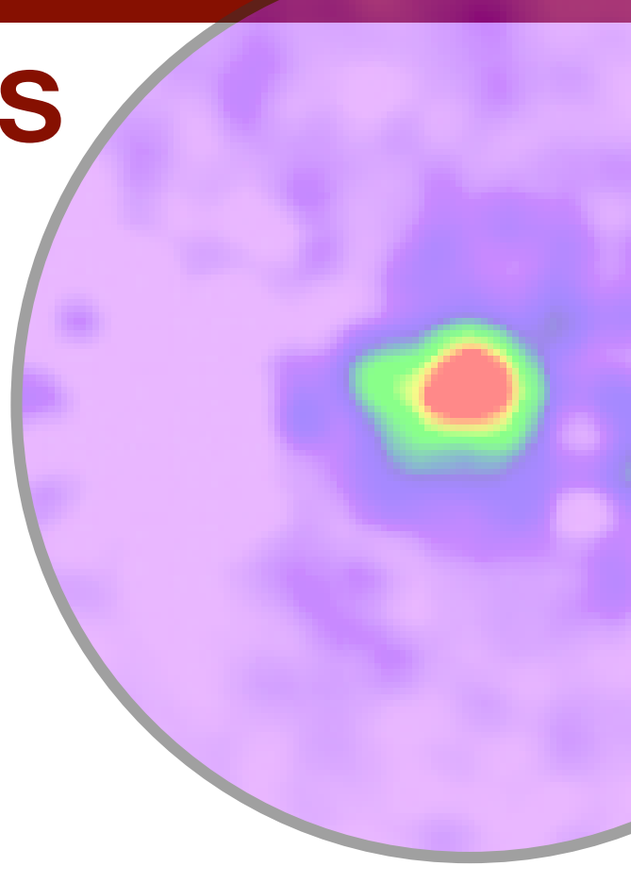


… use this

See, for example: Shepherd et al. (1111.2359), Busoni et al. (1402.1275, 1405.3101), Buchmueller et al (1308.6799, 1407.8257), Harris et al. (1411.0535), Abdullah et al. (1409.2893), …

Case Study: Fermi γ-ray excess

Fermi-LAT Collaboration, S. Murgia; 2014 Fermi Symposium



- Possible indirect detection signal
- There are reasons to be skeptical

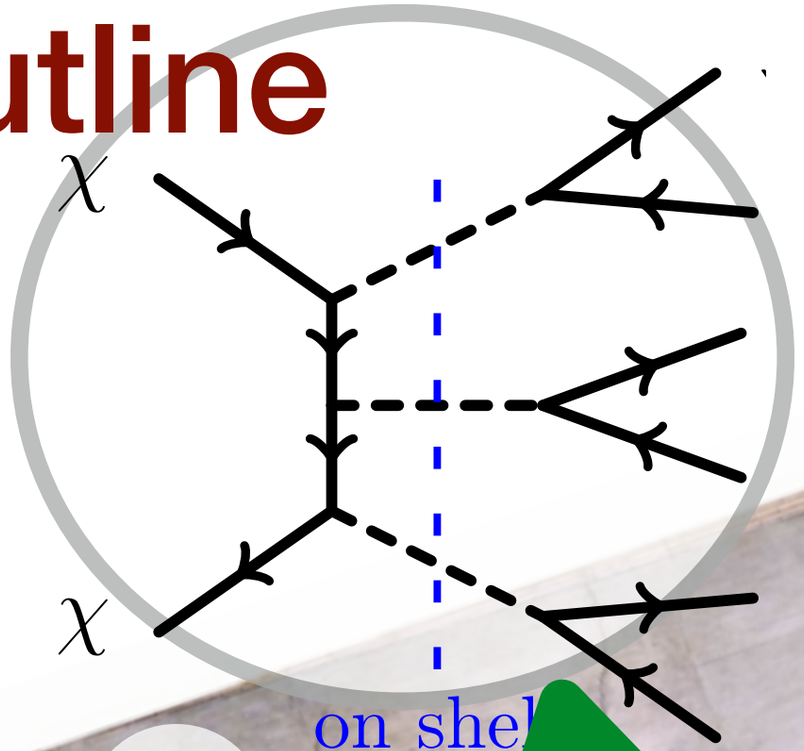
  We'll address these soon.

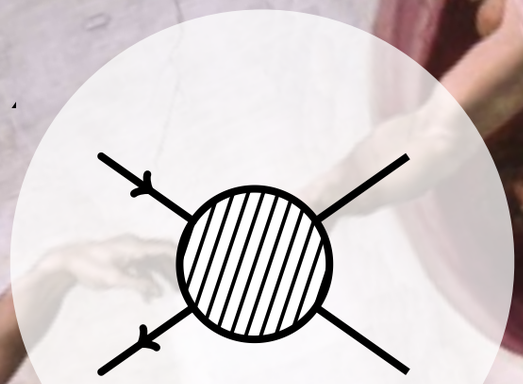
- Framework to play with new ideas

  … that can be applied more broadly than any specific signal

Goodenough & Hooper (0910.2998, 1010.2752), Hooper & Linden (1110.0006), Abazajian et al. (1011.4275, 1207.6047, 1402.4090), Boyarsky et al. (1012.5839); Gordon & Macias (1306.5725); Daylan et al. (1402.6703); Calore et al. (1411.4647, 1502.02805); Agrawal et al. (1411.2592); Fermi-LAT collaboration (2014 Symposium)

Outline

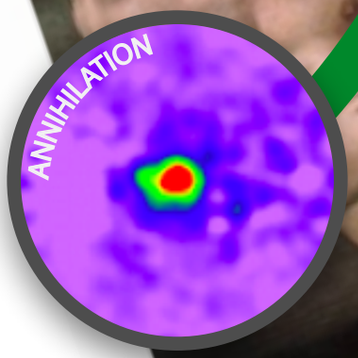


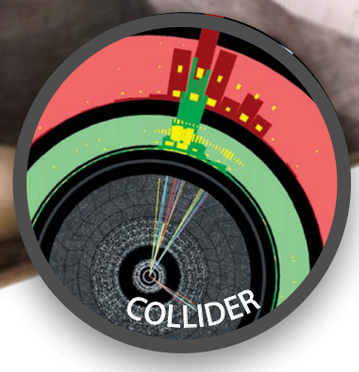


Nature

UV Models

Simplified Models





Experiments

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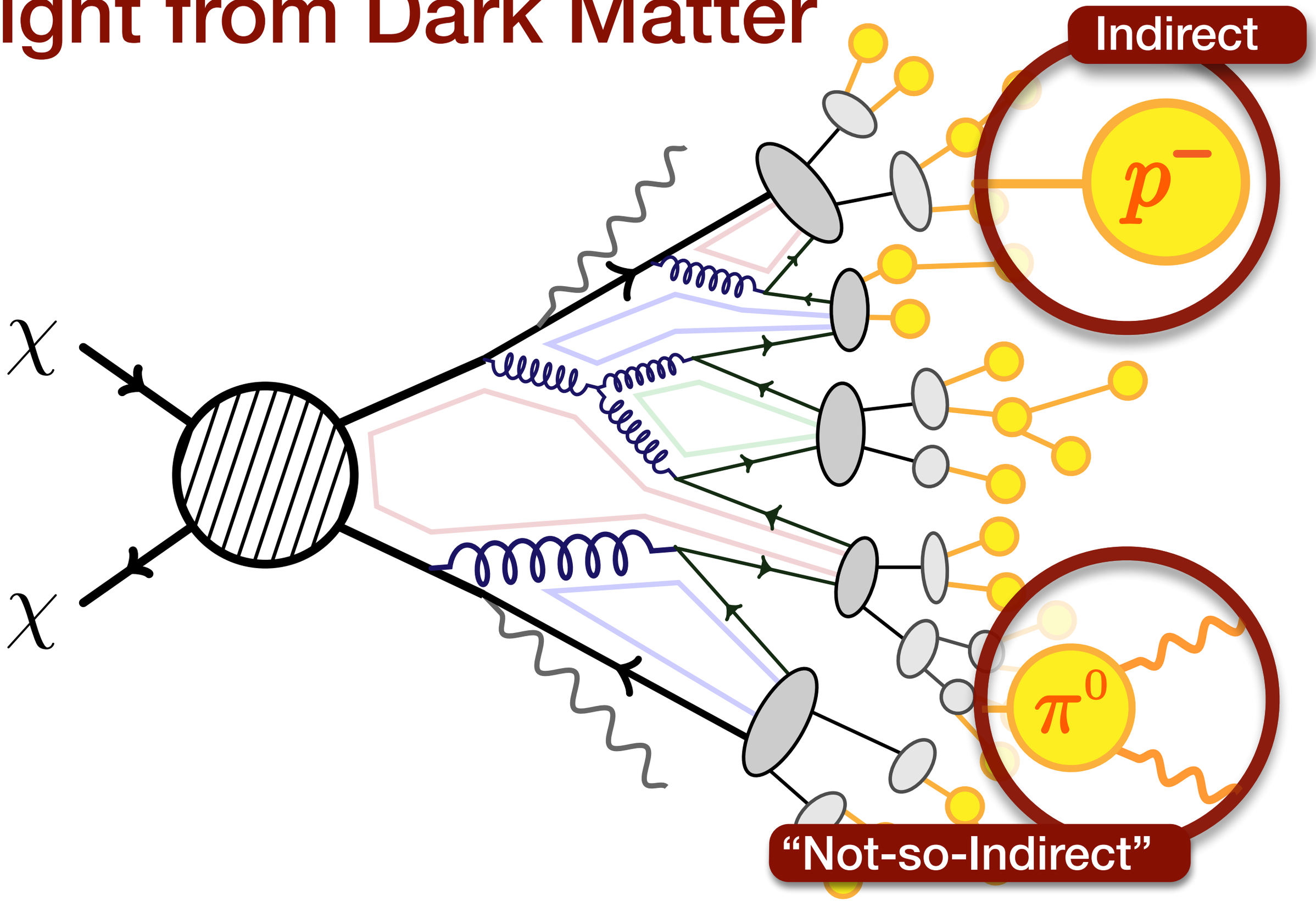
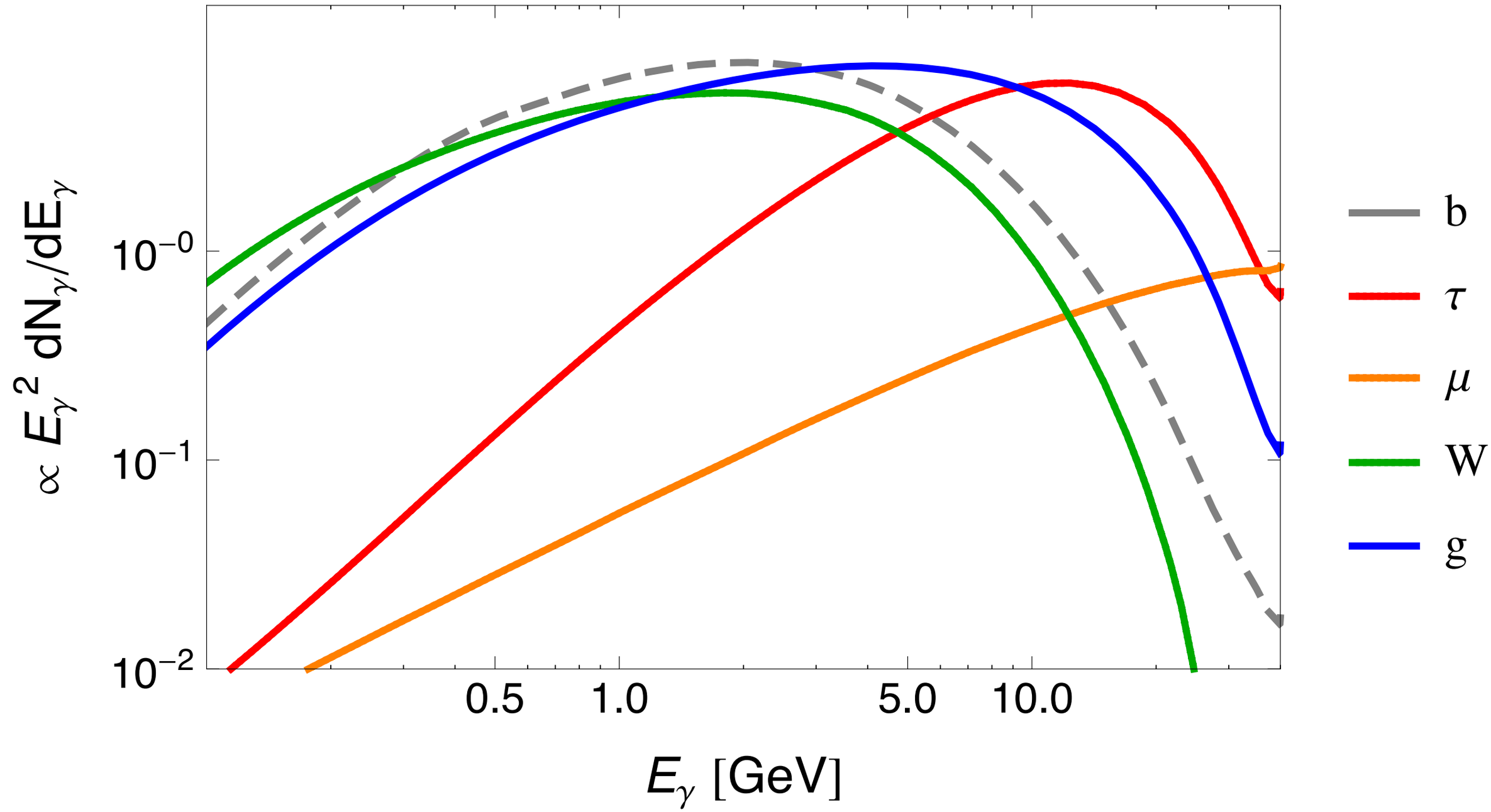
Light from Dark Matter



Adapted from D. Zeppenfeld PITP05 / S. Profumo TASI 2013

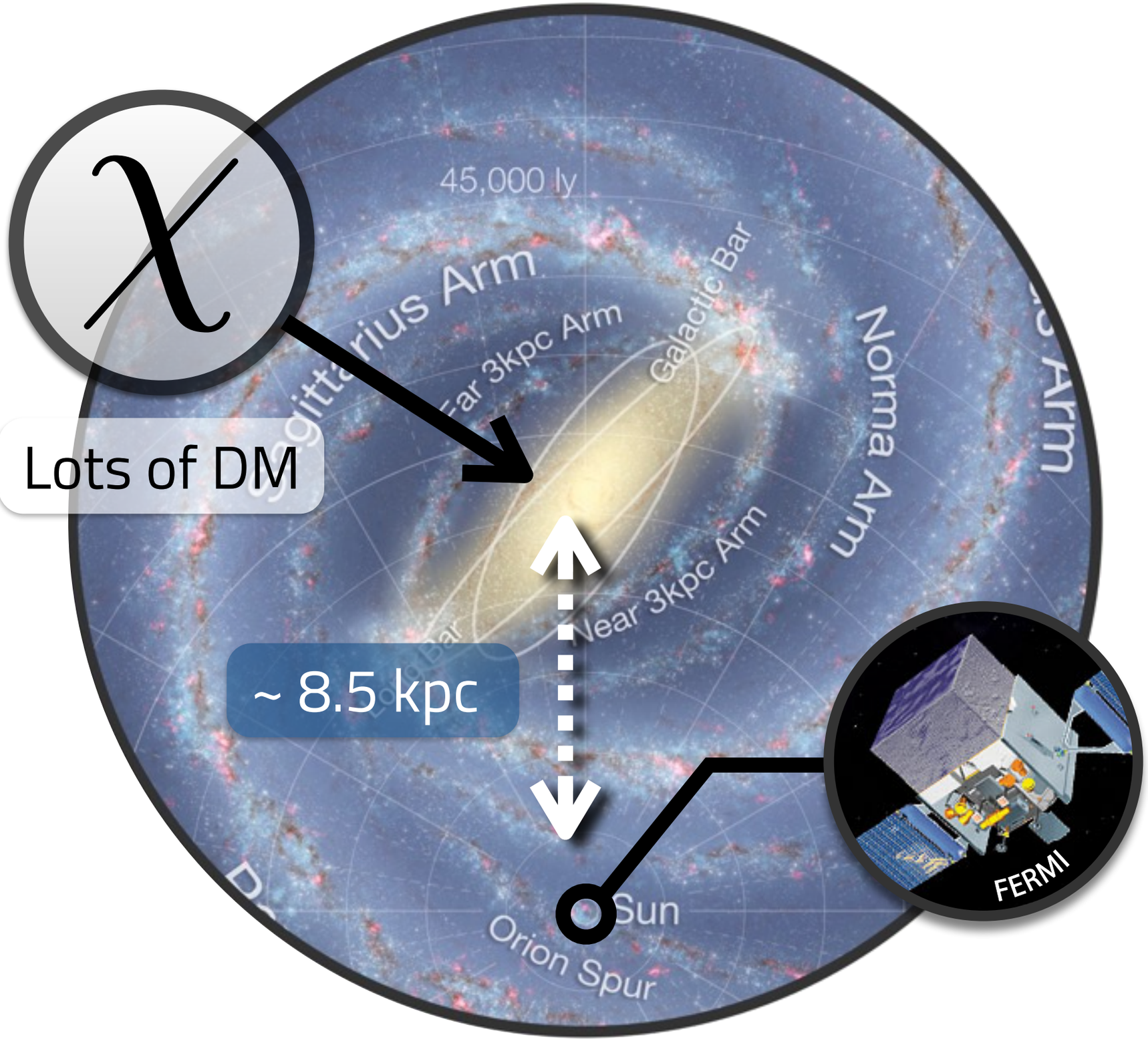
Light from Dark Matter

40 GeV DM annihilating into SM pairs



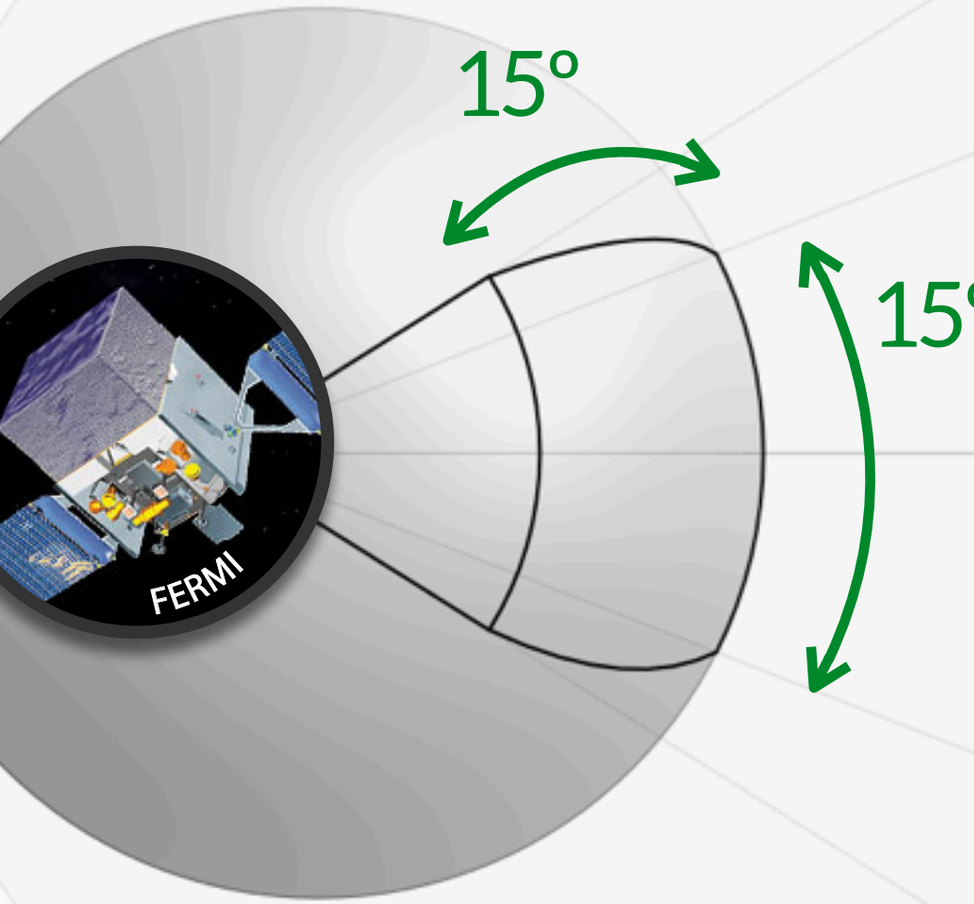
Extracted from Pythia via PPPC4DMID, Cirelli et al. 1012.4515

Where to look



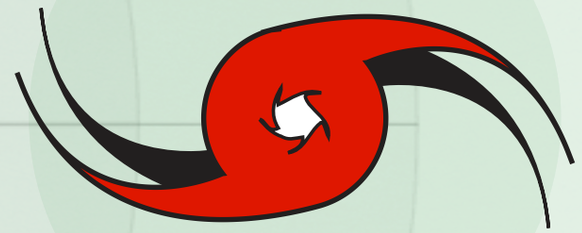
NASA/JPL-Caltech/ESO/R. Hurt

The FERMI Region



Dark Matter

Subtract



Galactic Plane

J-factor (astrophysics)

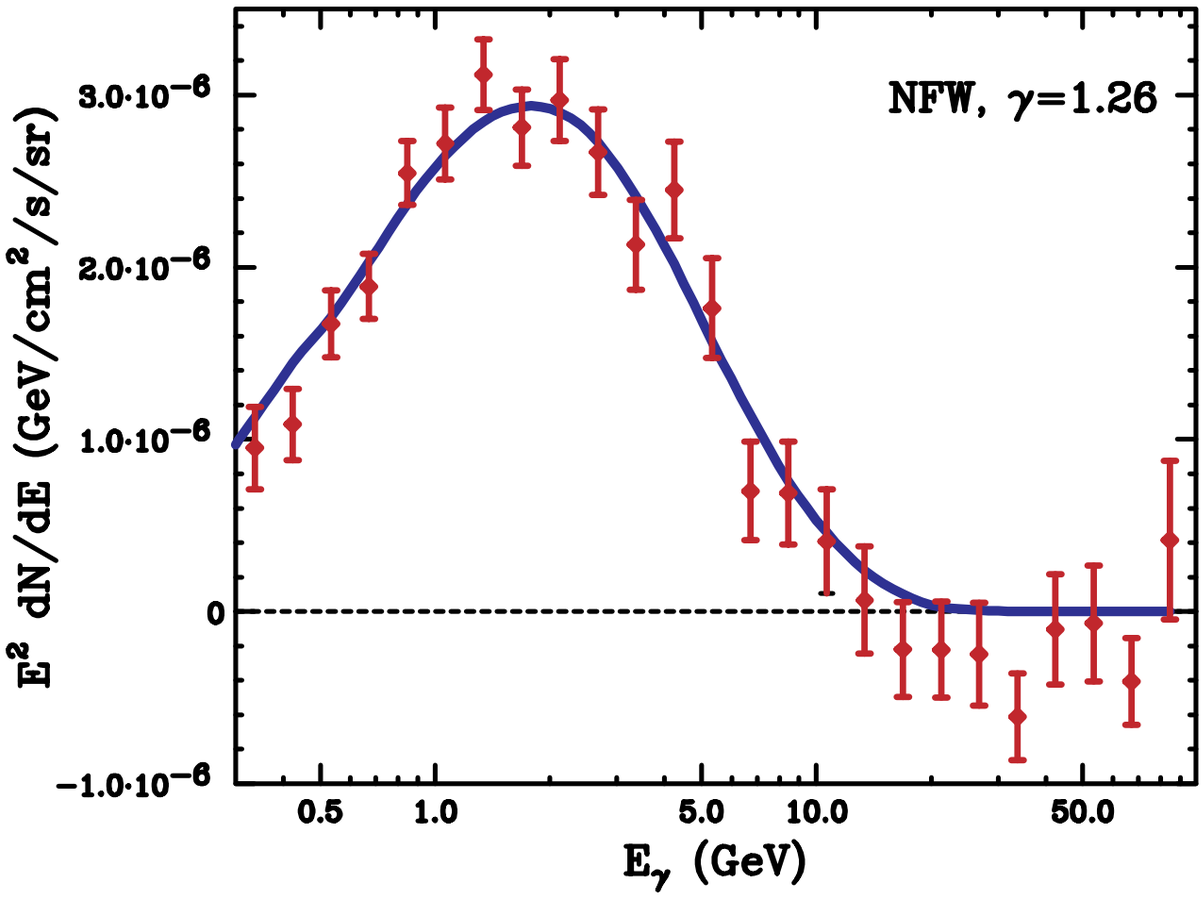
$$J \sim \int dV \, \frac{1}{4\pi r} \rho^2(x)$$

Galactic Center Excess, circa 2014

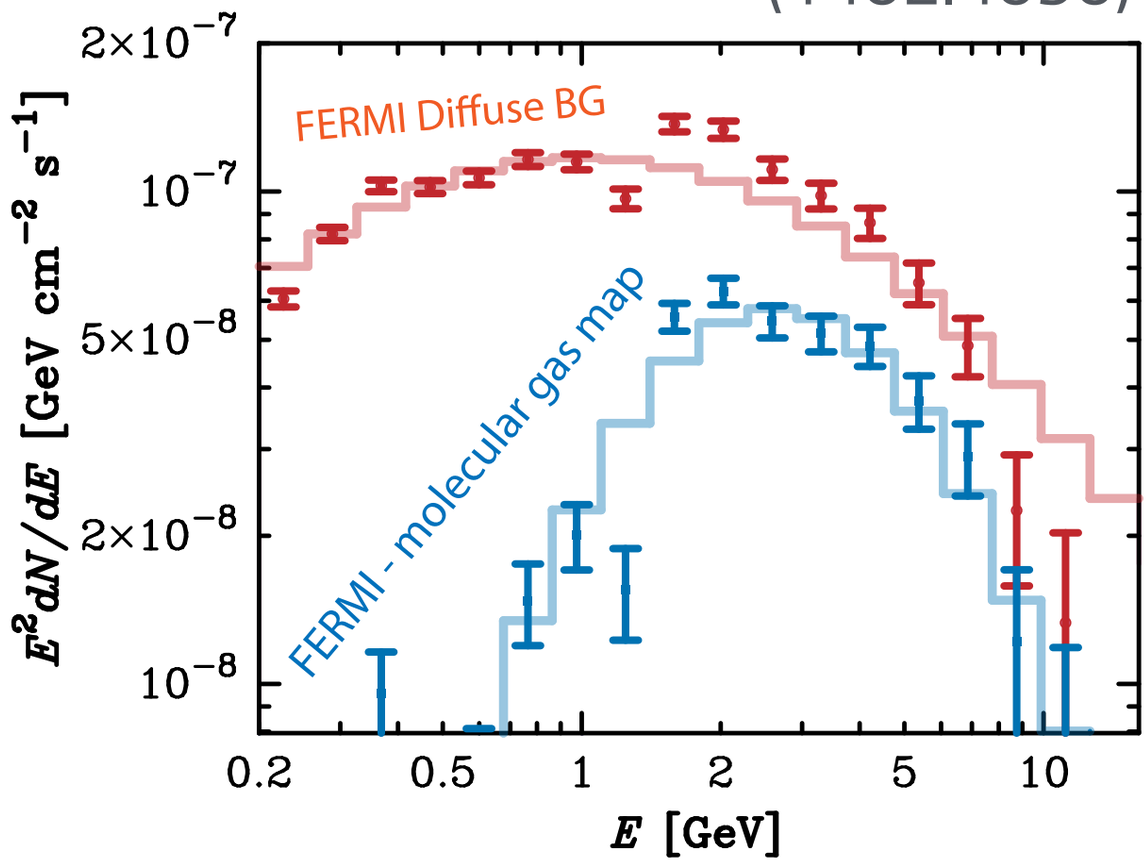
Goodenough & Hooper (0910.2998, 1010.2752), Hooper & Linden (1110.0006), Abazajian et al. (1011.4275, 1207.6047, 1402.4090), Boyarsky et al. (1012.5839); Gordon & Macias (1306.5725); Daylan et al. (1402.6703) …

All based on Fermi Pass-7 point source background

(1402.6703)



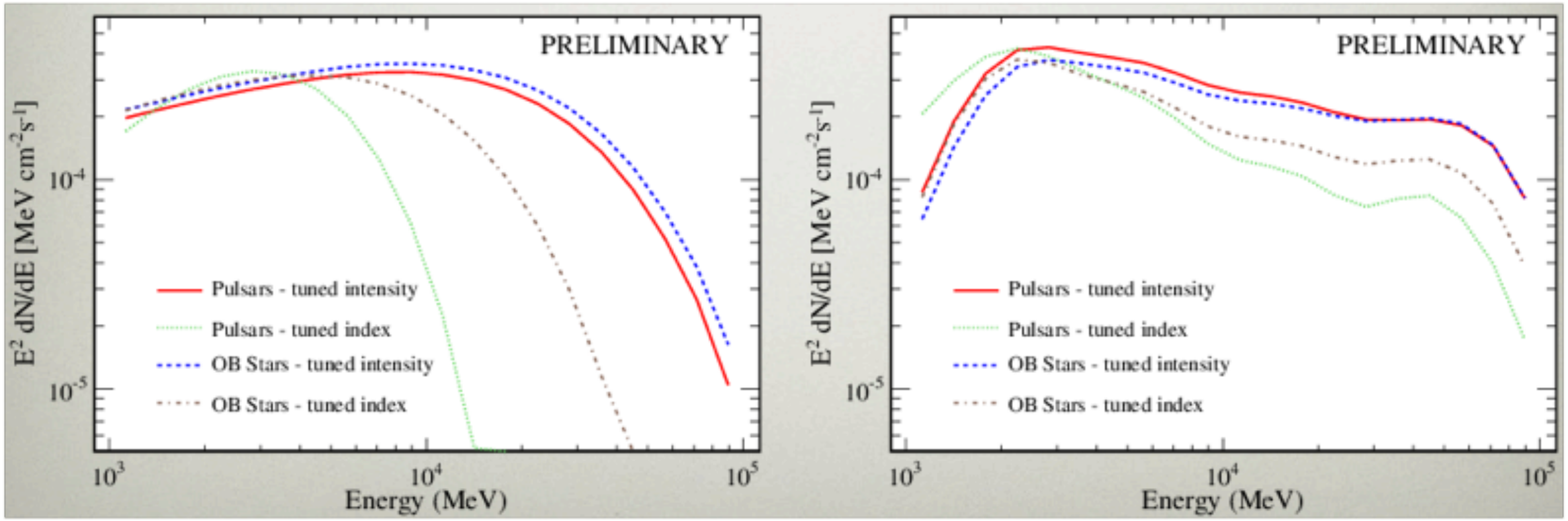
(1402.4090)



Daylan et al. 1402.6703; Abazajian et al. 1402.4090

Galactic Center Excess today

Calore et al. (1411.4647, 1502.02805); **Agrawal et al.** (1411.2592); **Fermi-LAT Collaboration** (in progress, see Fermi Symposium 2015)



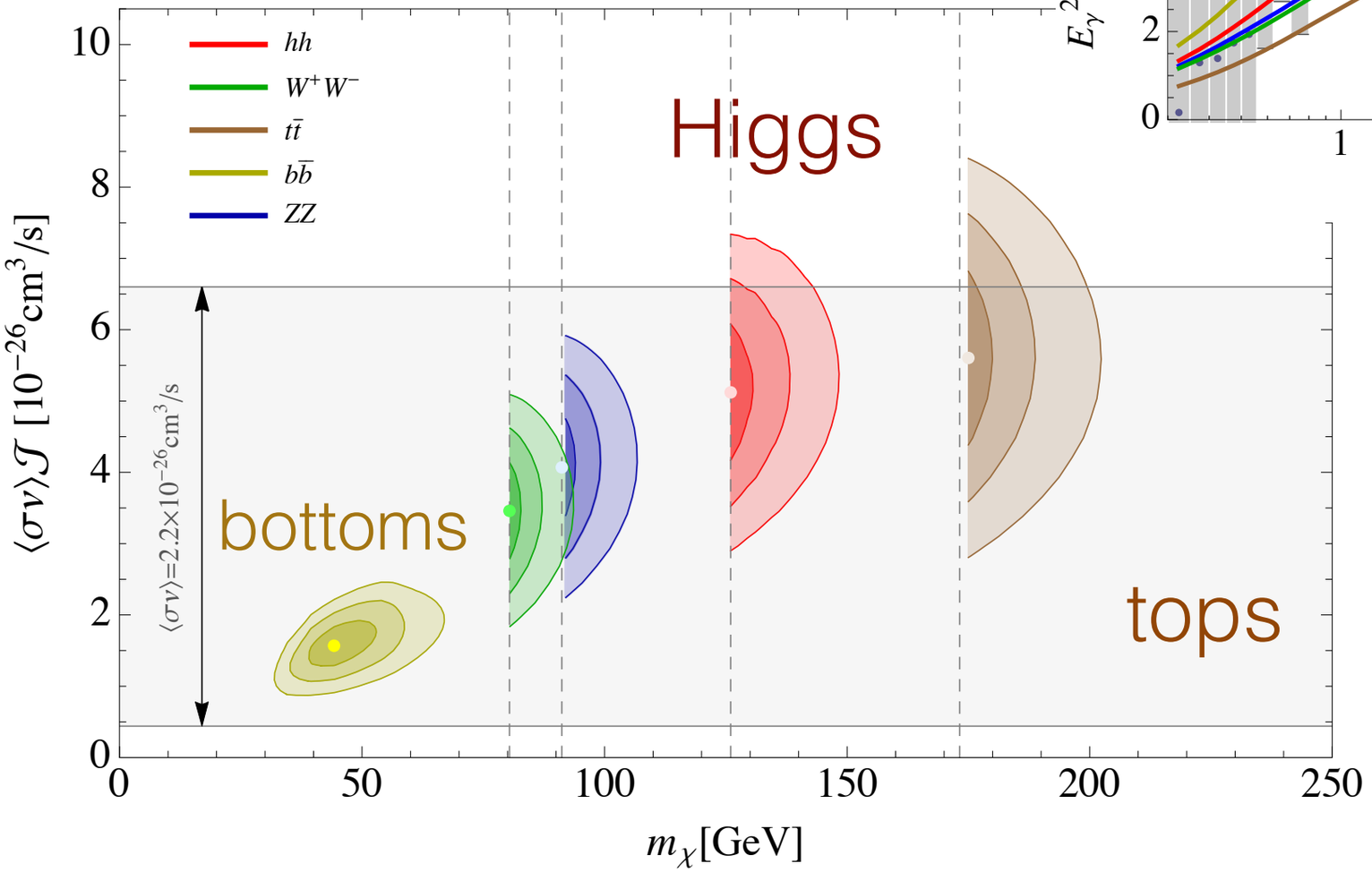
more quantification of systematic uncertainties

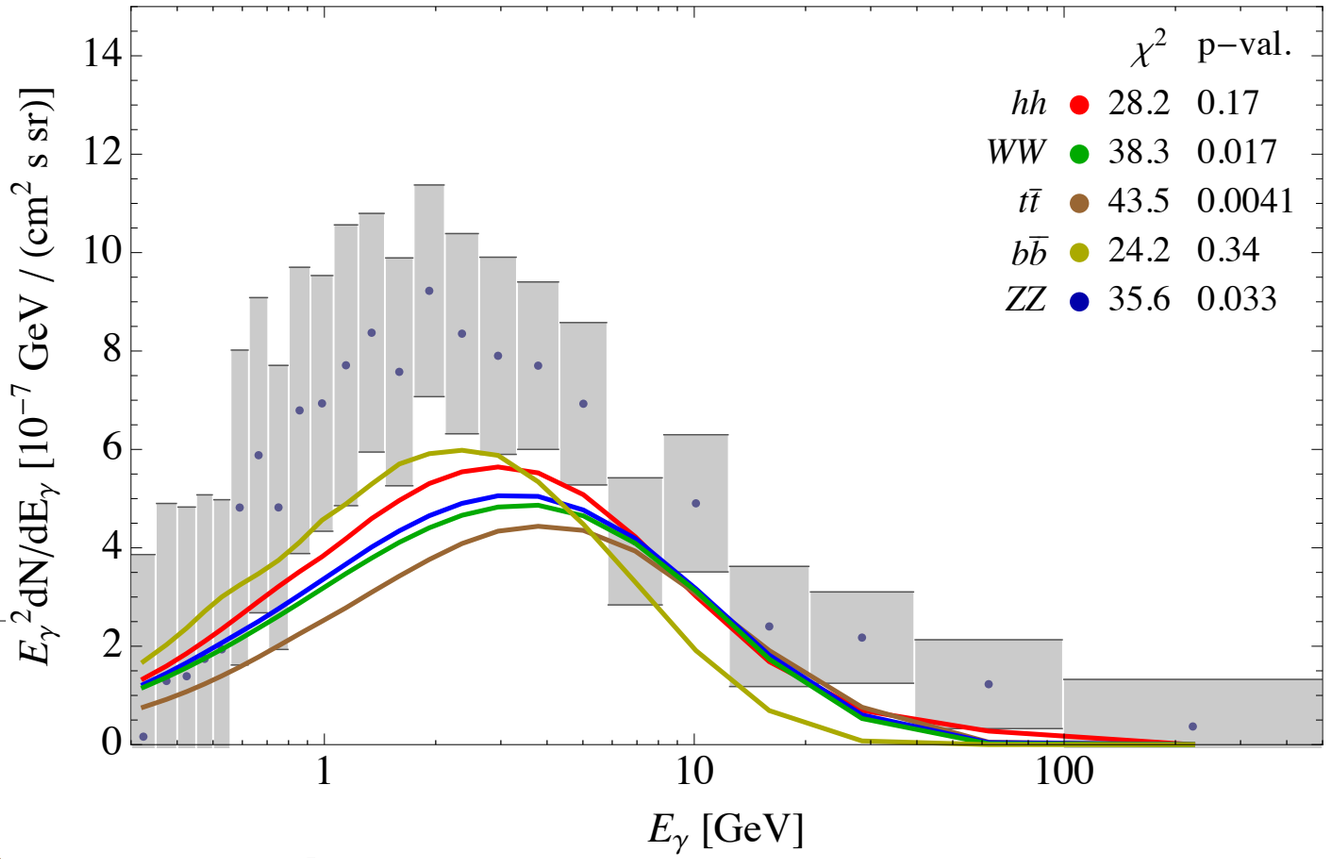
Fermi-LAT Collaboration, S. Murgia; 2014 Fermi Symposium

Other Fits

DM can be heavier

Uncertainties give wiggle room in final states.

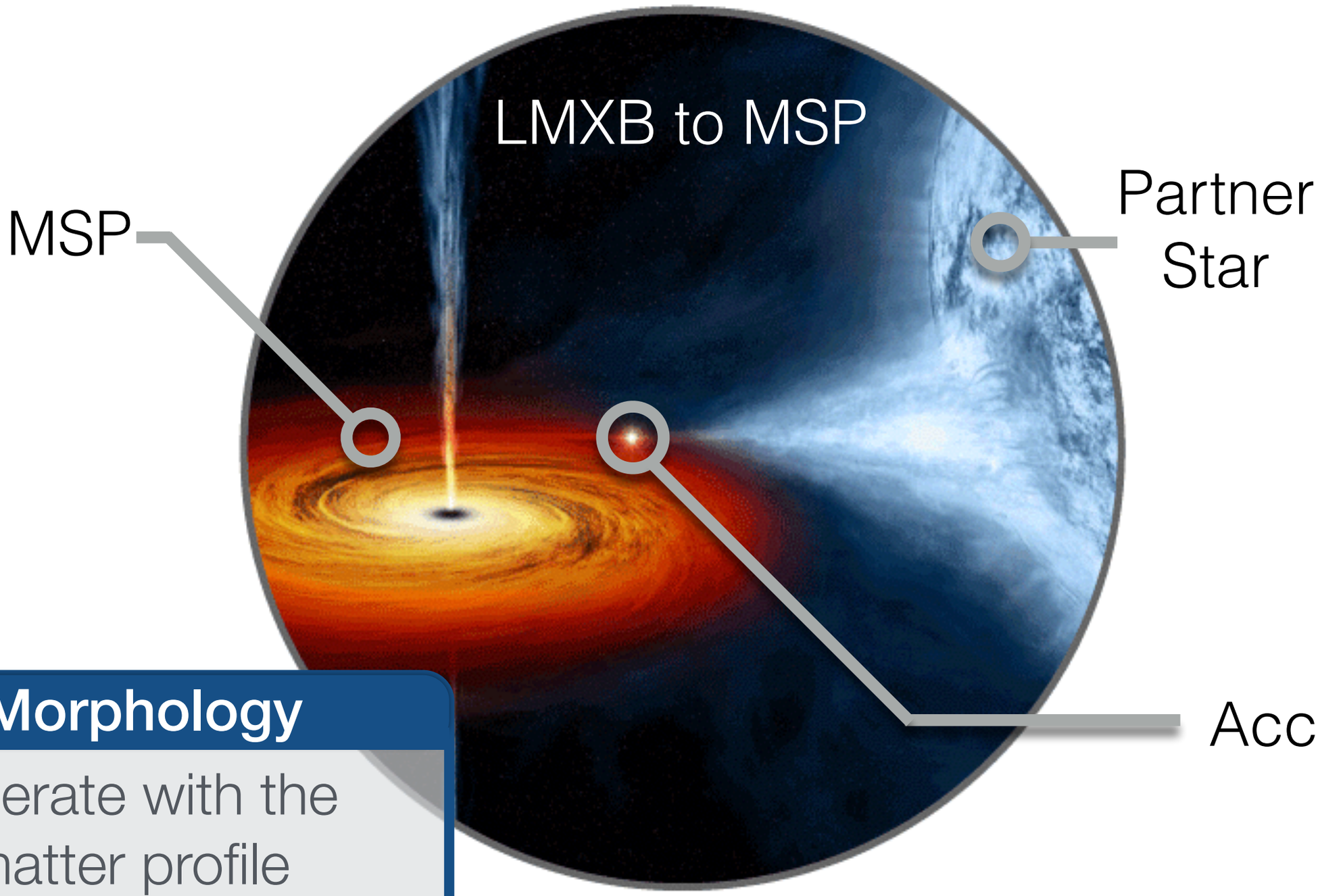




Agrawal et al. 1411.2592 w/ uncertainties from Calore et al. 1409.0042.

Millisecond Pulsars

Hooper et al. 1010.2752, 1110.0006; Abazajian et al. 1011.4275, 1207.6047 1402.4090
Wharton et al. 1111.4216, Yuan et al. 1404.2318, Mirabal 1309.3248 n.b.: Hooper et al. 1305.0830

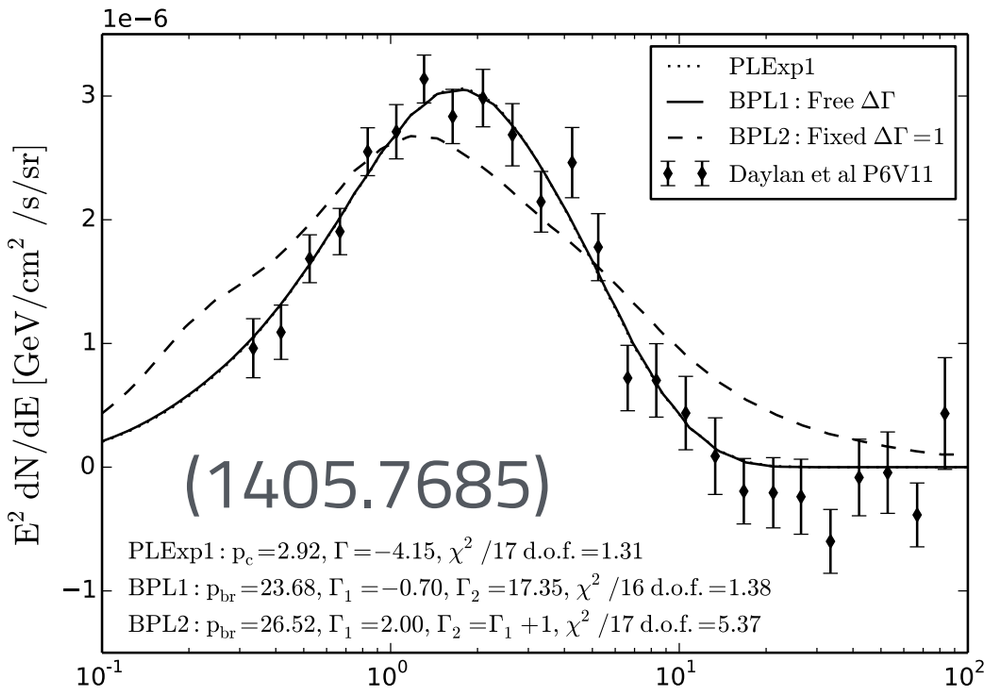


MSP Morphology

Degenerate with the dark matter profile

NASA/CXC/M.Weiss

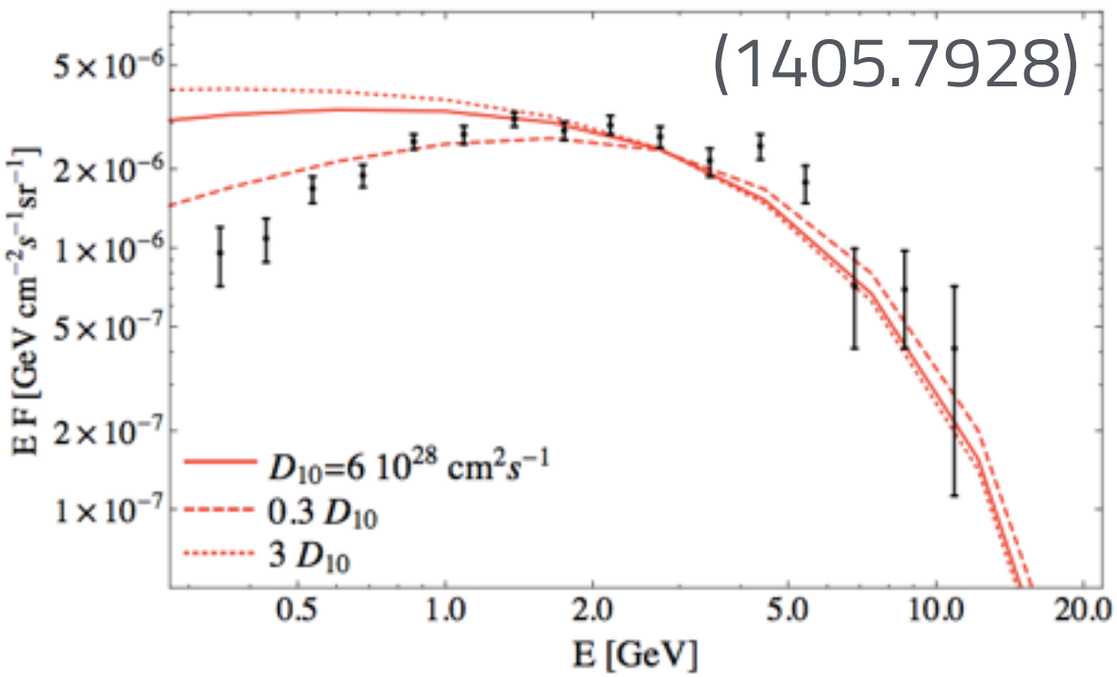
Alternate Sources of SM particles



New source of cosmic ray p^+

γ-ray spectrum, intensity, morphology can closely resemble the FERMI excess

Carlson & Profumo Phys. Rev. D90, 023015



New source of electrons

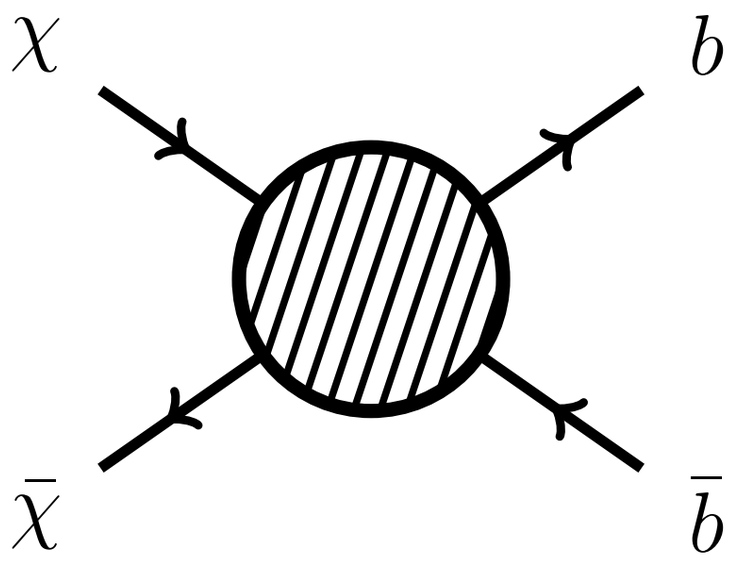
Inject 10^{52} erg, 10^6 years ago. Inverse Compton scattering on starlight to match spectrum.

Petrovic et al. JCAP 1410 (2014) 10, 052

Not clear if there exists a single astrophysical story for all scales

The "Hooperon"

Goodenough & Hooper (0910.2998, 1010.2752), Hooper & Linden (1110.0006), Abazajian et al. (1011.4275, 1207.6047, 1402.4090), Boyarsky et al. (1012.5839); Gordon & Macias (1306.5725); Daylan et al. (1402.6703) …



$E_b = 40$ **GeV**

fits γ **spectrum**

$m_\chi = 40$ **GeV**

10 GeV τ also fits

Overall normalization set by present annihilation rate

$$\langle \sigma_{b\bar{b}} v \rangle = 5 \quad (1.5) \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

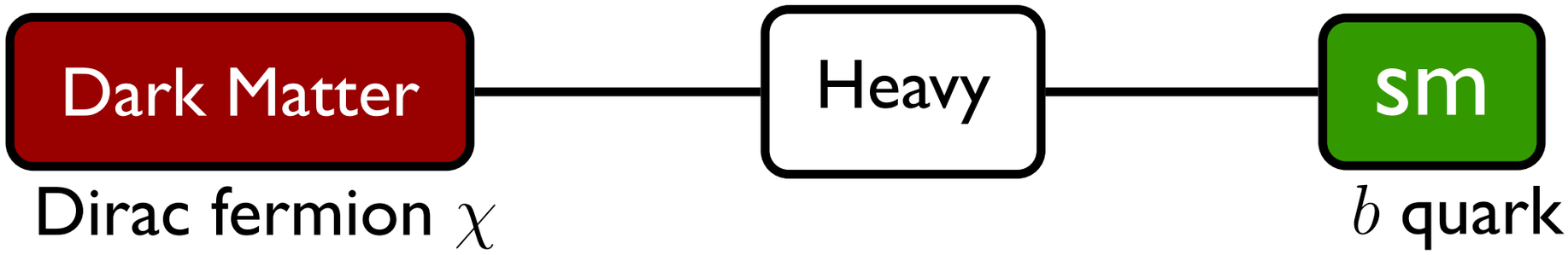
$\gamma = 1.12$ (1402.4090)

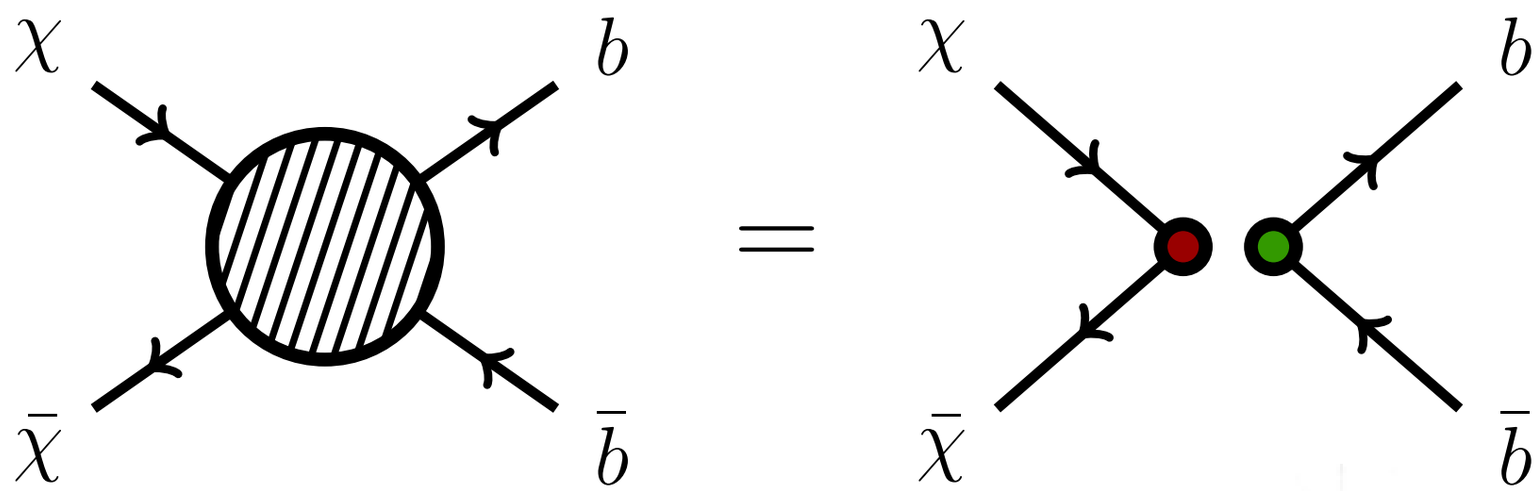
$\gamma = 1.26$ (1402.6703)

$$\rho \sim r^{-\gamma}(1 + r^{\alpha})^{\frac{\gamma-\beta}{\alpha}}$$

Same ballpark as thermal relic σ (if s-wave)

Contact Interactions





DM–SM interaction parameterized by a single coupling Λ^{-2}.

$$\mathcal{O} = \frac{1}{\Lambda^2} \left(\bar{\chi}\Gamma_\chi \chi\right) \left(\bar{b}\Gamma_b b\right)$$

Parameterization: UCI 1008.1783; **Fit**: UCSC 1403.5027

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

D2	$\bar{\chi}\gamma^5\chi \cdot \bar{q}q$
D4	$\bar{\chi}\gamma^5\chi \cdot \bar{q}\gamma^5 q$
D5	$\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu q$
D6	$\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu q$
D7	$\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$
D8	$\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu} q$
D10	$\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu}\gamma_5 q$
D12	$\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}G^{\mu\nu}$
D14	$\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$

CMS 1206.5663, LUX 1310.8214

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

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D5 ~~$\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu q$~~

D6 $\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu q$

D7 $\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$

D8 ~~$\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$~~

D9 $\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu} q$

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D12 $\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}G^{\mu\nu}$

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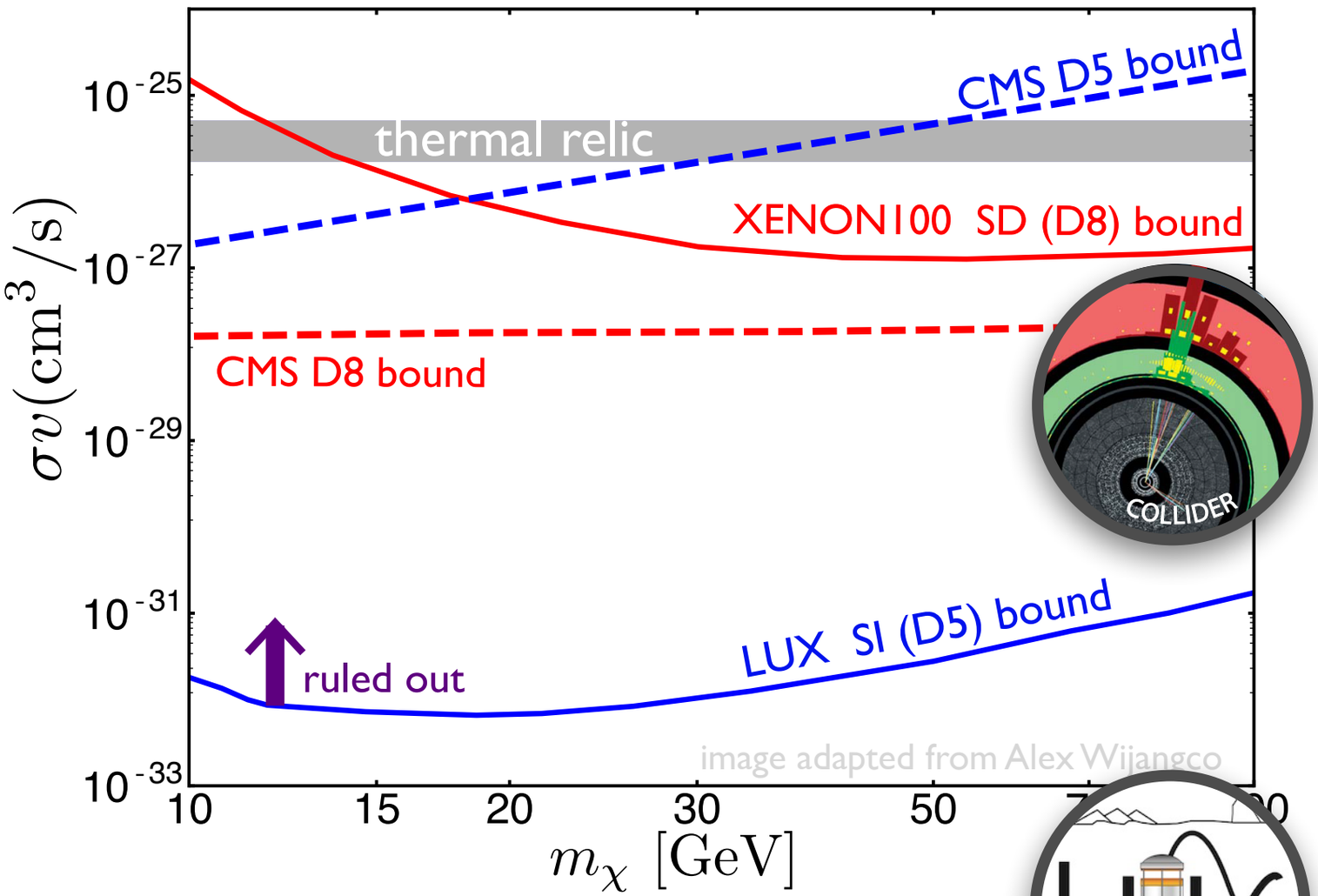

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D8 ~~$\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$~~

D9 $\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu}q$

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D12 $\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}G^{\mu\nu}$

D14 $\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$

Chiral SM Couplings

$$\bar{q}\gamma_\mu\gamma_5 q \subset \bar{q}P_L q$$

e.g. we expect D5 & D7 to have same order couplings

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

D2	$\bar{\chi}\gamma^5\chi \cdot \bar{q}q$
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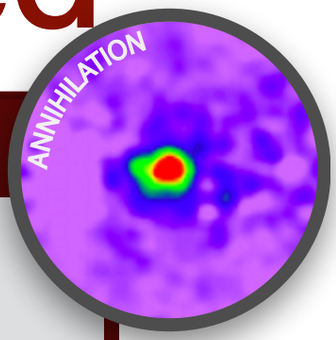
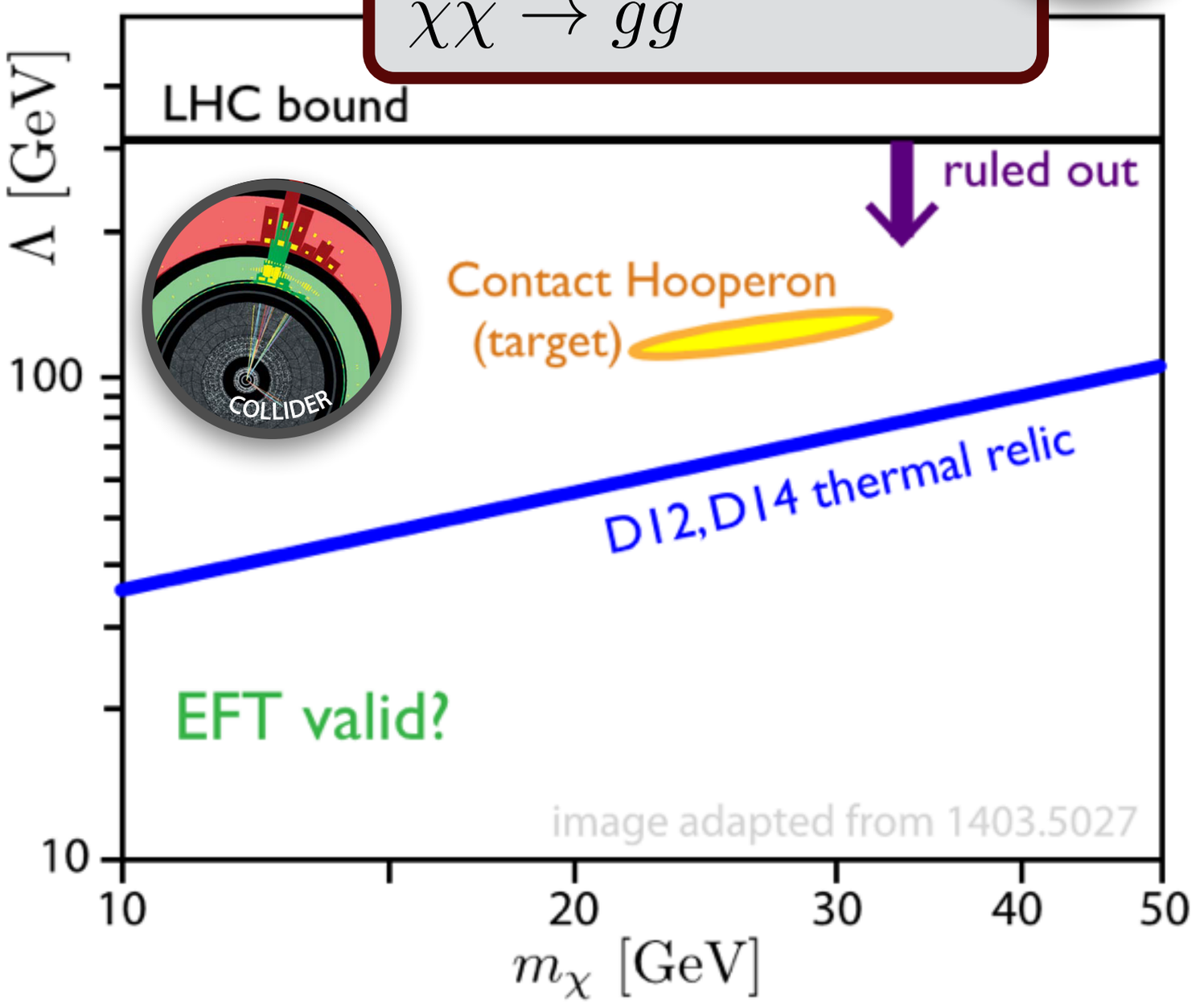
D12	$\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}G^{\mu\nu}$
D14	$\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$

gluon spectrum

doesn't seem to fit

$\chi\bar{\chi} \to gg$





Alves, Profumo, Quieroz, Shepherd, "The Effective Hooperon" (1403.5027)

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

D2 $\bar{\chi}\gamma^5\chi \cdot \bar{q}q$

D4 $\bar{\chi}\gamma^5\chi \cdot \bar{q}\gamma^5 q$

looks okay?

D5 $\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu q$

D6 $\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu q$

D7 $\bar{\chi}\gamma^\mu\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$

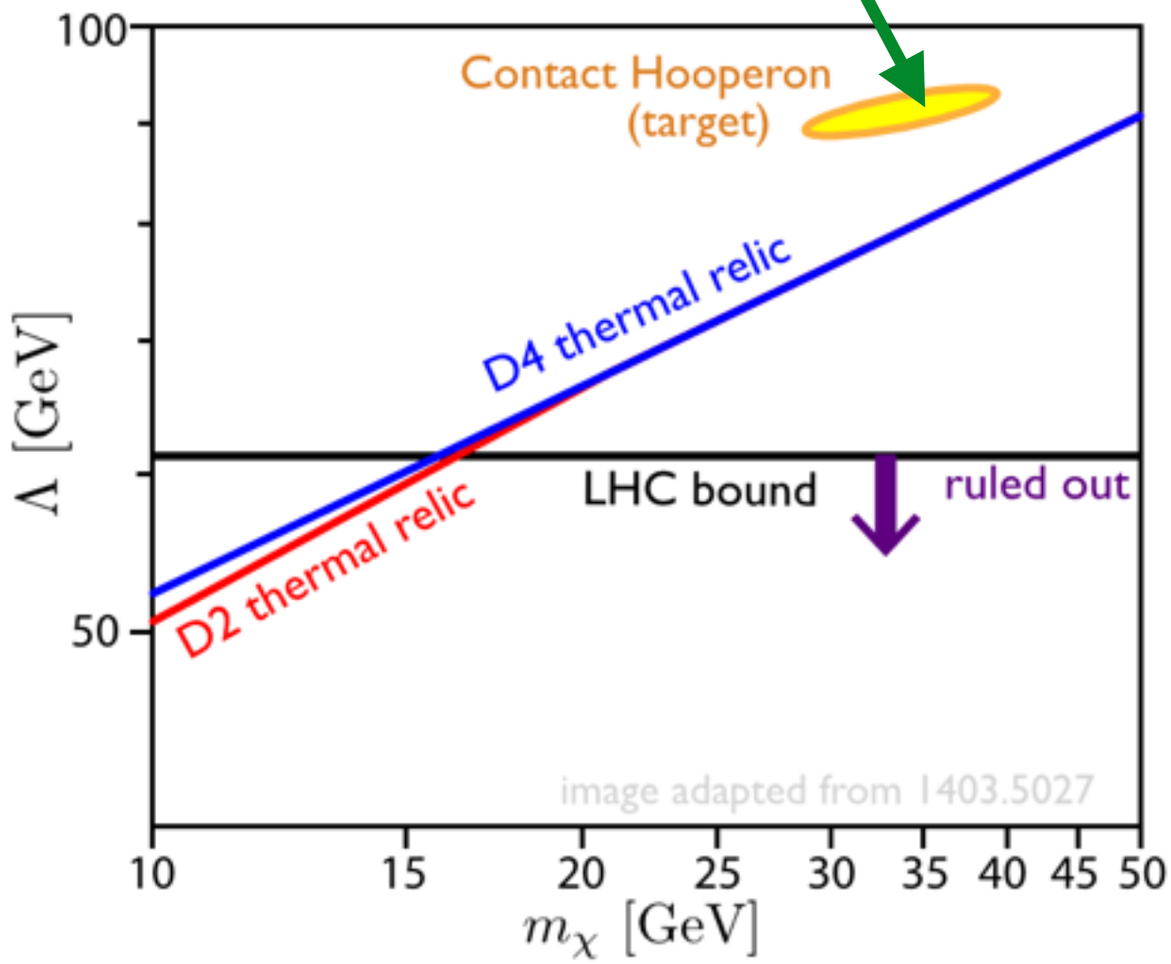
D8 $\bar{\chi}\gamma^\mu\gamma_5\chi \cdot \bar{q}\gamma_\mu\gamma_5 q$

D9 $\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu} q$

D10 $\bar{\chi}\sigma^{\mu\nu}\chi \cdot \bar{q}\sigma_{\mu\nu}\gamma_5 q$

D12 $\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}G^{\mu\nu}$

D14 $\bar{\chi}\gamma_5\chi \cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$



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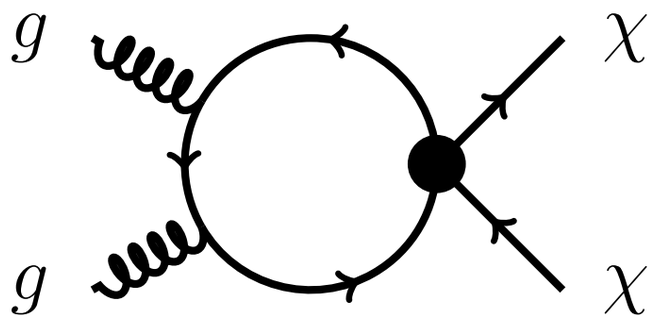
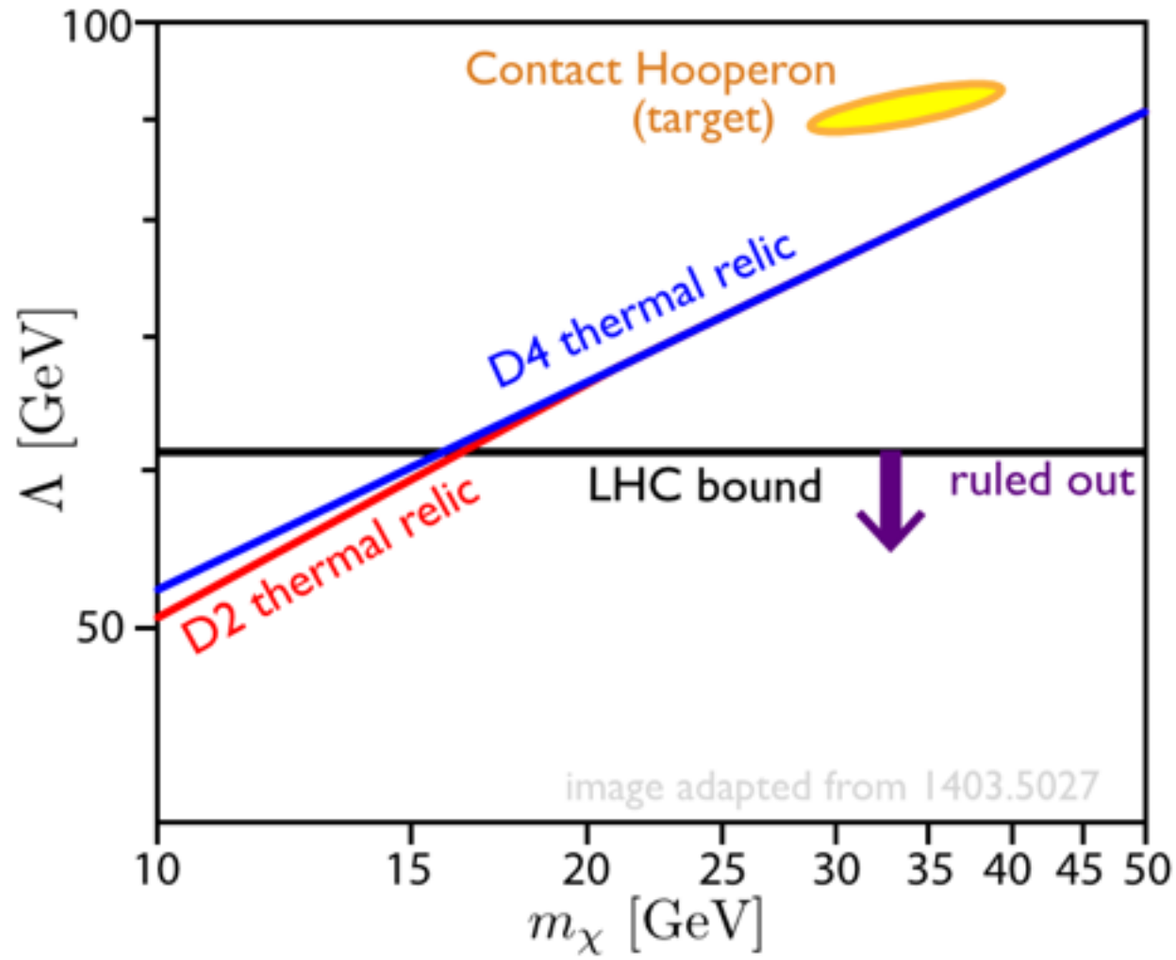
D14 $\bar{\chi}\gamma_5\chi\cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$





Alves, Profumo, Quieroz, Shepherd, "The Effective Hooperon" (1403.5027)

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

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D6 $\bar{\chi}\gamma^\mu\gamma_5\chi\cdot\bar{q}\gamma_\mu q$

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D12 $\bar{\chi}\gamma_5\chi\cdot G_{\mu\nu}G^{\mu\nu}$

D14 $\bar{\chi}\gamma_5\chi\cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$

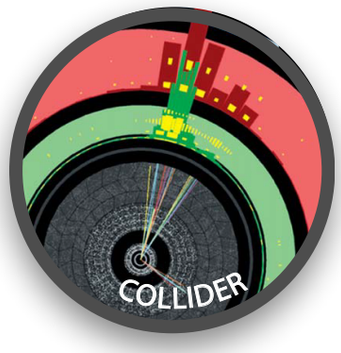
Ignore spin-2 mediators
… even heavy ones

Decoupled Mediators Disfavored

Requirement: s-wave annihilation

D2 $\bar{\chi}\gamma^5\chi\cdot\bar{q}q$

D4 $\bar{\chi}\gamma^5\chi\cdot\bar{q}\gamma^5 q$



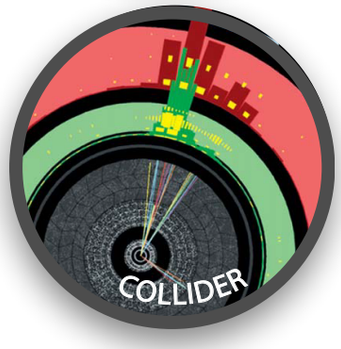
via D12 & D14

D5 $\bar{\chi}\gamma^\mu\chi\cdot\bar{q}\gamma_\mu q$

D6 $\bar{\chi}\gamma^\mu\gamma_5\chi\cdot\bar{q}\gamma_\mu q$

D7 $\bar{\chi}\gamma^\mu\chi\cdot\bar{q}\gamma_\mu\gamma_5 q$

D8 $\bar{\chi}\gamma^\mu\gamma_5\chi\cdot\bar{q}\gamma_\mu\gamma_5 q$



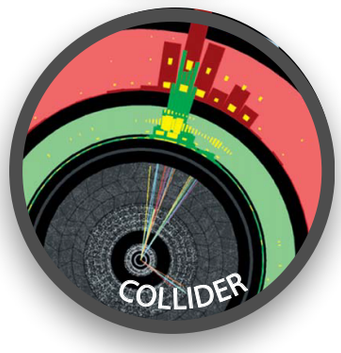
& SM chirality

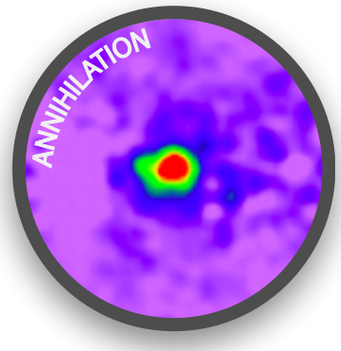
D9 $\bar{\chi}\sigma^{\mu\nu}\chi\cdot\bar{q}\sigma_{\mu\nu}q$

D10 $\bar{\chi}\sigma^{\mu\nu}\chi\cdot\bar{q}\sigma_{\mu\nu}\gamma_5 q$

D12 $\bar{\chi}\gamma_5\chi\cdot G_{\mu\nu}G^{\mu\nu}$

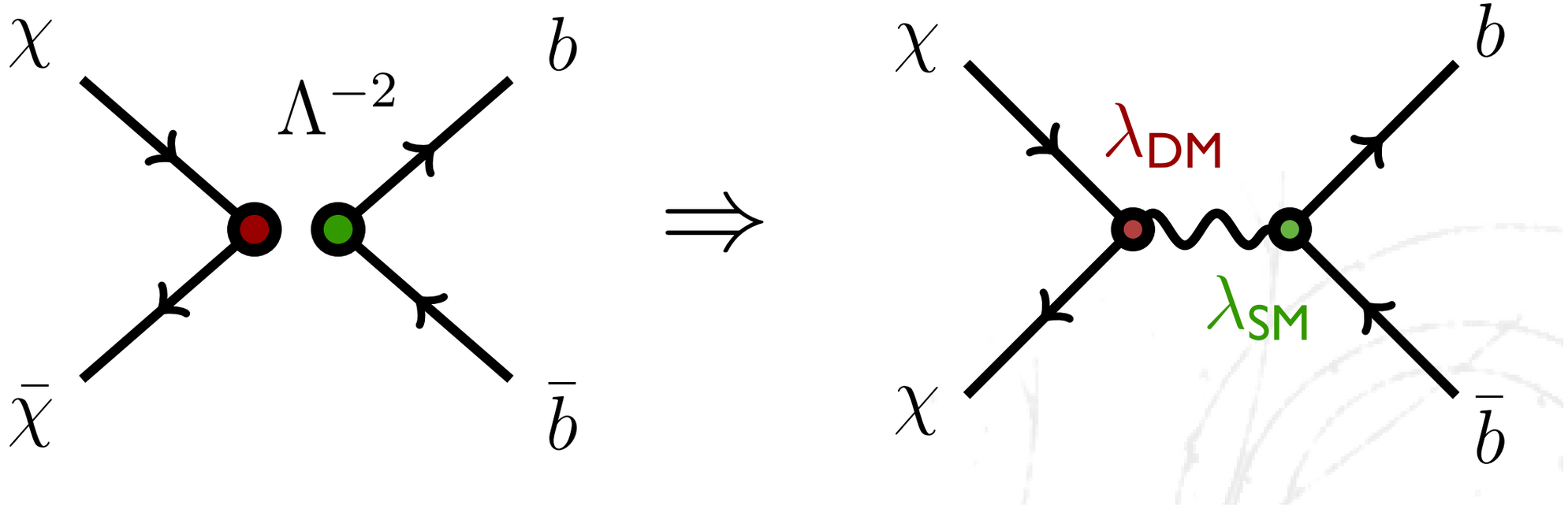
D14 $\bar{\chi}\gamma_5\chi\cdot G_{\mu\nu}\tilde{G}^{\mu\nu}$





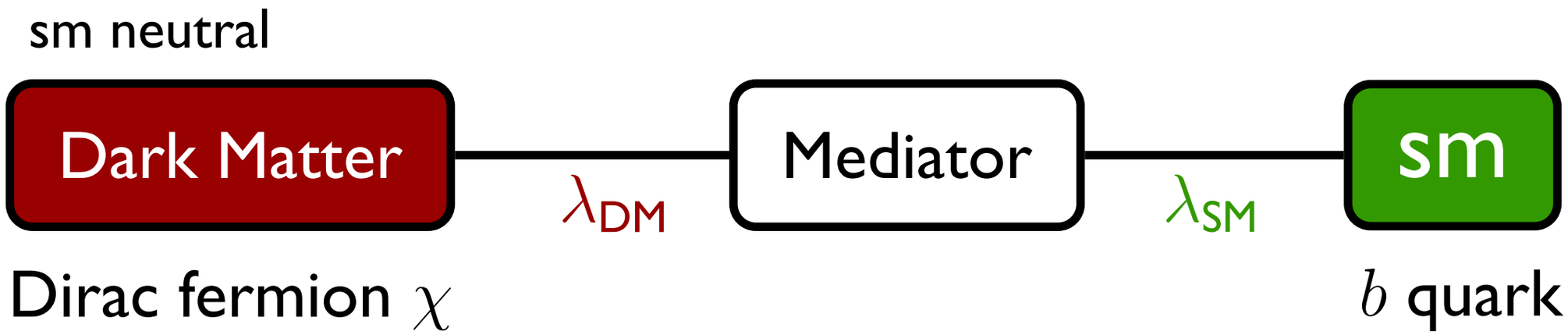
Heavy Mediator: exceptions

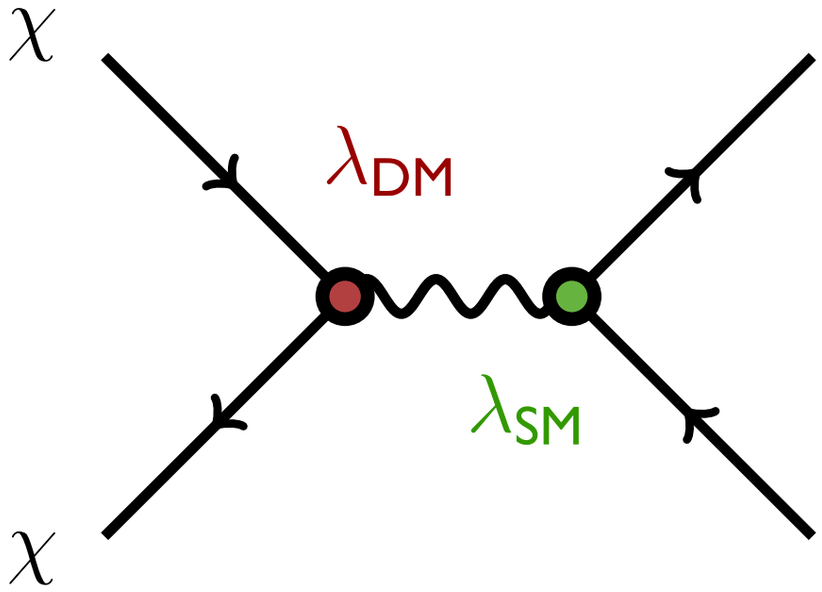
1. Majorana Dark Matter $\chi\bar{\gamma}^{\mu}\chi = 0$
2. Tuning of chiral couplings e.g. $Z\ell^{+}\ell^{-}$
3. Non-decoupled mediator $m_{\rm med} <$ heavy



Simplified Models

Renormalizable, capture physics of mediator (1105.2838)





Systematic studies:

Chicago: 1404.0022

Perimeter: 1404.2018

Explicit examples

Coy Dark Matter 1401.6458

Boehm, Dolan, et al.

Z' portal 1501.03490

Alves, Berlin, Profumo, Queiroz

Simplest Simplified Models (off shell)

Berlin et al. 1404.0022 and Izaguirre et al. 1404.2018 for a detailed survey of **off-shell** simplified models. See Boehm et al. 1401.6458 for a prototype.

Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B_\mu^\dagger B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$			
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1\pm\gamma^5)b$			
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1\pm\gamma^5)b$			
8	Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1\pm\gamma^5)$			
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1\pm\gamma^5)$			

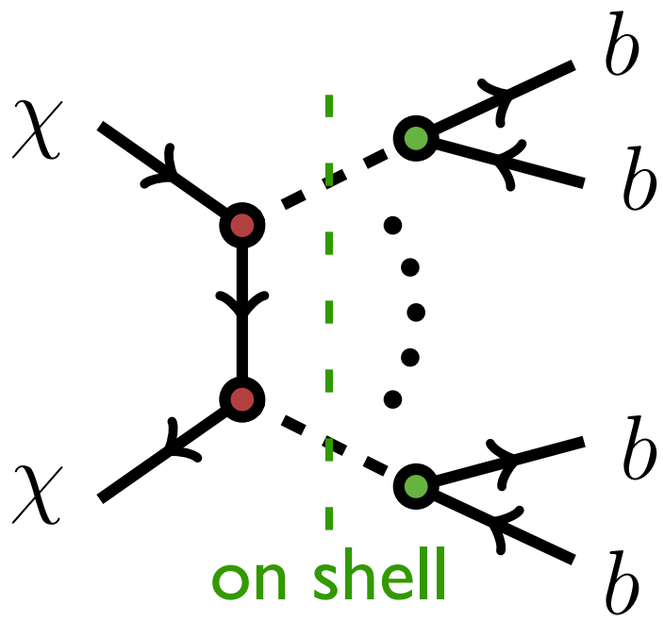
Looks like we're all done?

Comprehensive study of *s*- and *t*-channel diagrams.

Berlin et al. 1404.0022

On-Shell mediators

The m_{med} < heavy regime also includes $m_{med} < m_\chi$ where the mediator is accessible as an on shell annihilation mode



- Can be dominant mode
- Separates λ_{DM} from λ_{SM}
- Admits $\lambda_{DM} \gg \lambda_{SM}$

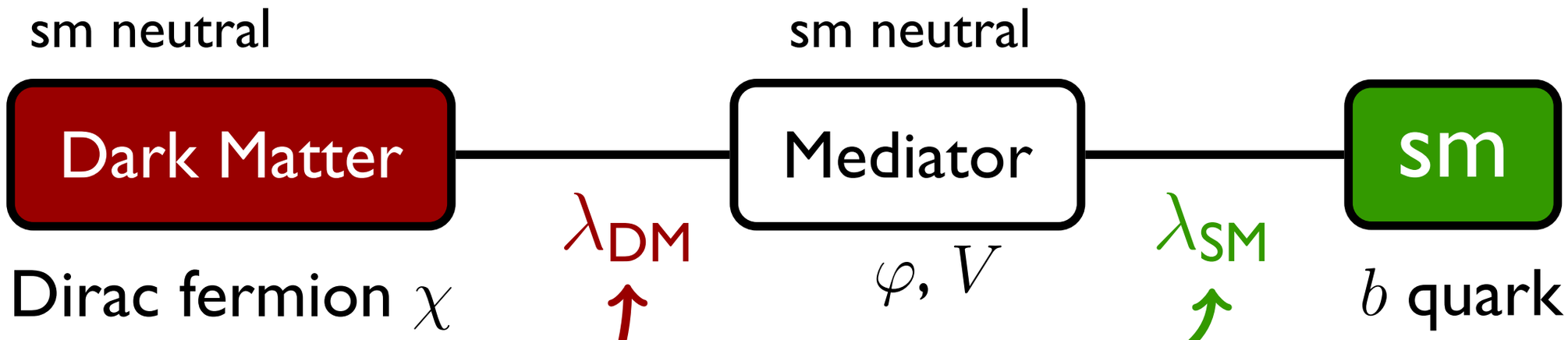
Application to the Hooperon:

FT et al.	1404.6528, 1503.05919
Dolan et al	1404.4977
Martin et al.	1405.0272
Elor et al.	1503.01773

Previously: PAMELA

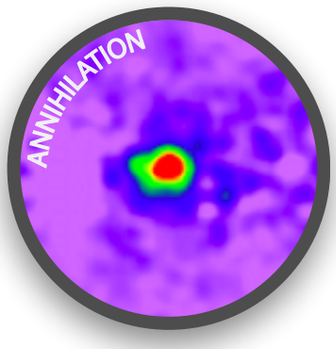
Axion Portal	0810.5397
Cascades	0901.2926

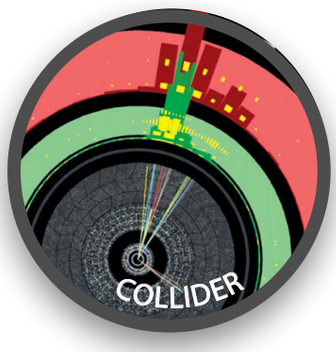
On-Shell Simplified Models



Annihilation, $\langle \sigma v \rangle$
γ-ray excess, relic abundance

Constraints
direct detection, colliders

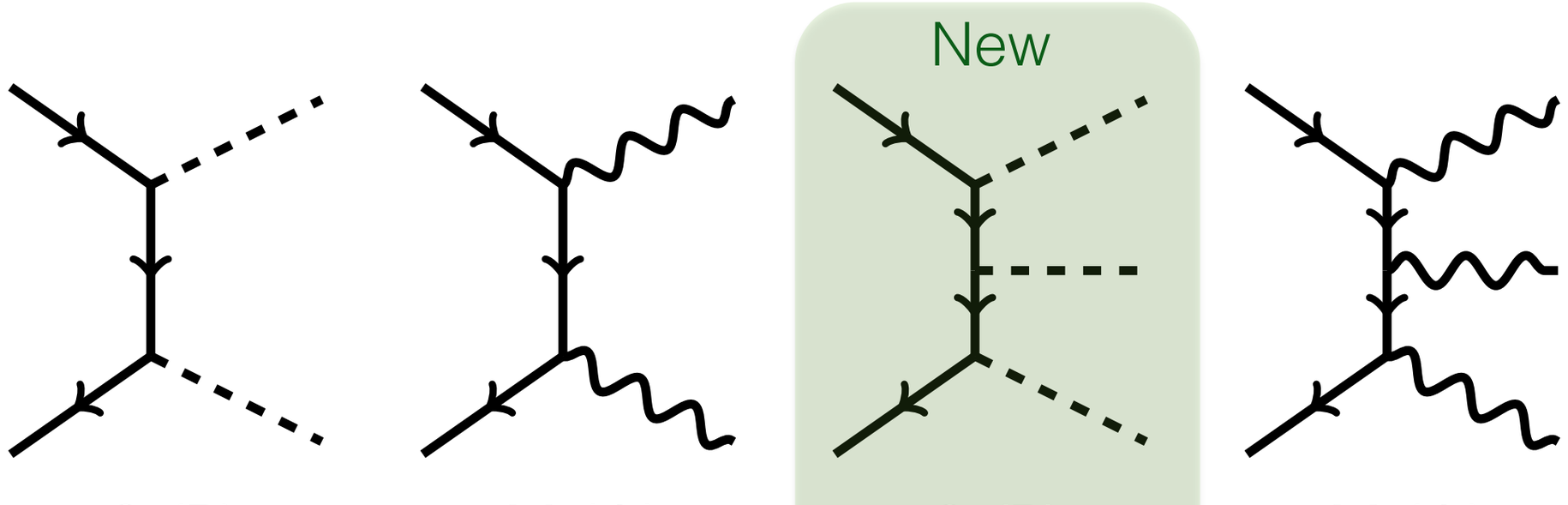




$$m_{V,\varphi} > 2m_b \qquad \lambda_{DM} \sim 1 \qquad \lambda_{SM} \ll 1$$

On-Shell Options

Require **s-wave** annihilation

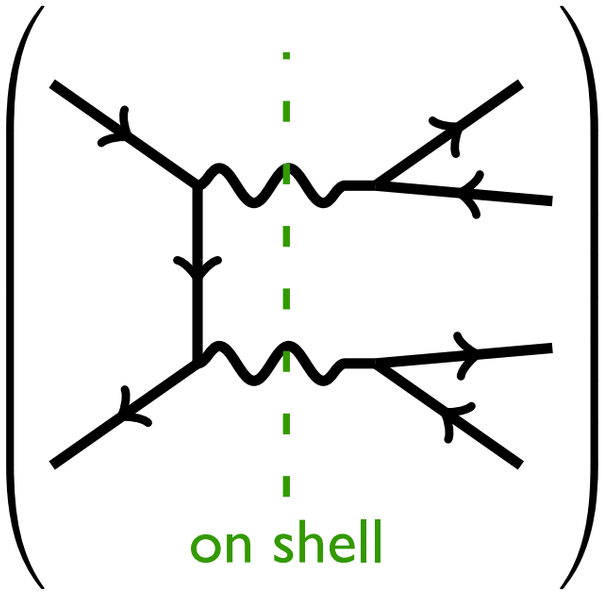


Med.	S (P)	V (A)	S (P)	V (A)
ℓ-Wave	p (p)	s (s)	p (s)	p (p)
m_χ	≈ 80 GeV	≈ 80 GeV	≈ 120 GeV	≈ 120 GeV

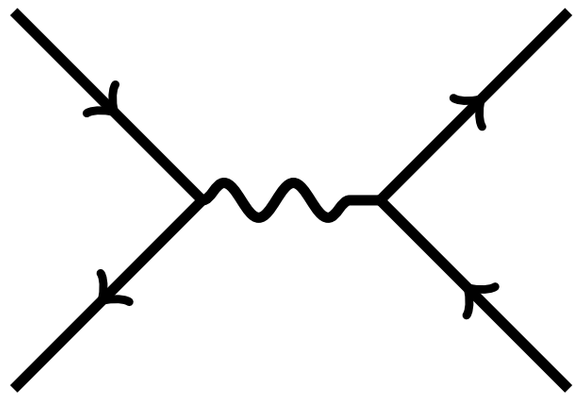
Further Requirements:

$$2m_\chi > \begin{cases} 2m_V & \text{for a spin-1 mediator} \\ 3m_\varphi & \text{for a spin-0 mediator} \end{cases}$$

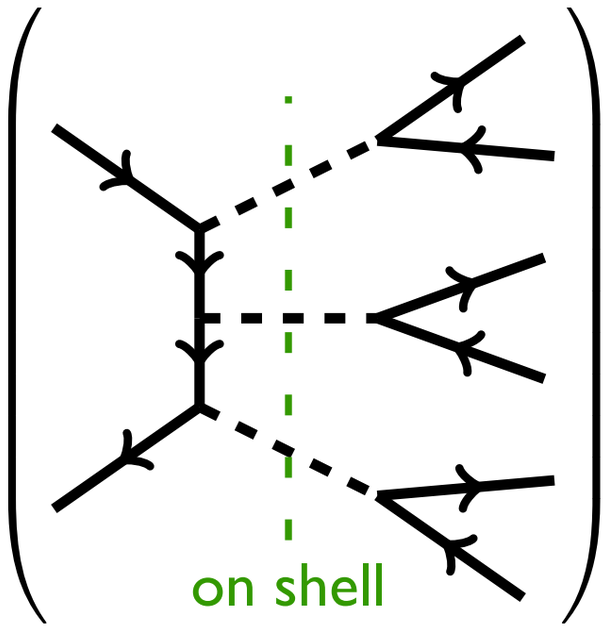
Dominance over off-shell



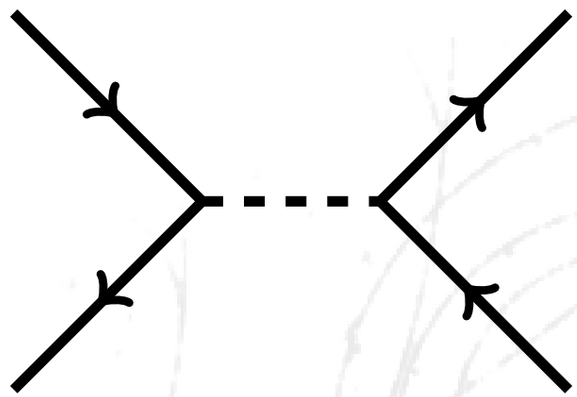
$\sim \lambda_{dm}{}^2 \gg$



$\sim \lambda_{dm}\lambda_{sm}$



$\sim \frac{\lambda_{dm}{}^3}{\sqrt{4\pi}} \gg$



$\sim \lambda_{dm}\lambda_{sm}$

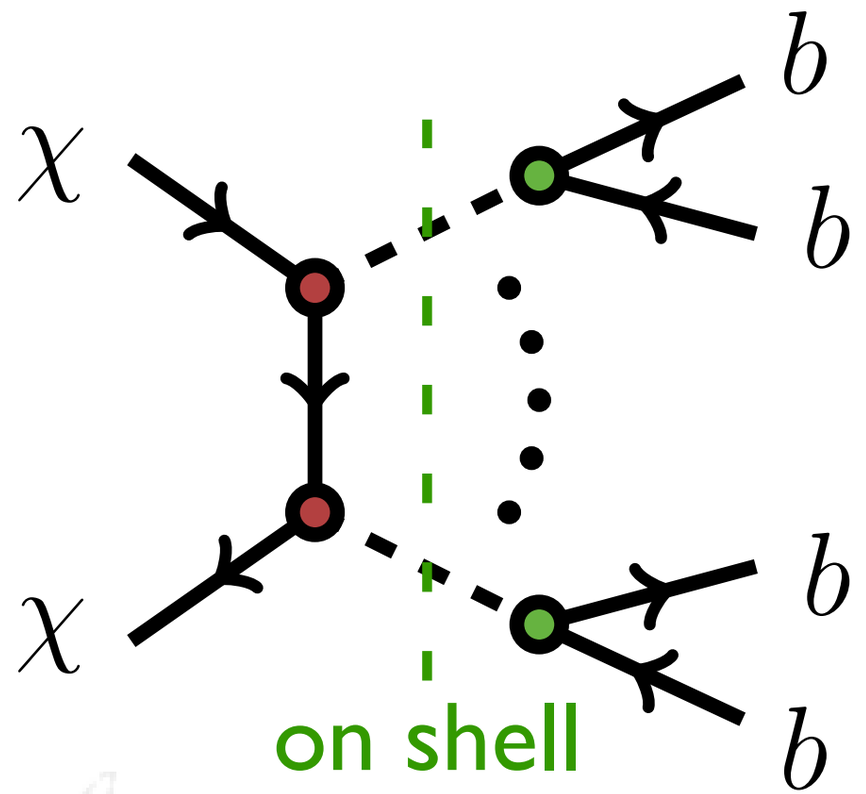
Back of the Envelope

Using *bb* final state as a reference fit

$$m_\chi \approx n \times \text{(40 GeV)}$$

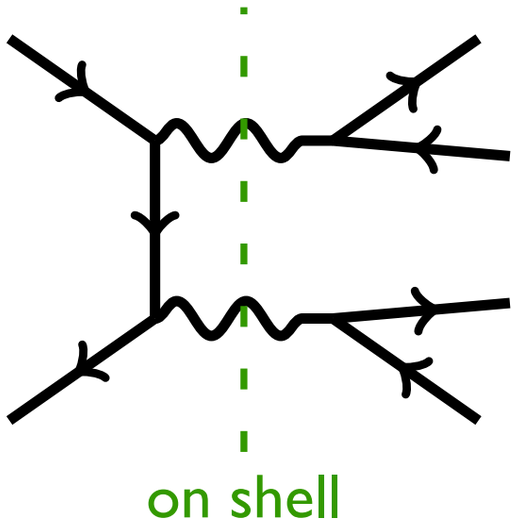
$$\langle \sigma v \rangle \approx n \times \langle \sigma v \rangle_{bb}$$

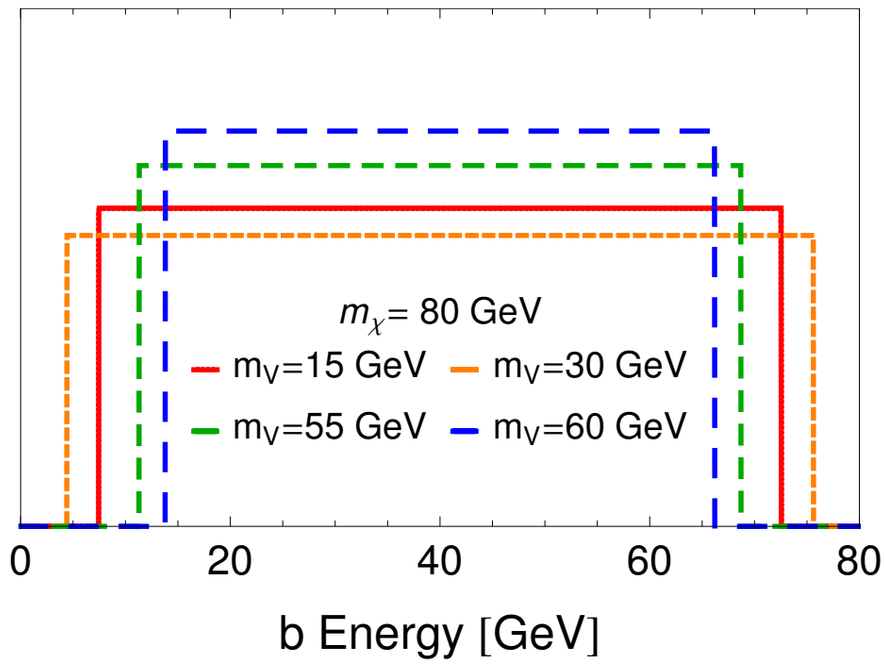
$$\lambda_{\text{DM}} \approx 0.35\ (1.25) \quad \text{for spin-1(0)}$$



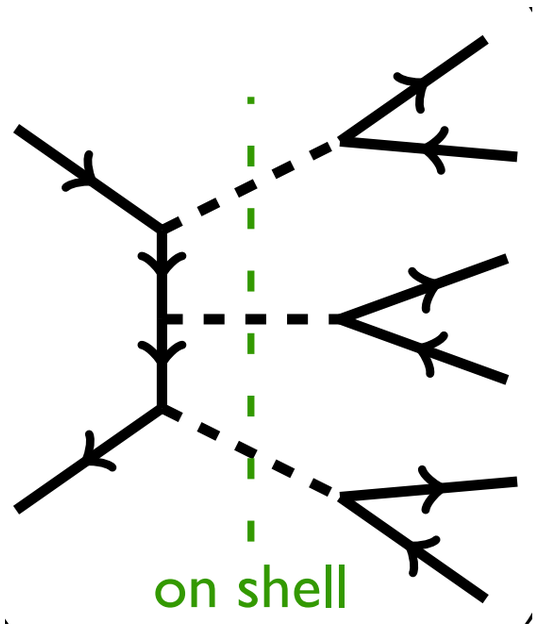
$$\frac{d\Phi(b,\ell)}{dE_\gamma} = \frac{\langle \sigma v \rangle_{\text{ann}}}{16\pi} \frac{dN_\gamma}{dE_\gamma} \int_{\text{los}} dx \left(\frac{\rho}{m_\chi}\right)^2$$

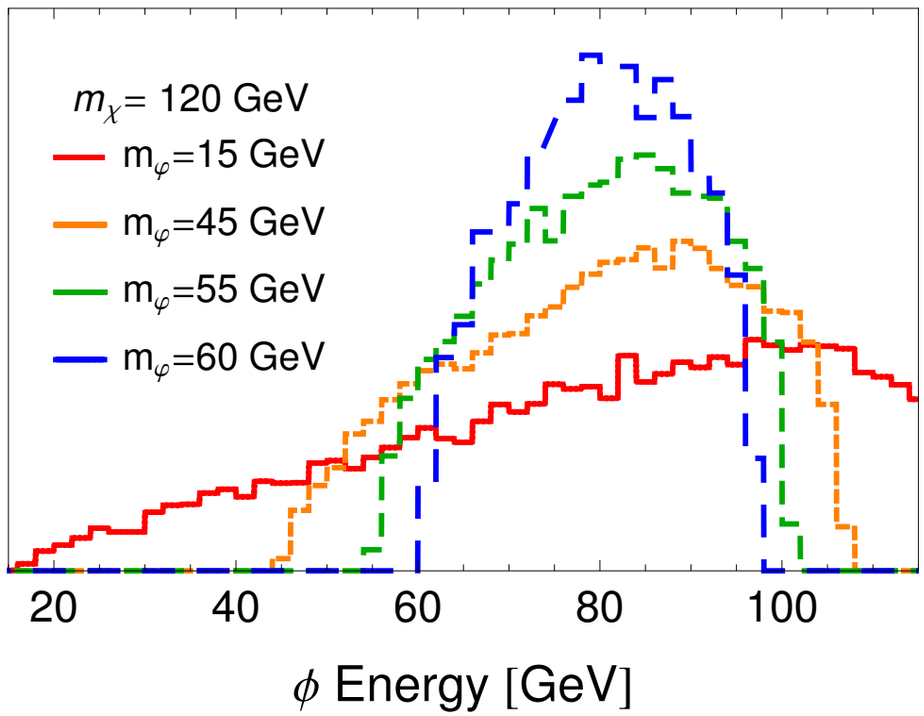
Boosted Mediators

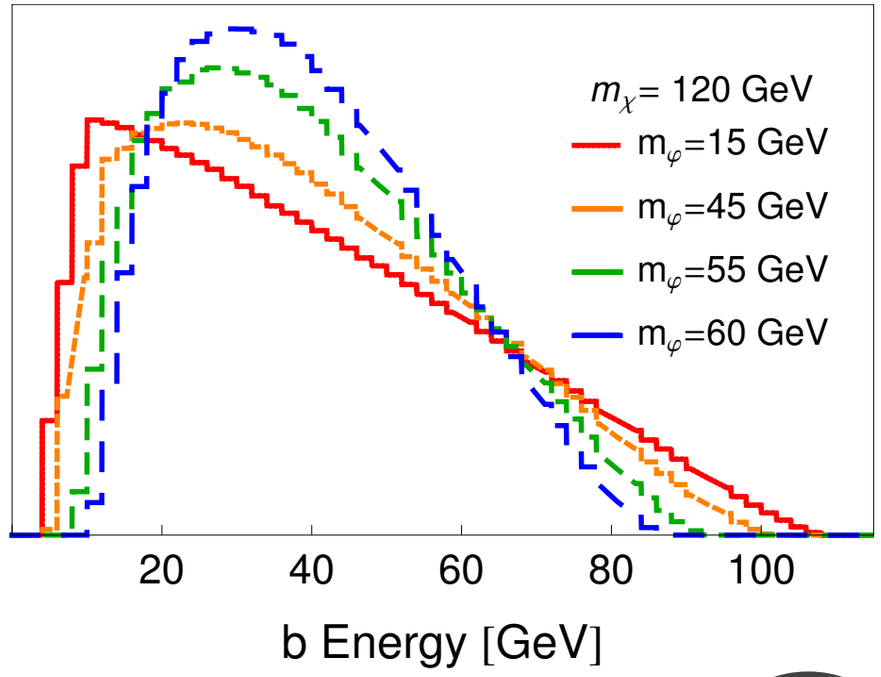




change spectrum of SM primaries, change spectrum of secondary γ's



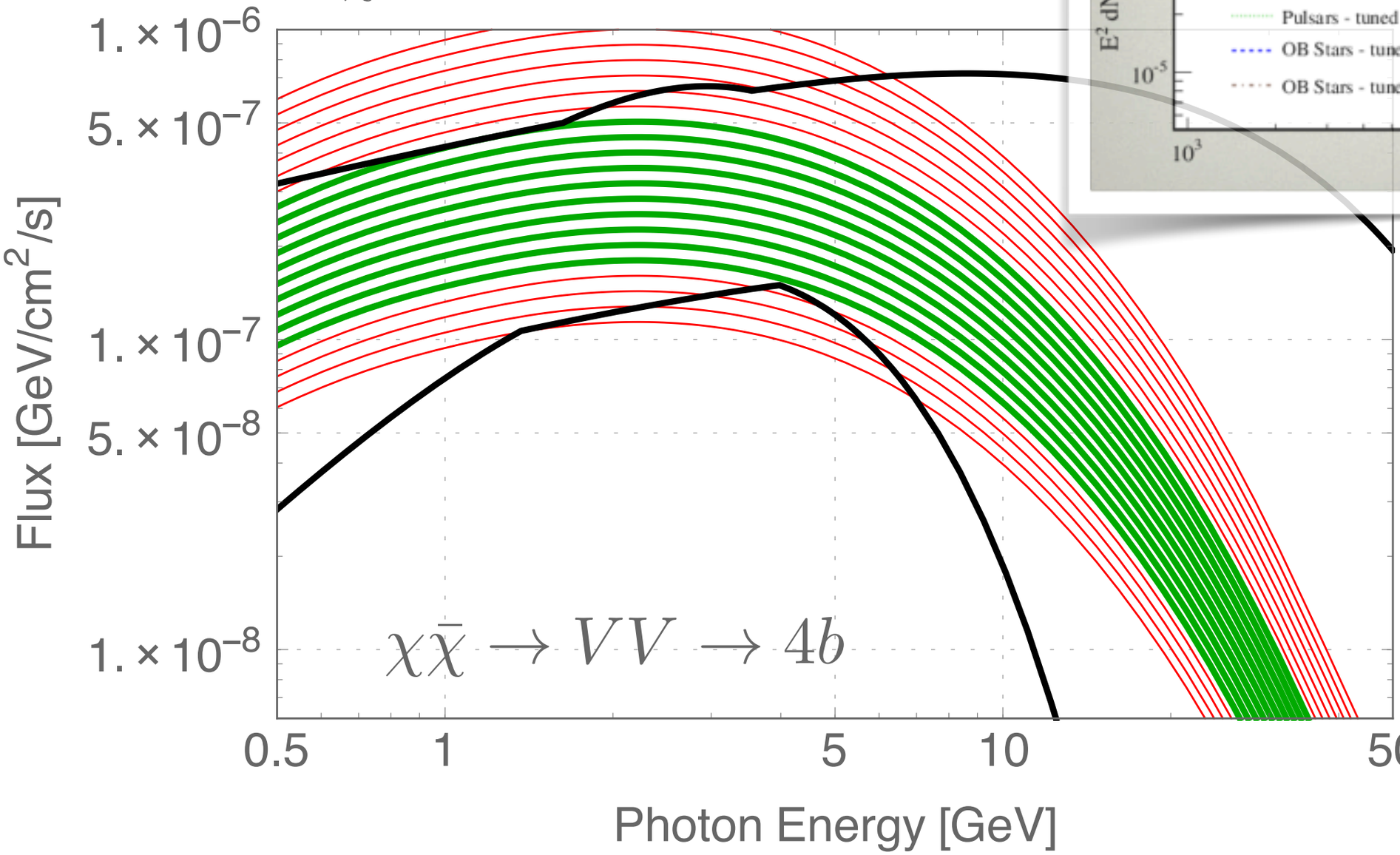




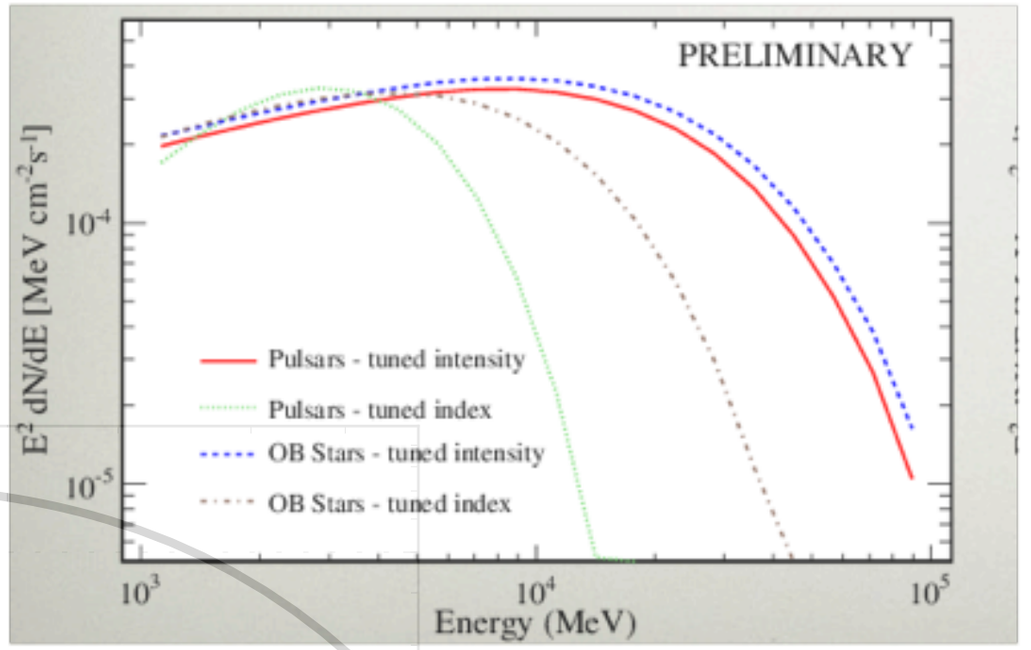
Spectral Shape

Factor of 2 on envelope size

m_χ = 81 GeV m_V = 39 GeV



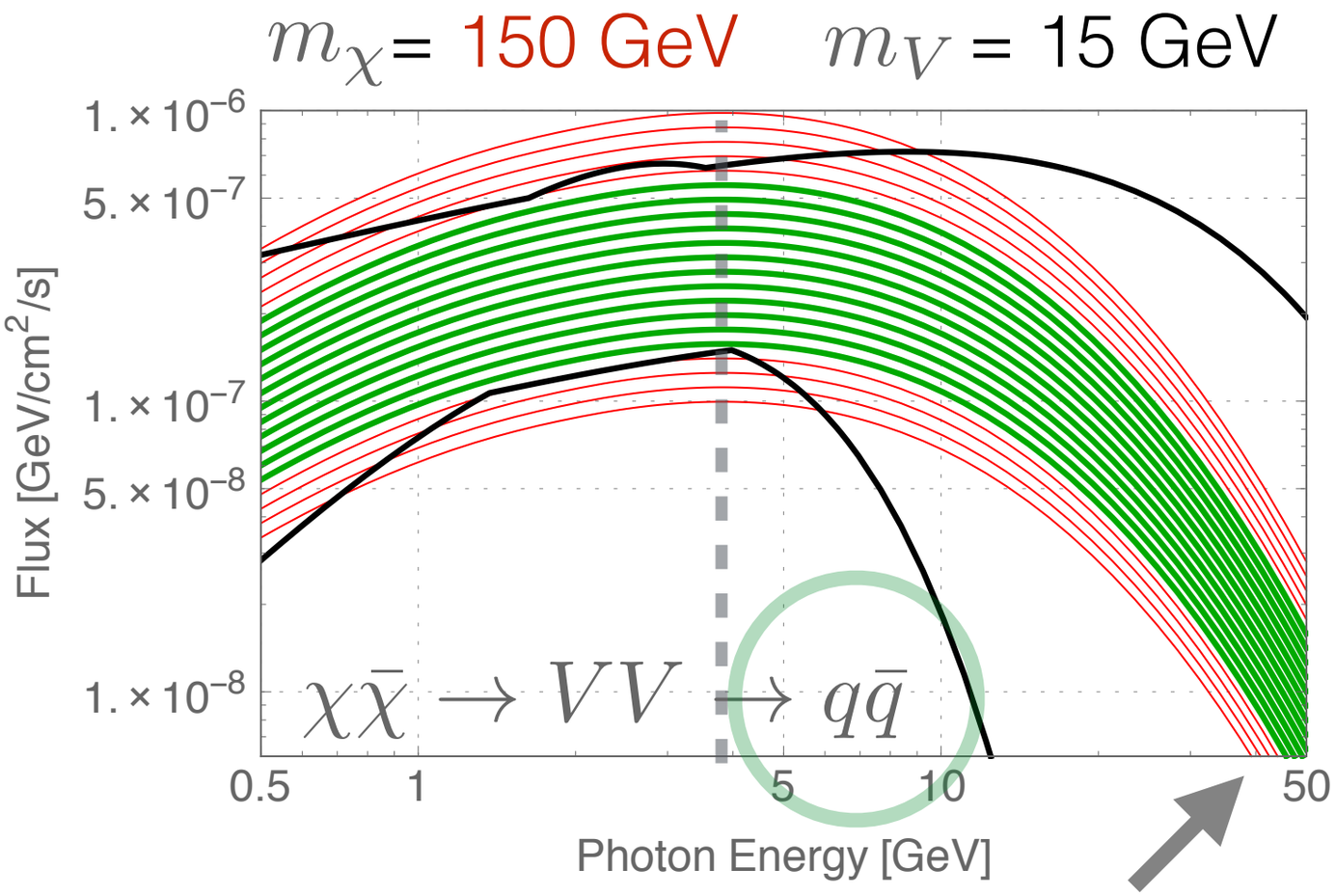
FT, Smolinsky & Rajaraman
arXiv:1503.05919

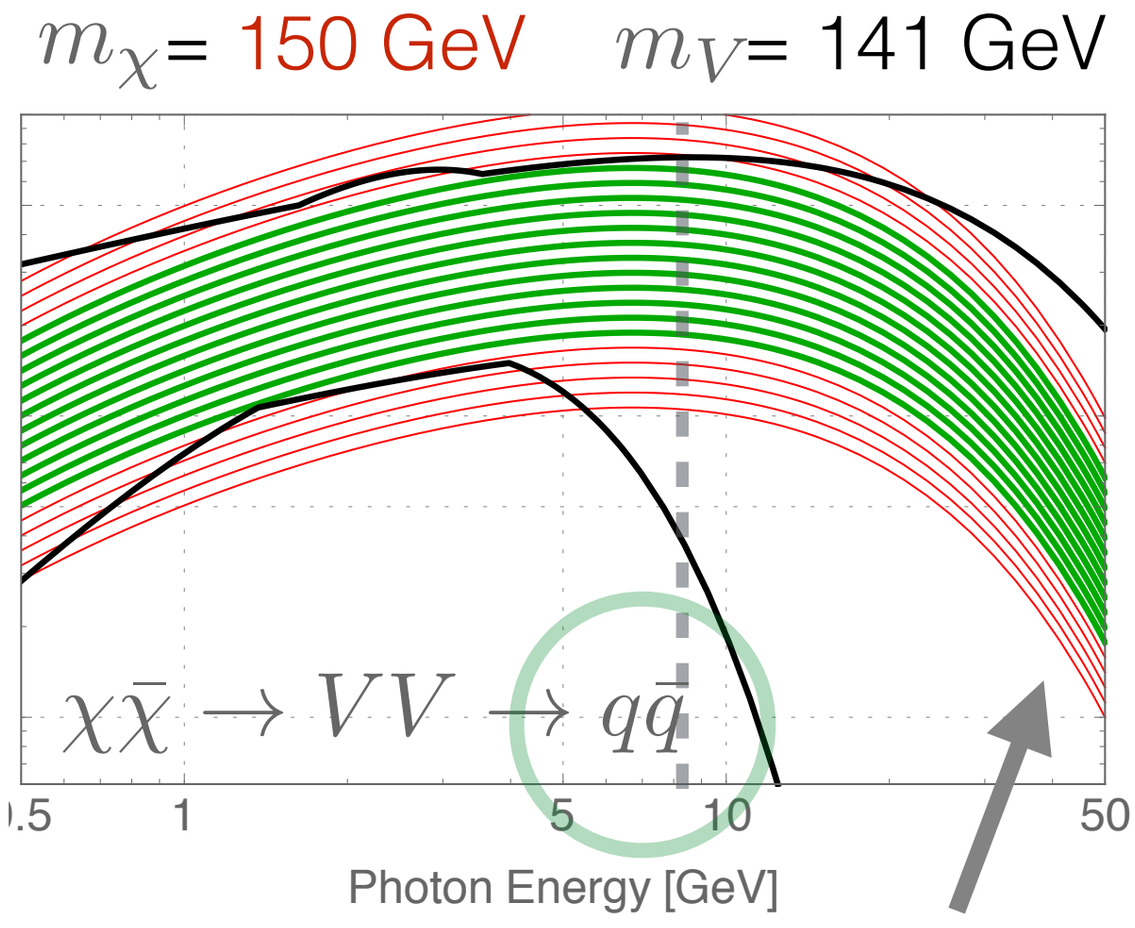


Simona Murgia
Fermi Collaboration
Fermi Symposium '14

Plots using FT, "PPPC Machine" tools based on PPPC4DMID by M. Cirelli 1012.4515

Spectral Shape

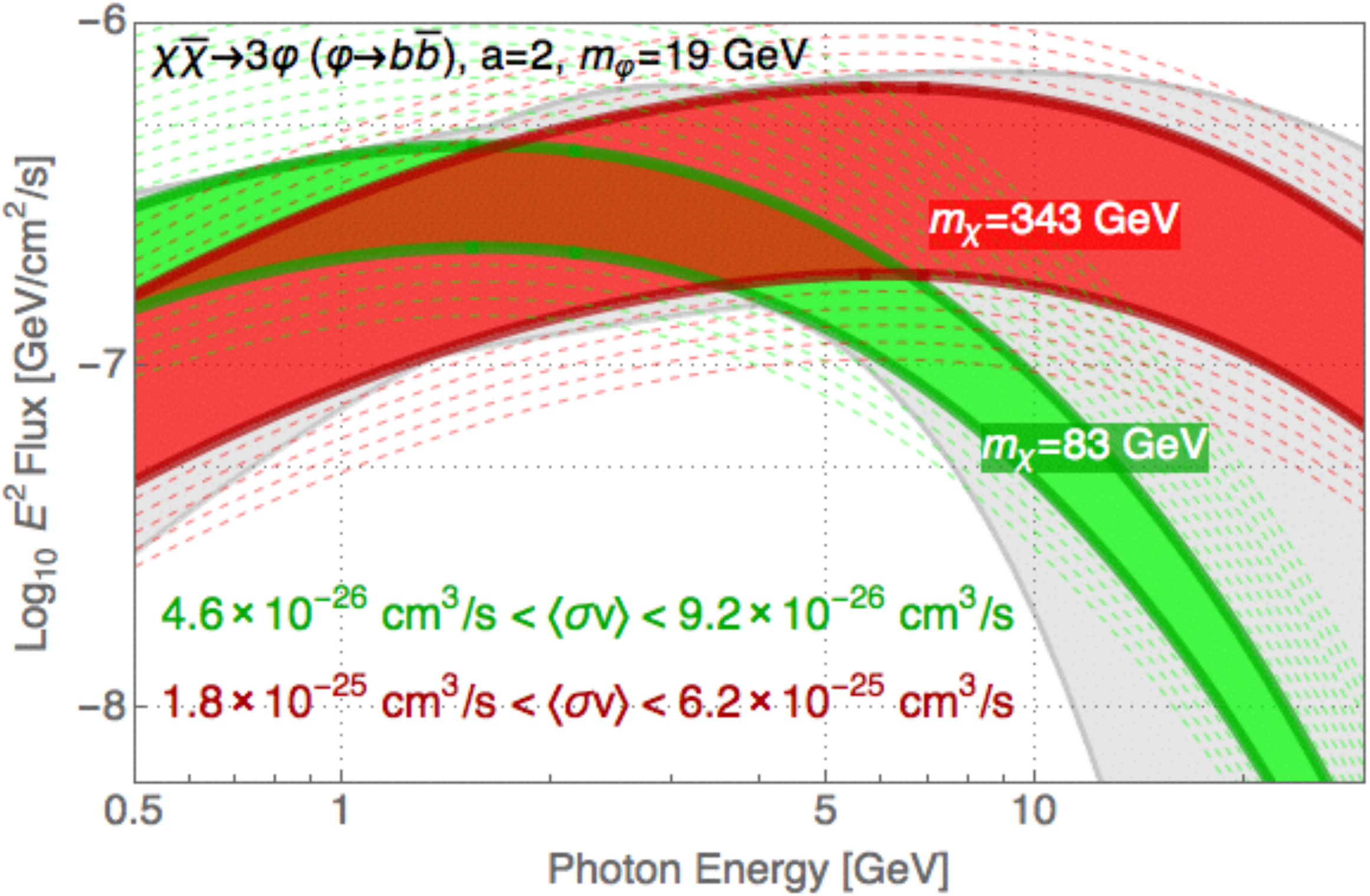




- Boost factor can bend shape!
  Shape is not just a function of SM primary
- Fermi analysis allows heavier DM
  See also Calore et al. 1502.02805, Agrawal et al. 1411.2592

FT, Smolinsky & Rajaraman arXiv:1503.05919

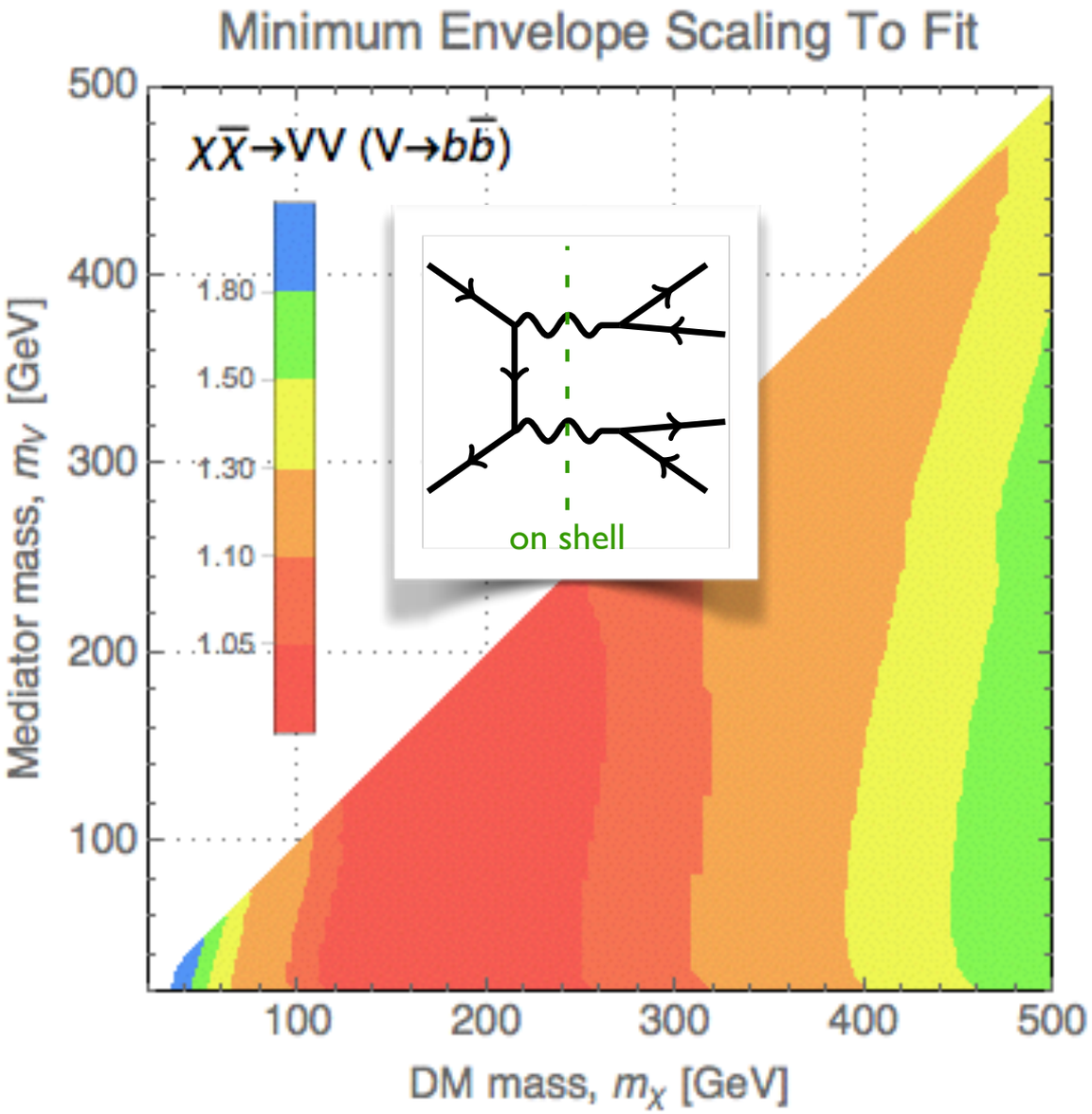
Examples with 3φ



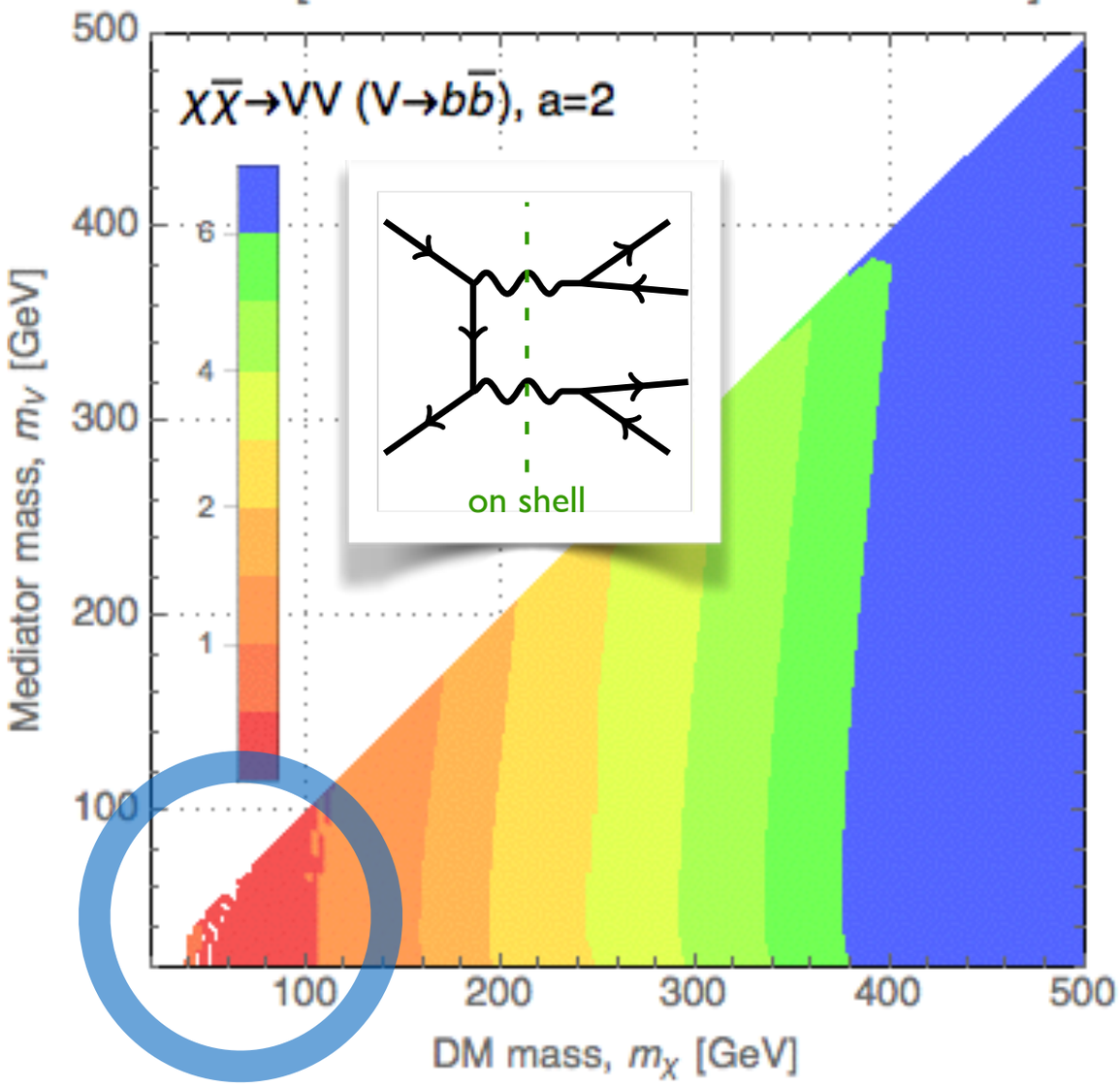
FT, Smolinsky & Rajaraman arXiv:1503.05919

Fit: on-shell vector mediator

(shape fit)



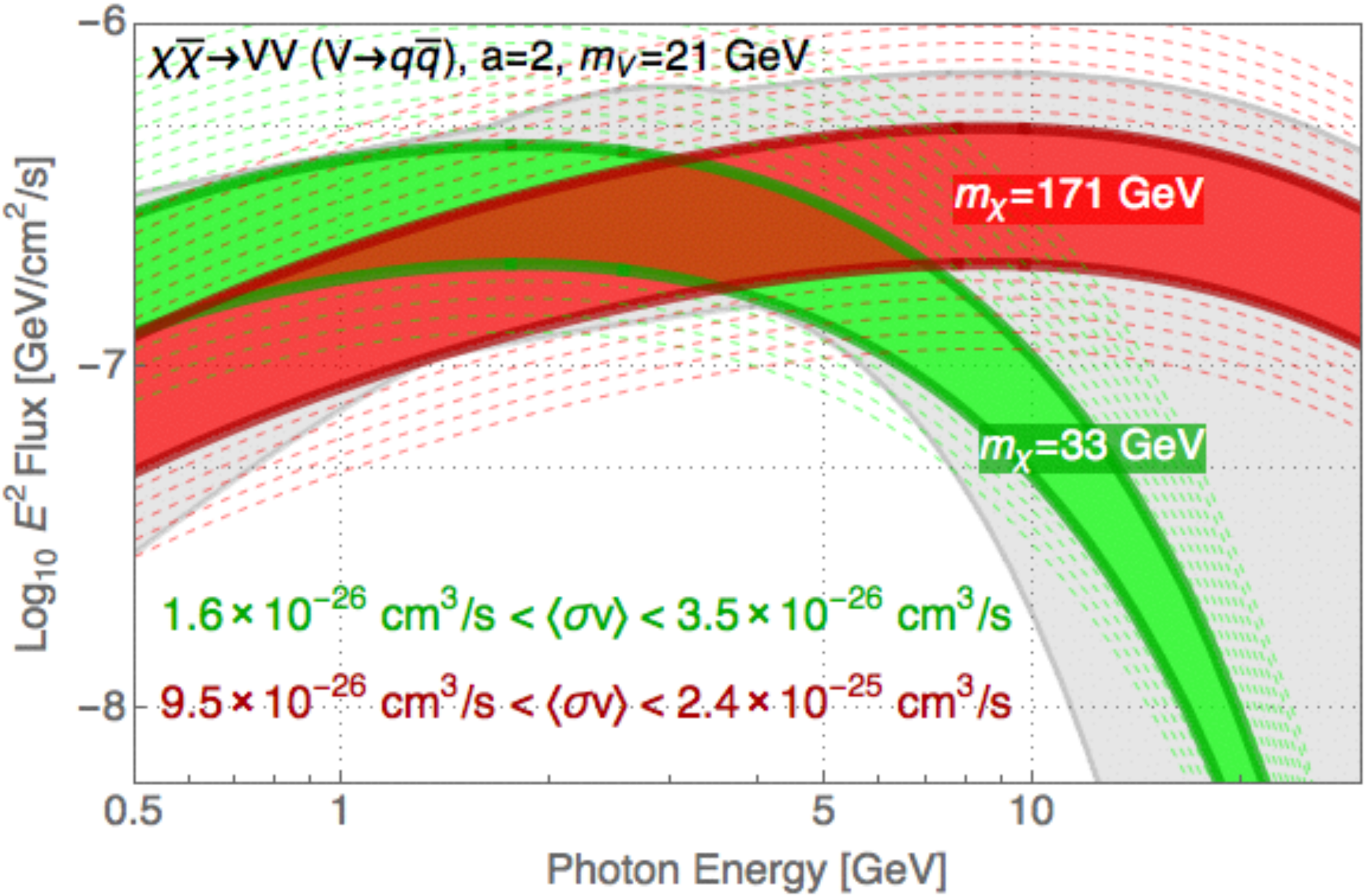
(normalization fit)



Similar for annihilation into light quarks
n.b. vector mediators typically couple flavor universally

FT, Smolinsky & Rajaraman arXiv:1503.05919

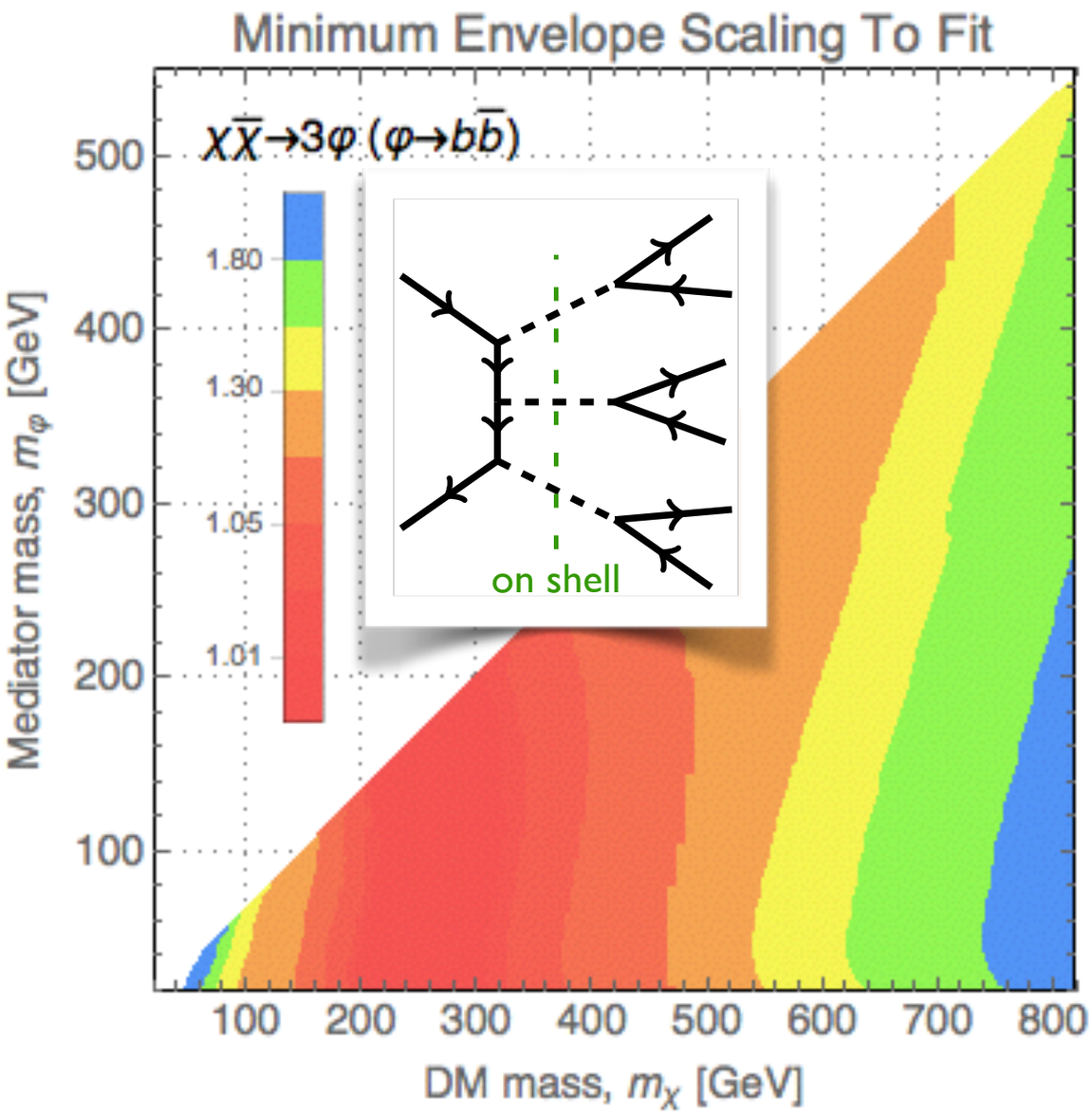
On Shell Vector



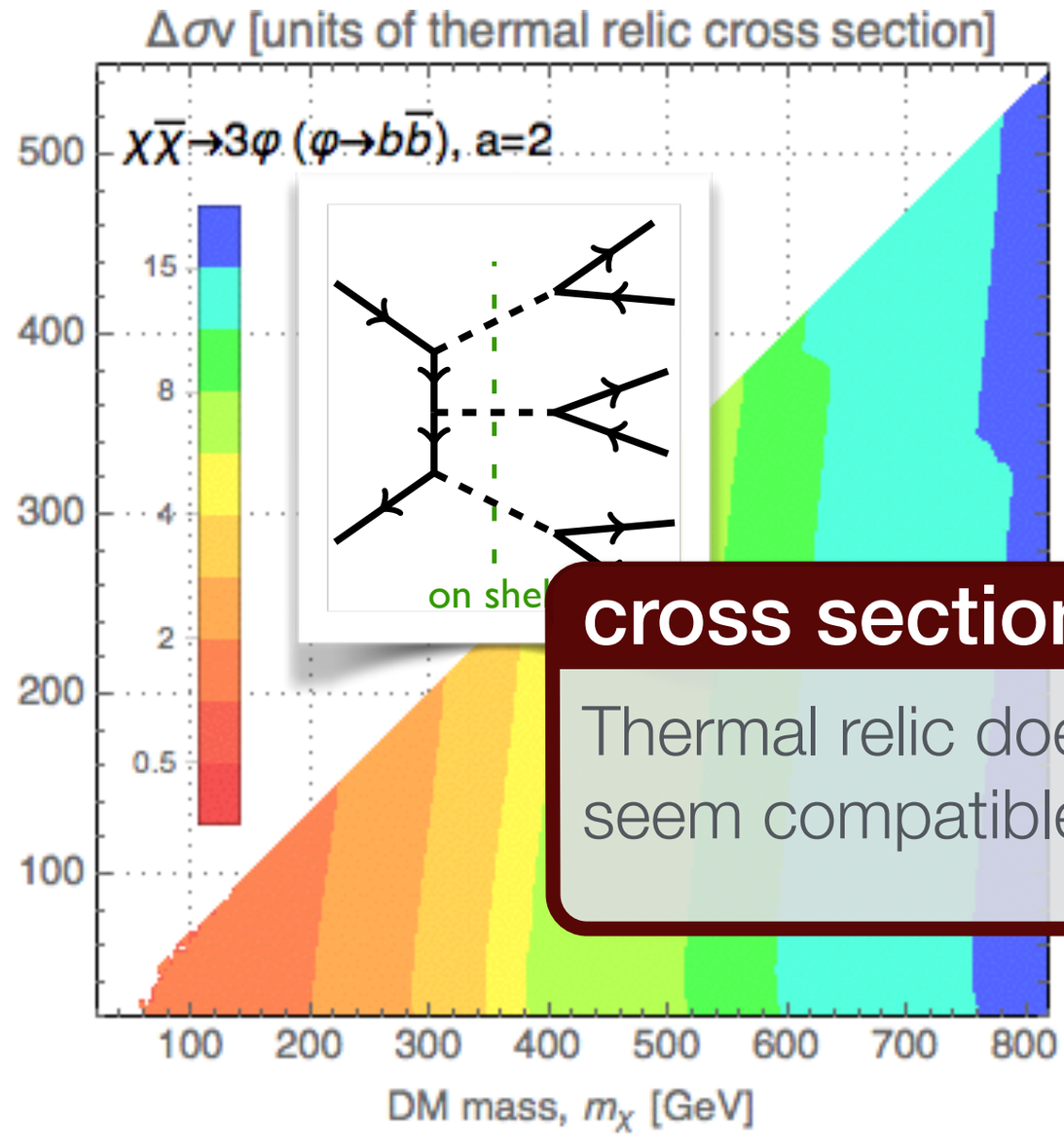
FT, Smolinsky & Rajaraman arXiv:1503.05919

Fit: on-shell pseudoscalar mediator

(shape fit)



(normalization fit)



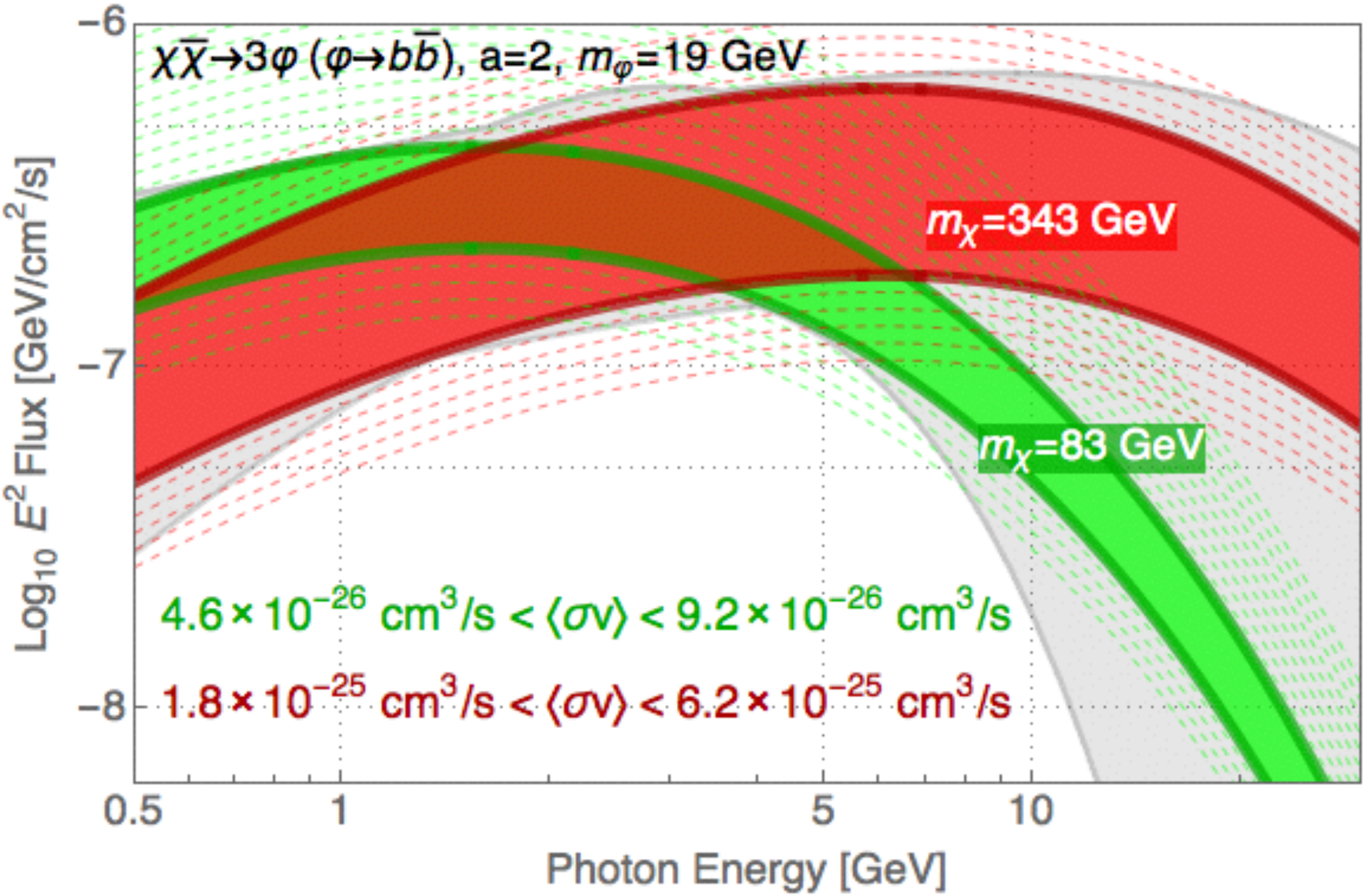
cross section

Thermal relic doesn't seem compatible!

Similar for annihilation into light quarks
n.b. scalar mediators typically couple ~ mass

FT, Smolinsky & Rajaraman arXiv:1503.05919

On Shell Pseudoscalar



FT, Smolinsky & Rajaraman arXiv:1503.05919

Relic Abundance

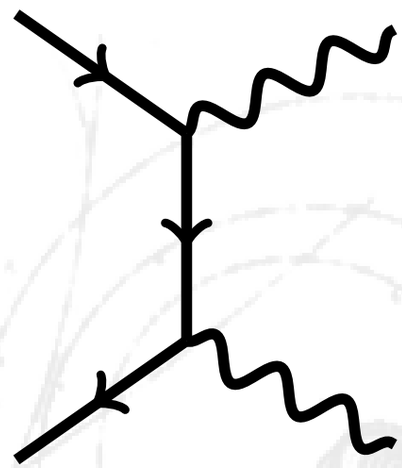
Works for vector mediator; back of the envelope:

Traditional "Hooperon" ($\chi\chi$ to bb)

$$\langle \sigma_{b\bar{b}} v \rangle = (1.5) \quad 5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$\gamma = 1.26$ (1402.6703)

$\gamma = 1.12$ (1402.4090)



Ballpark of thermal relic σ

$\langle \sigma v \rangle_{\text{ann.}}$ between 3 – 10 $\times 10^{-26}$ cm^3 s^{-1}

Vector mediator works for Dirac χ

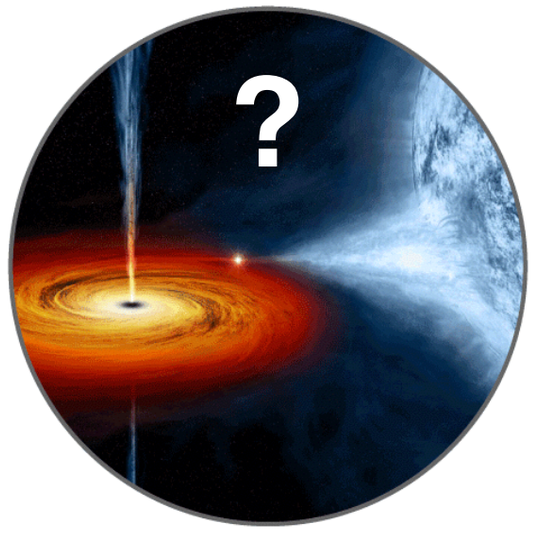
$$\langle \sigma v \rangle_{\text{ann}} \approx n \langle \sigma_{b\bar{b}} v \rangle$$

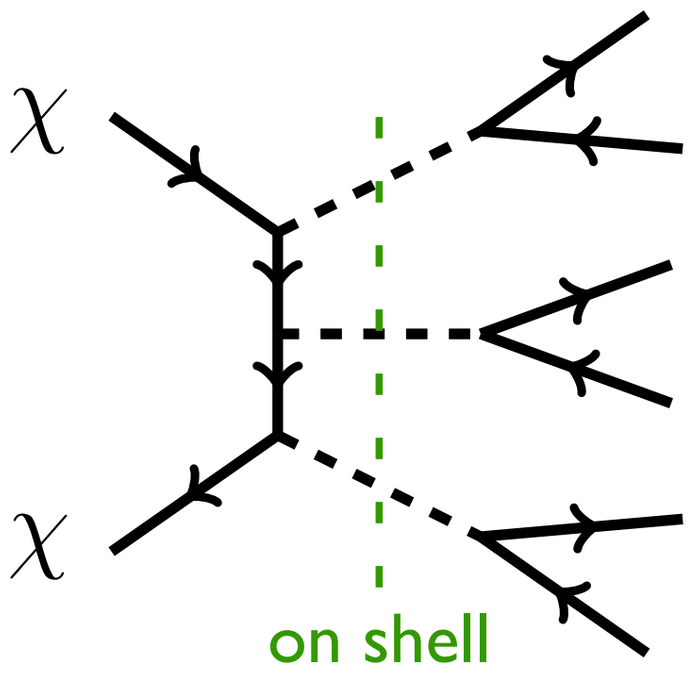
Relic Abundance

Vector mediator can accommodate thermal relic.

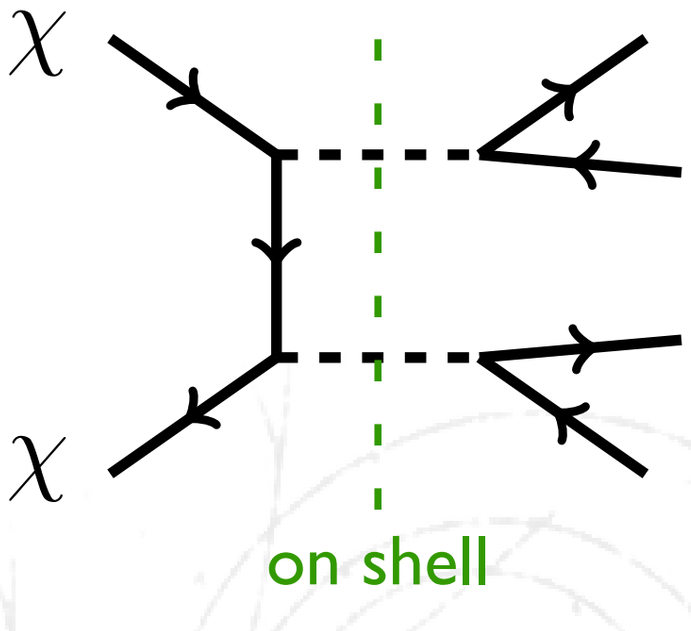
Scalar mediator is more difficult,

1. $\langle \sigma v \rangle_{\text{ann}} = 3 \times \langle \sigma v \rangle_{b\bar{b}}$
2. p-wave irreducible contributions

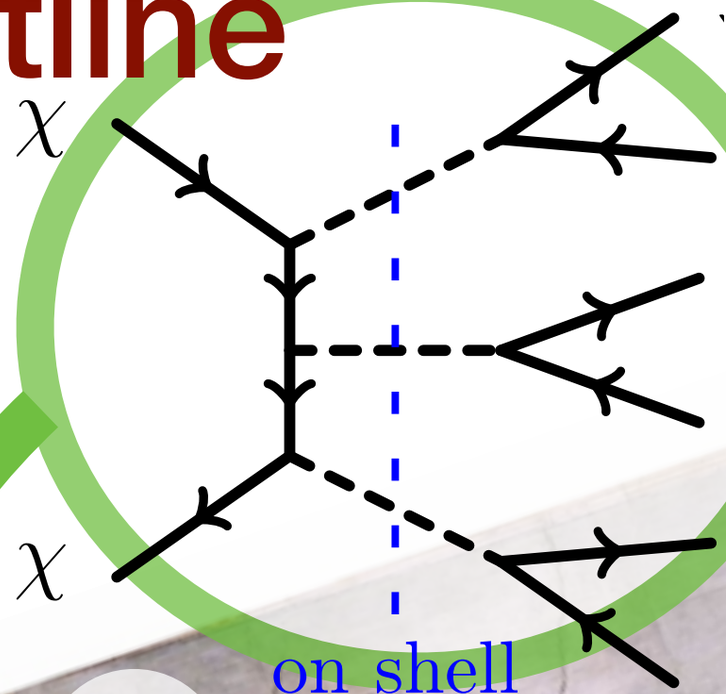




$$\sim \frac{\lambda_{\text{dm}}}{\sqrt{4\pi}} \sqrt{\frac{x_f}{3}}$$

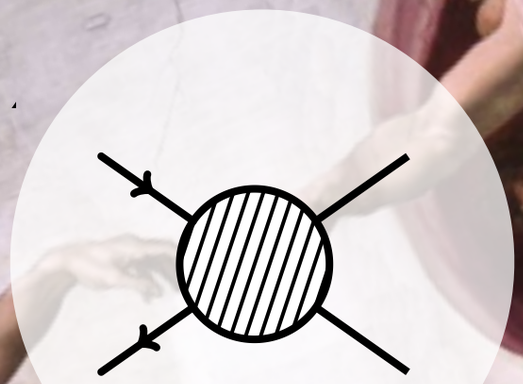


Outline

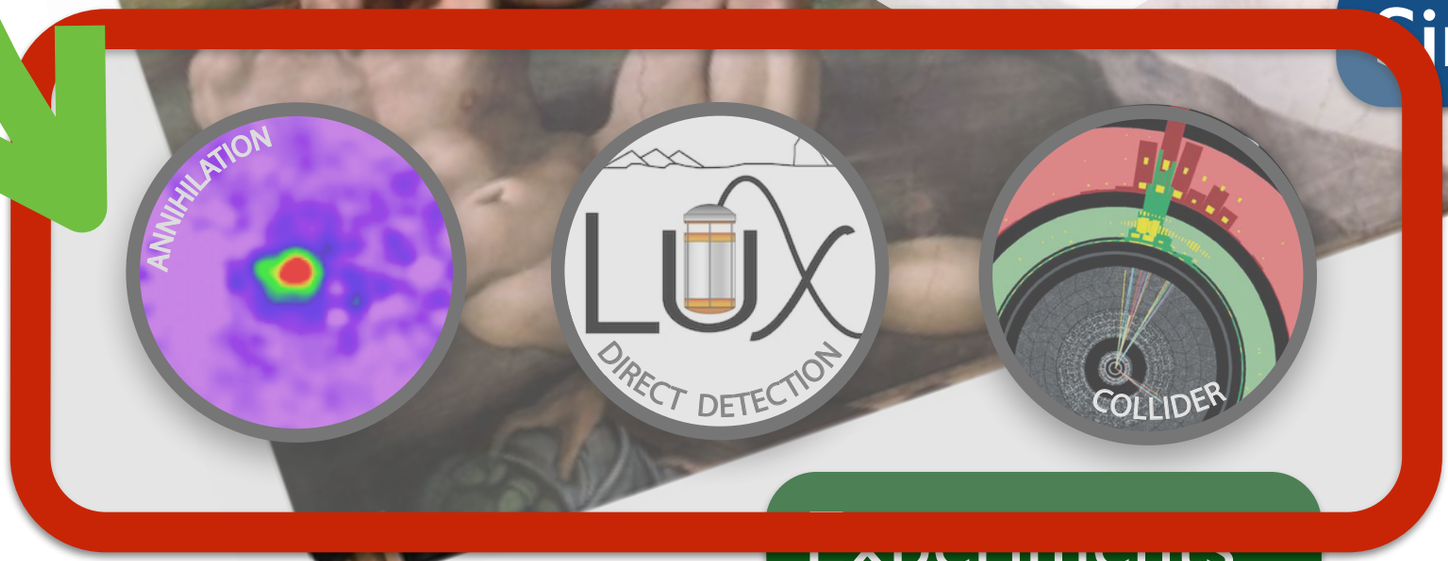


Nature

UV Models



Simplified Models

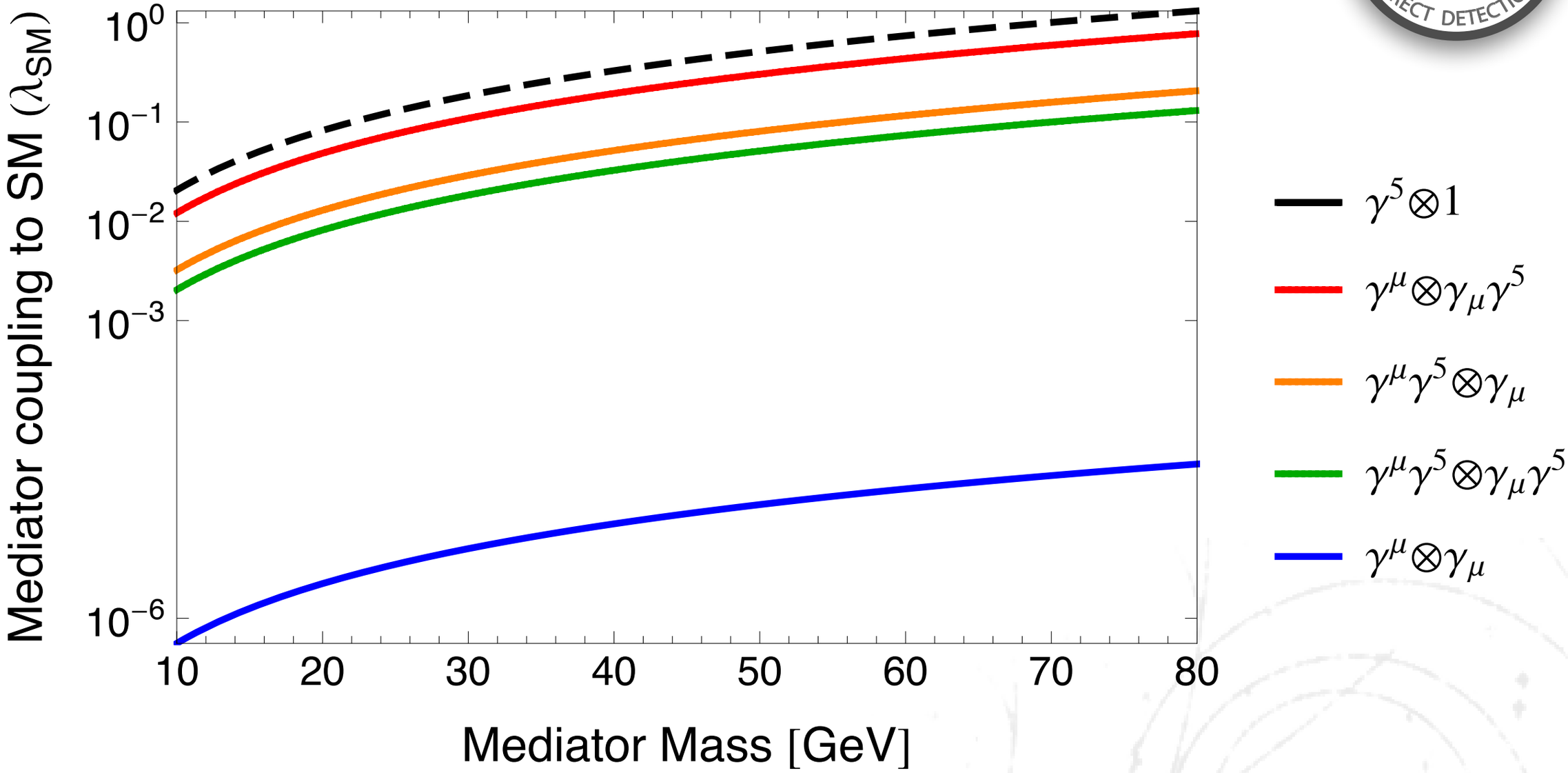


Experiments

Michelangelo Buonarroti,
"Creation of Adam" (1510)

Direct Detection: roughly

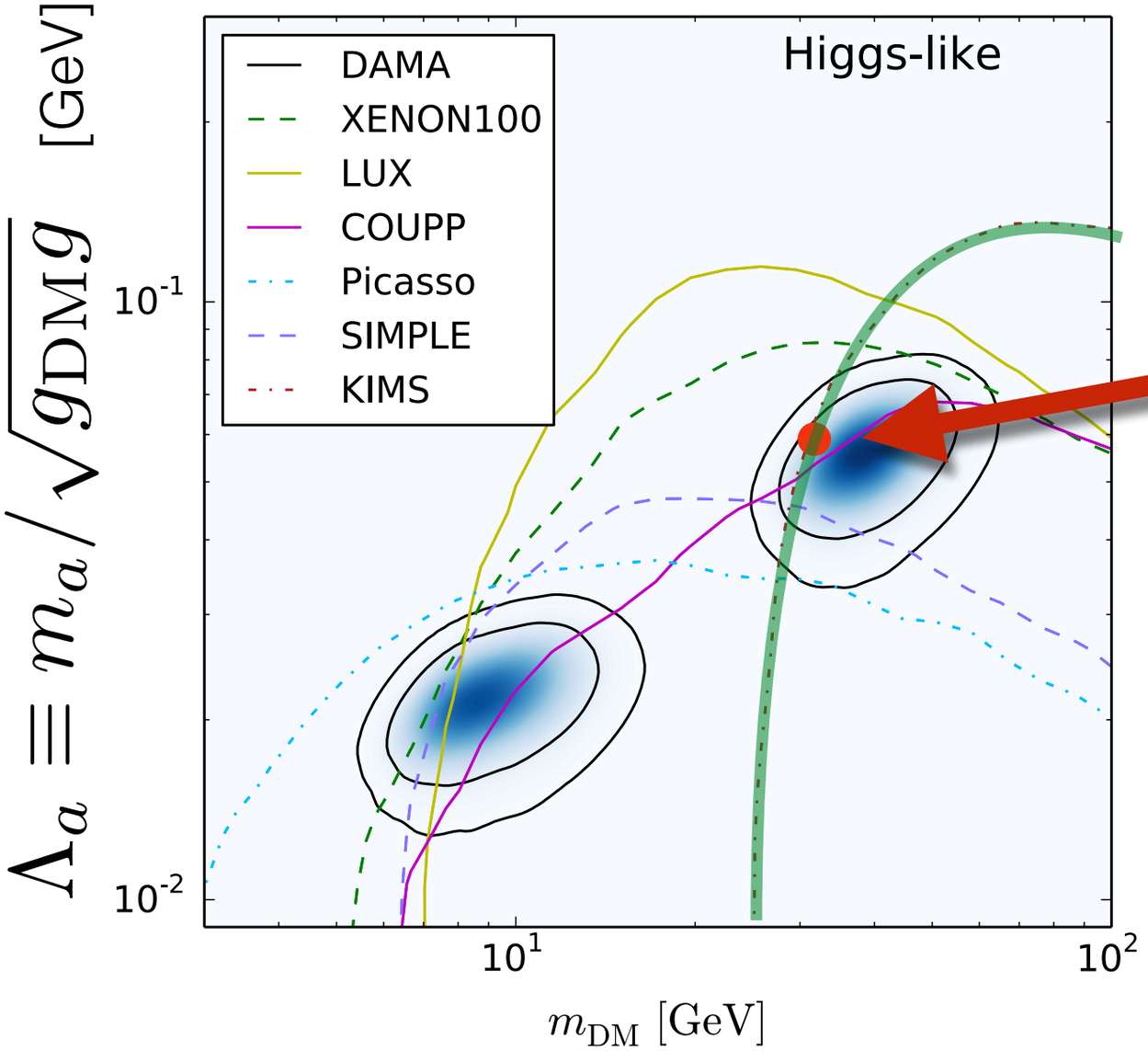
LUX SI 1310.8214, XENON100 SD 1207.5988



$\gamma^5 \otimes \gamma^5$ is q^4 suppressed, no bound below $\lambda_{SM} < \sqrt{4\pi}$.

Direct Detection (more carefully)

del Nobile et al. 1406.5542 $g_f = m_f/v$



Based on non-rel. EFT

Fitzpatrick et al. 1203.3542, 1211.2818, 1308.6288

KIMS experiment

Gal. Center & Thermal Relic

Pseudoscalar mediator

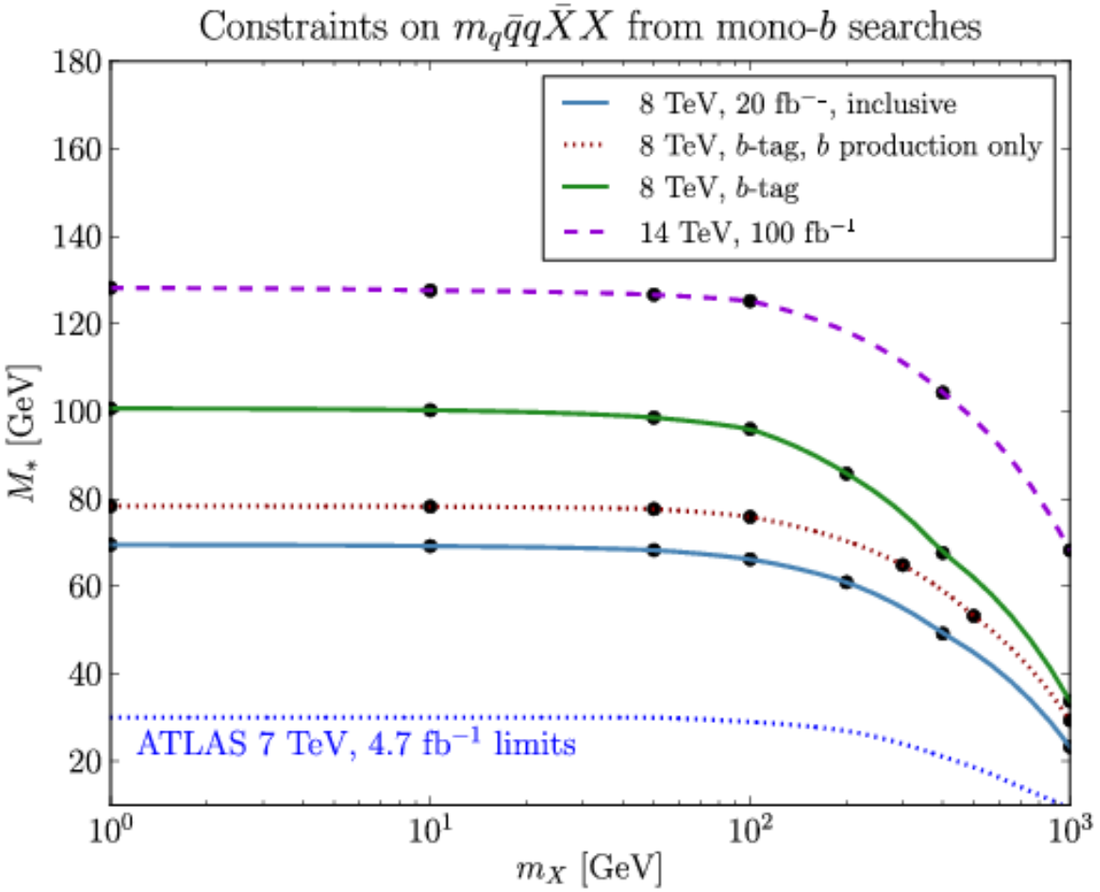
Spin-dependent interaction

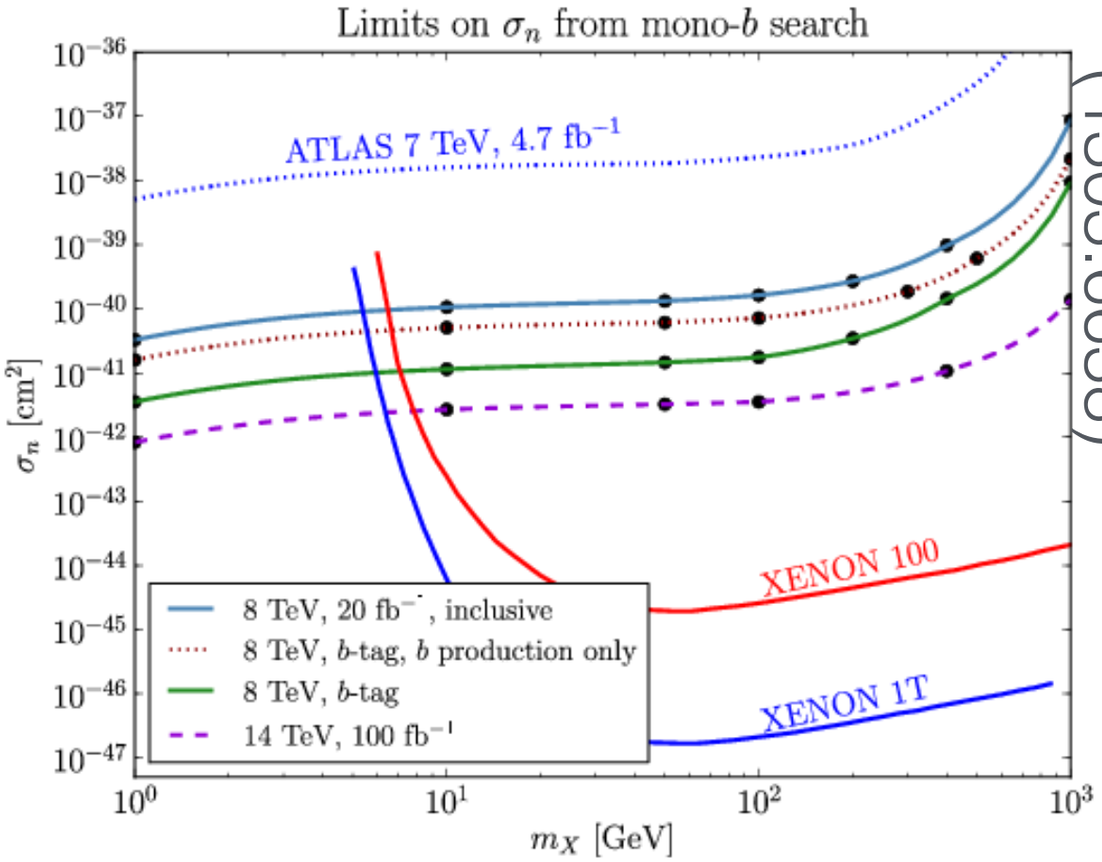
$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\, \bar{\chi}\gamma_5\chi - ig\sum_f \frac{g_f}{\sqrt{2}} a\, \bar{f}\gamma_5 f$$

del Nobile et al. 1406.5542, 1307.5955, 1502.07682

Collider: mono-*b*

Lin et al (1303.6638), Daylan et al. 1402.4090 (EFT), Izaguirre et al. 1404.1373 (simplified model).
Mono-object analyses: UCI (1005.1286, 1008.1783, 1108.1196), Fermilab (1005.3757, 1103.0240)

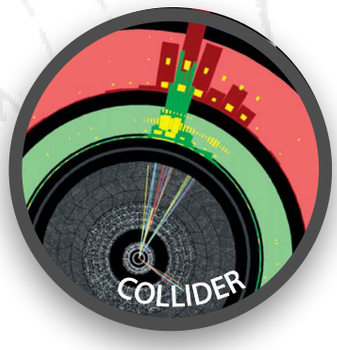




Lin et al. (1303.6638)

$$\lambda^{\varphi}_{\mathsf{SM}} \lesssim 0.2$$

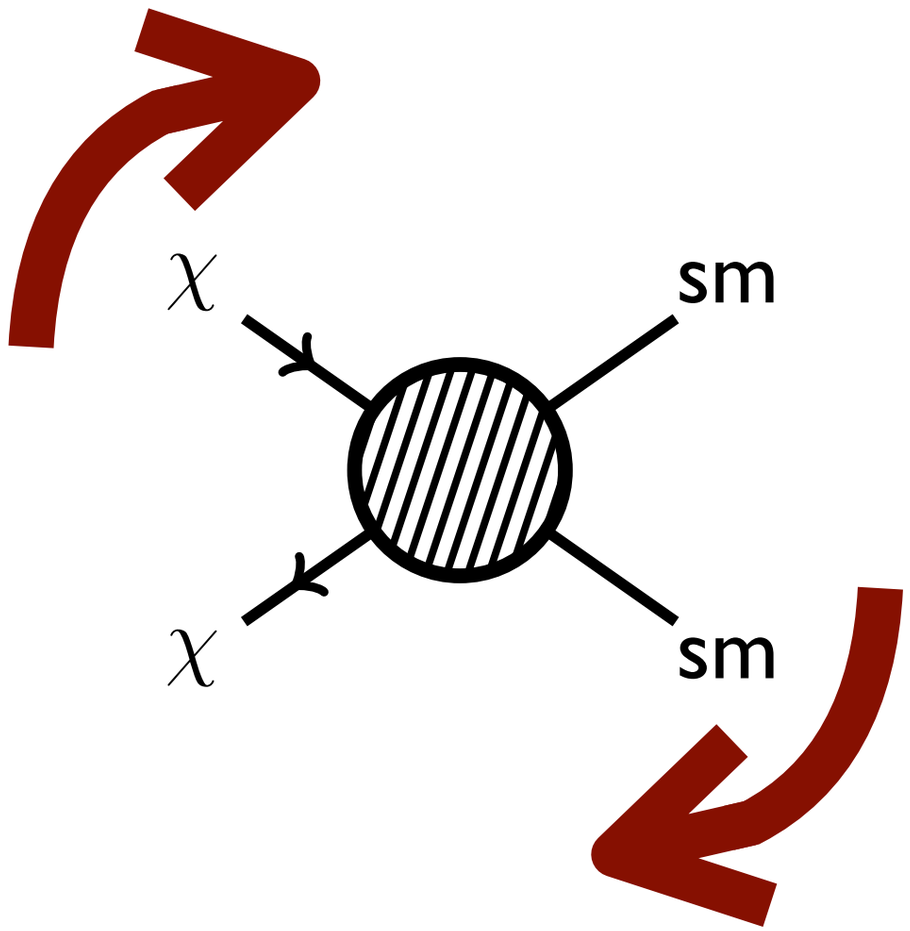
$$\lambda^{V}_{\mathsf{SM}} \lesssim 0.6$$



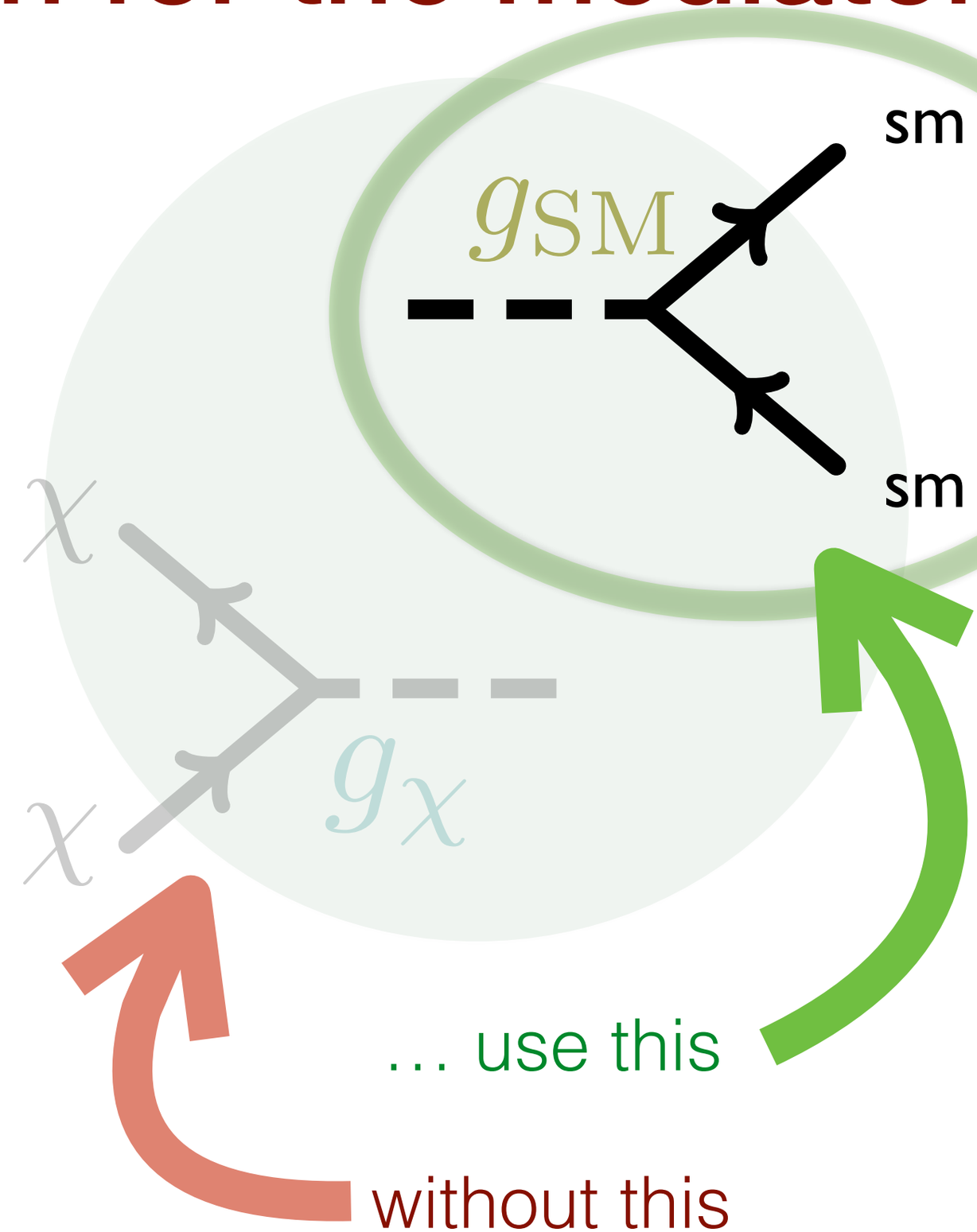
Conservative estimate: $m_q/M_*^3 \to \lambda_{\mathsf{DM}}\lambda_{\mathsf{SM}}s^{-1}$

More recently, simplified model analysis: Harris et al. 1411.0535; Buckley et al. 1410.6497

Alternative: search for the mediator

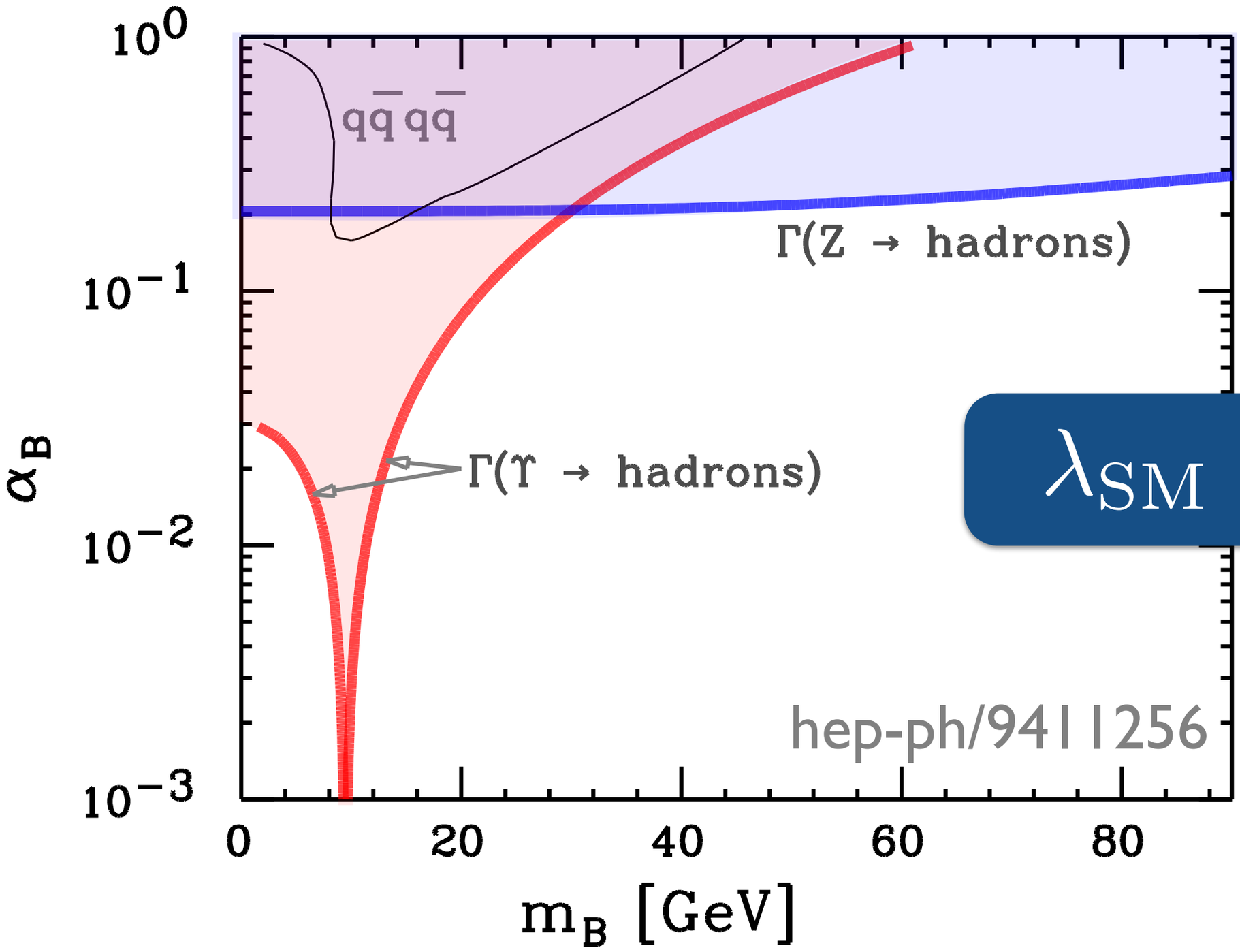


rather than this…



See, for example: Shepherd et al. (1111.2359), Busoni et al. (1402.1275, 1405.3101), Buchmueller et al (1308.6799, 1407.8257), Harris et al. (1411.0535), Abdullah et al. (1409.2893), …

Constraints on mediator—SM coupling



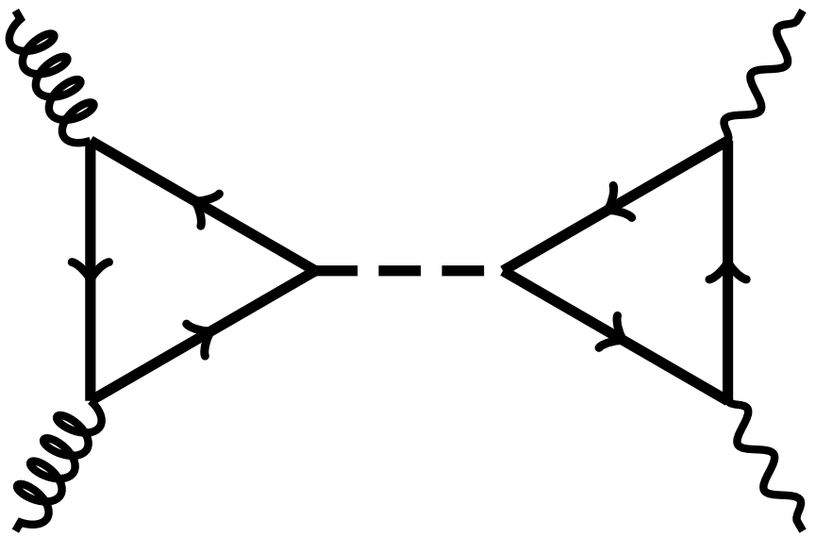
Template:
gauged $U(1)_B$
with O(10) GeV
gauge boson

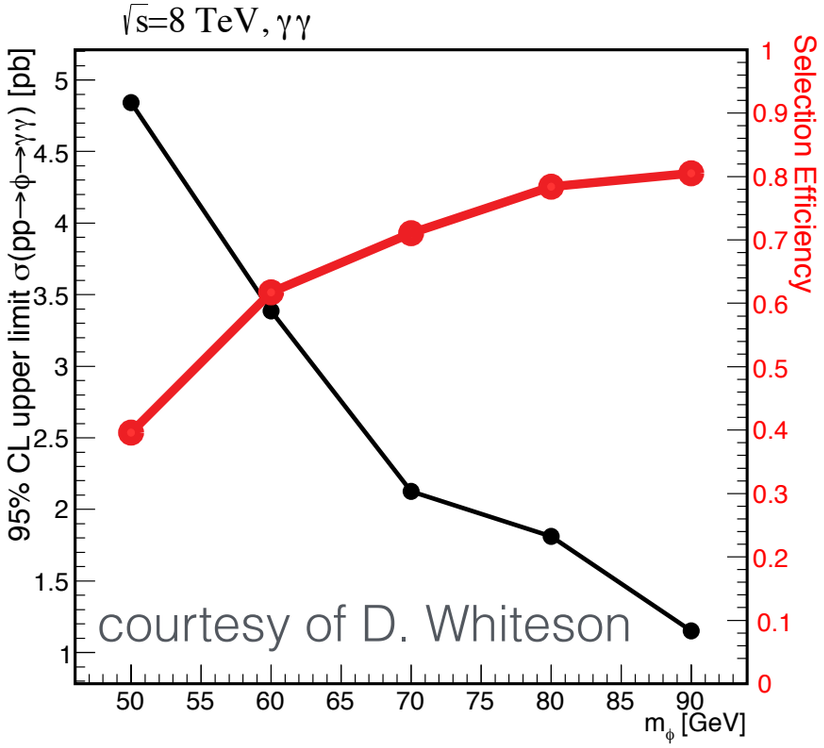
$$\lambda_{\rm SM} \lesssim 1$$

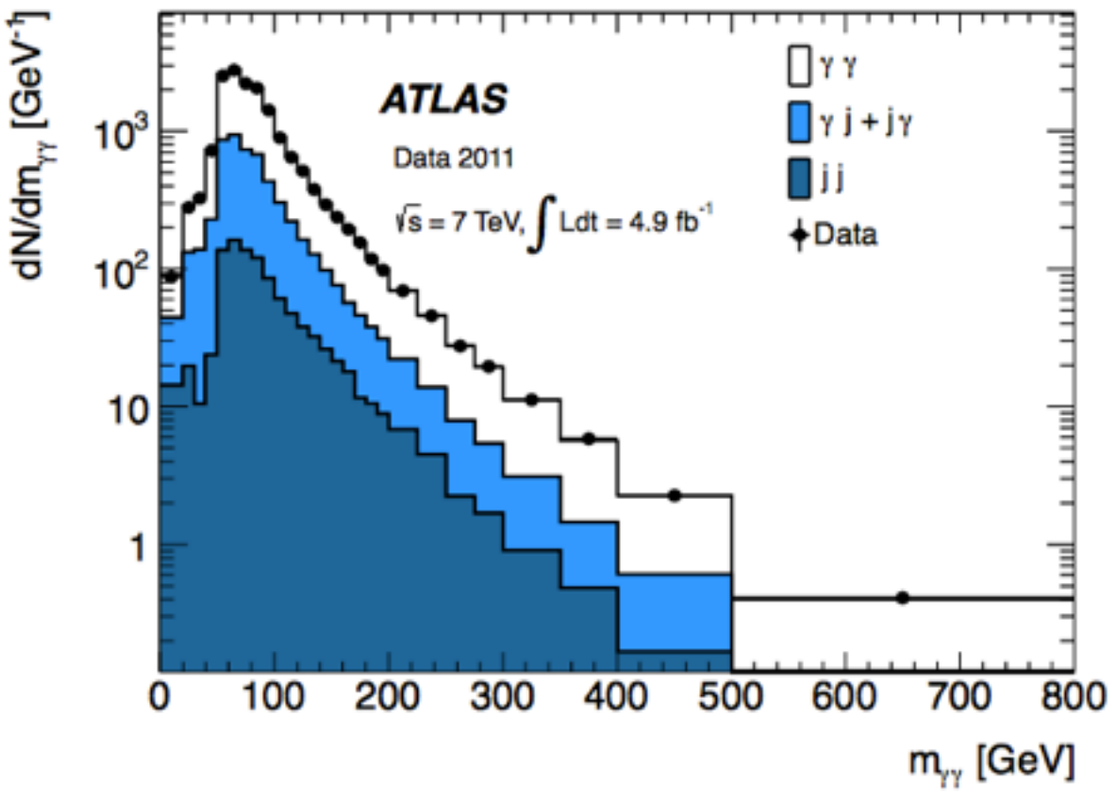
not very
constrained!

Carone and Murayama, Phys.Rev.Lett.74:3122 hep-ph/9411256

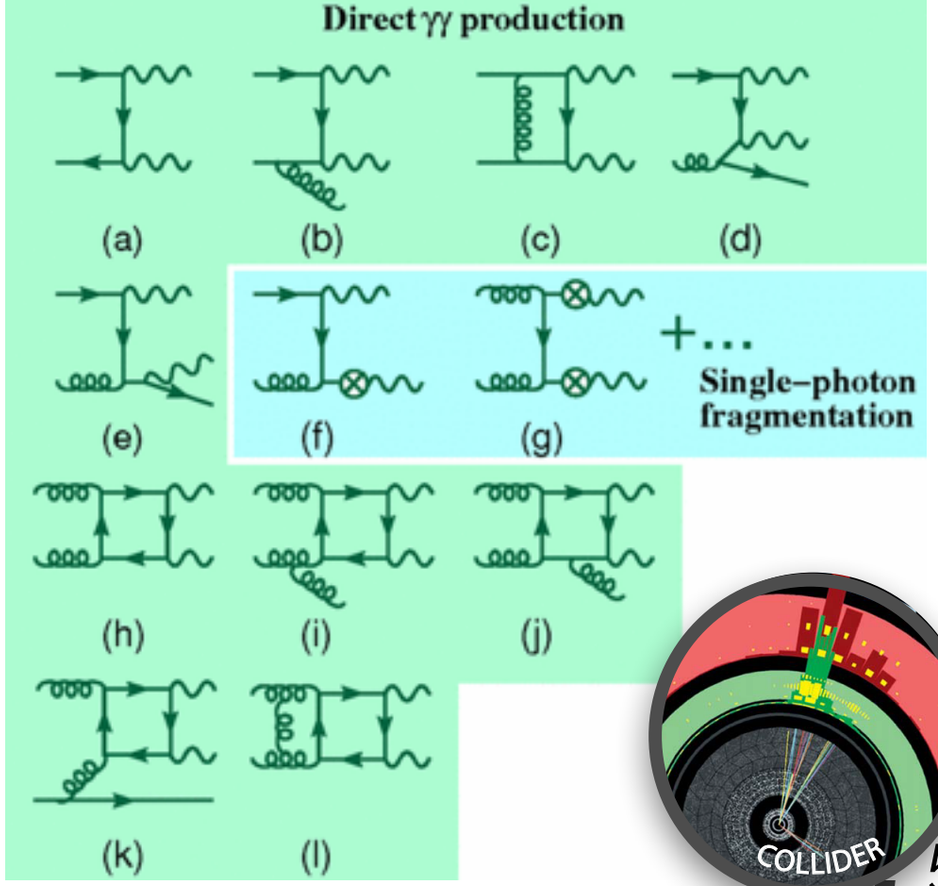
Suggestion: inclusive diphotons





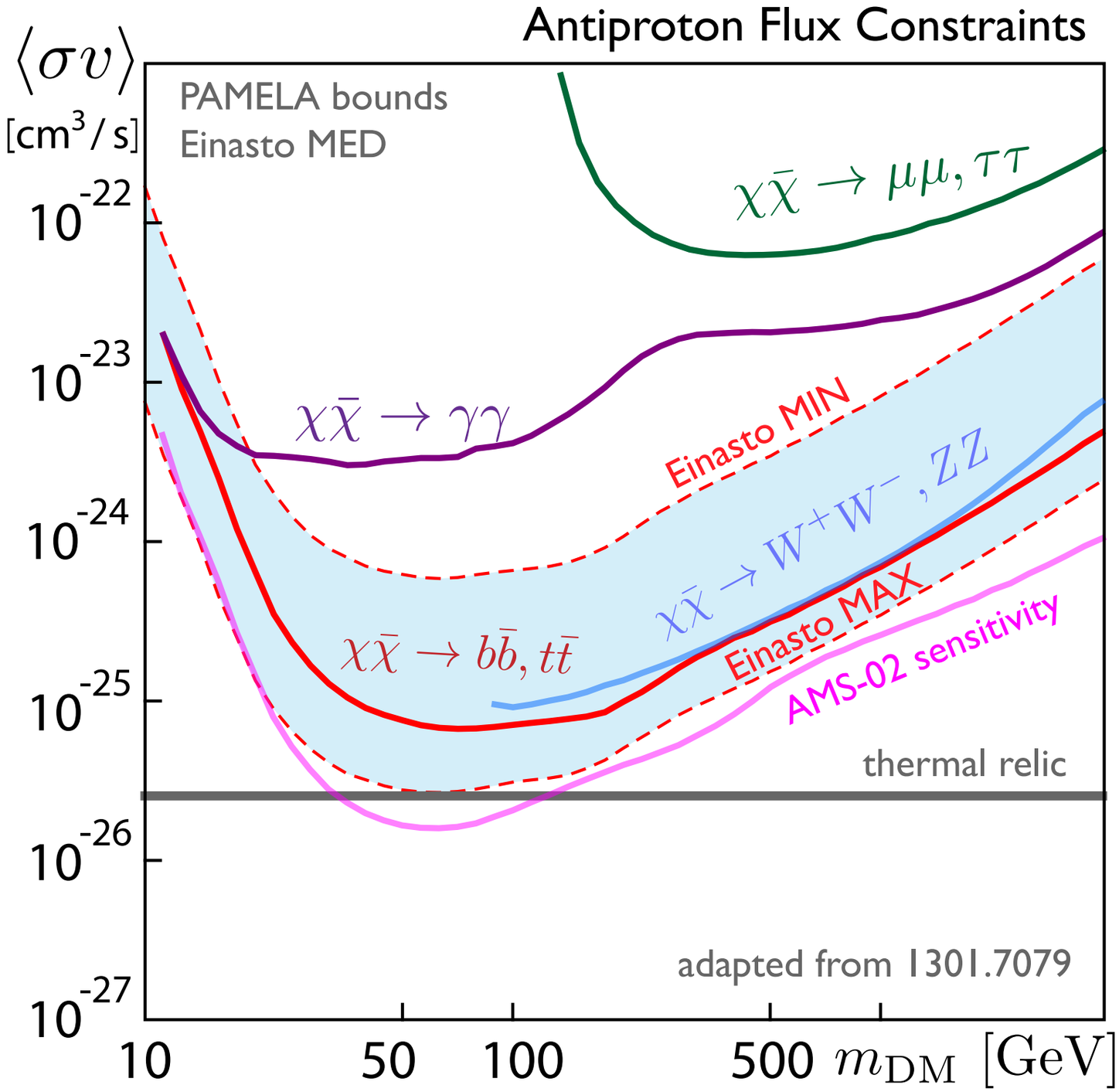


CP Yuan et al. RESBOS



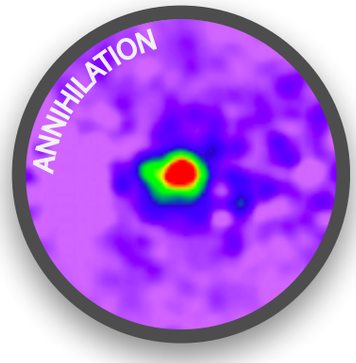
Work in Progress with I. Galon

Anti-protons



PAMELA p+ bounds: currently not constraining. Maybe AMS-02...

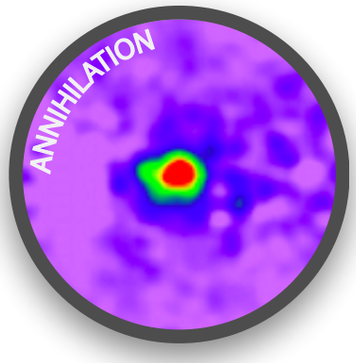
... but large propagation uncertainty, still lots of wiggle room.

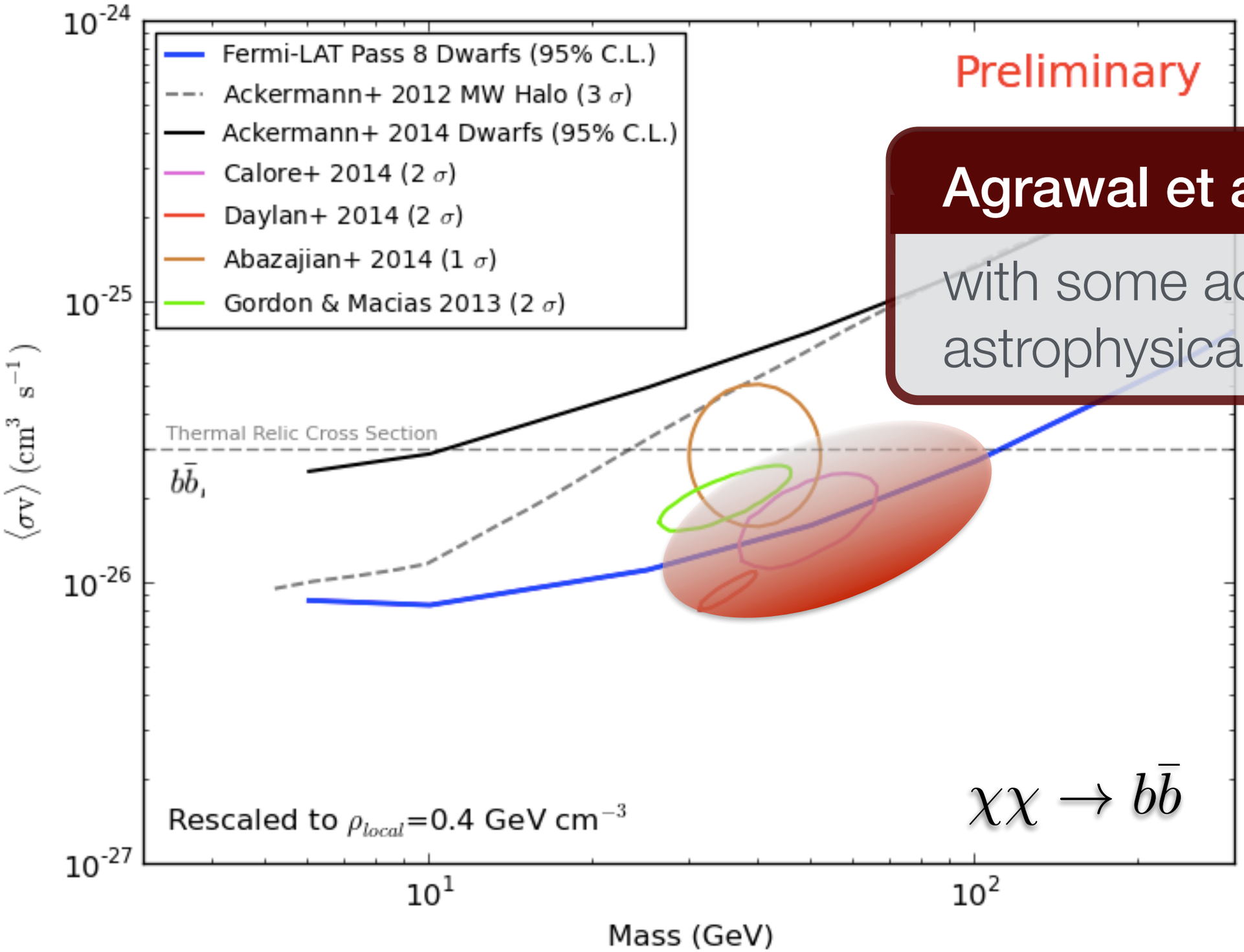


… still not the indirect detection bounds most people worry about.

Park et al. 1404.3741; Bringmann et al. 1406.6027

Dwarf Bounds from FERMI





Agrawal et al. (2014)

with some accounting for astrophysical systematics

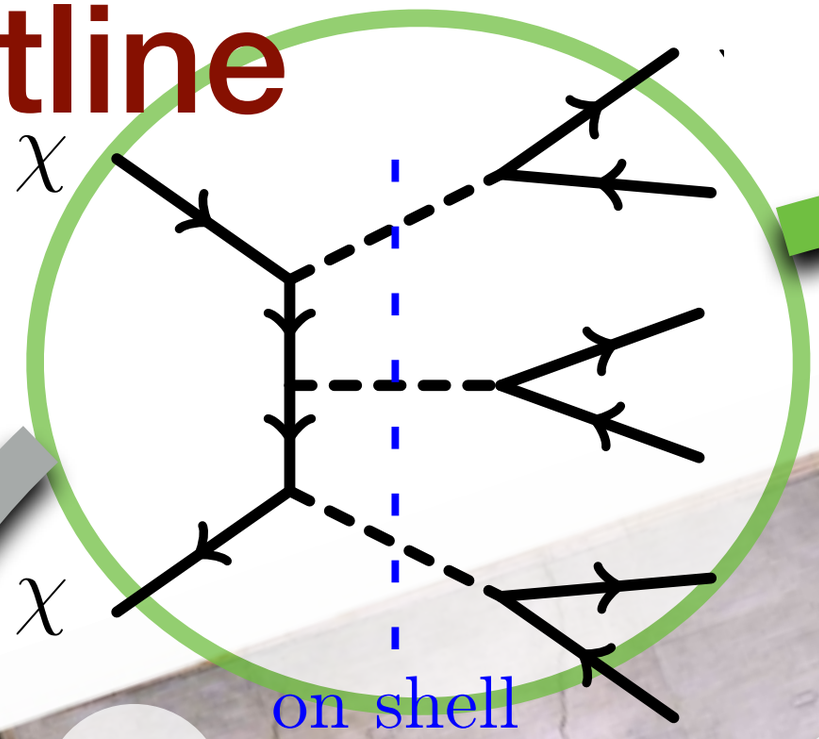
only a sketch

possibly a problem!

model building?

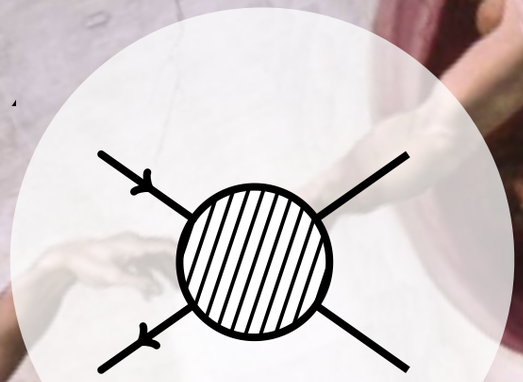
Brandon Anderson, 5th Fermi Symposium

Outline

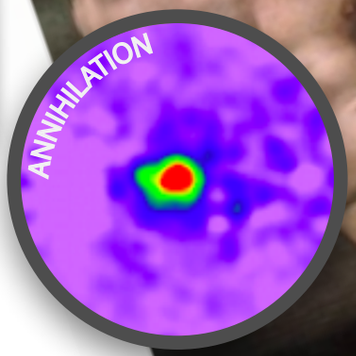


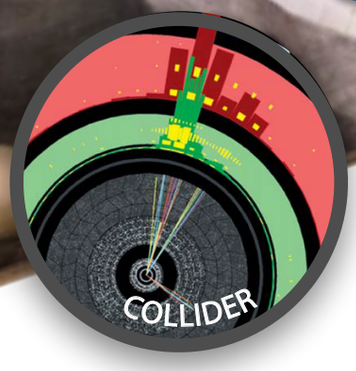
Nature

UV Models



Simplified Models





Experiments

Michelangelo Buonarroti,
“Creation of Adam” (1510)

Model Building

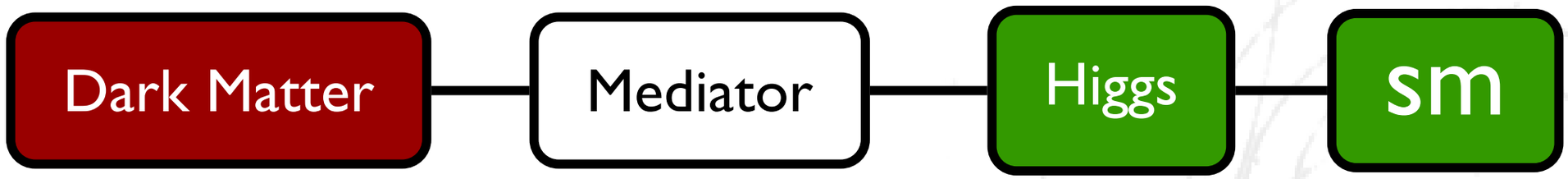
Spin-1 Mediator

Prototype is gauged $U(1)_B$, expect universal coupling to quarks.
Exception? ρ-like states in composite Higgs? (Contino et al. 1109.1570)

Spin-0 Mediator

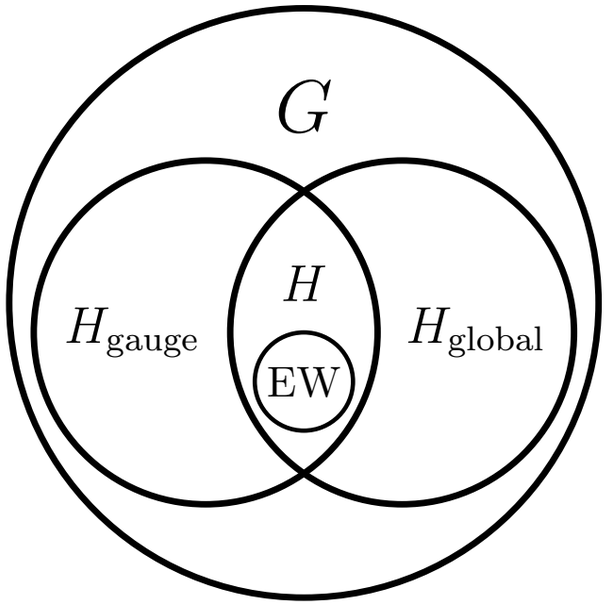
$$\mathcal{L}_{\varphi\text{-sm}} = \frac{\lambda_u y^u_{ij}}{\Lambda}\varphi H \cdot \bar{Q} u_R + \frac{\lambda_d y^d_{ij}}{\Lambda}\varphi \tilde{H} \cdot \bar{Q} d_R + \frac{\lambda_\ell y^\ell_{ij}}{\Lambda}\varphi \tilde{H} \cdot \bar{L} \ell_R$$

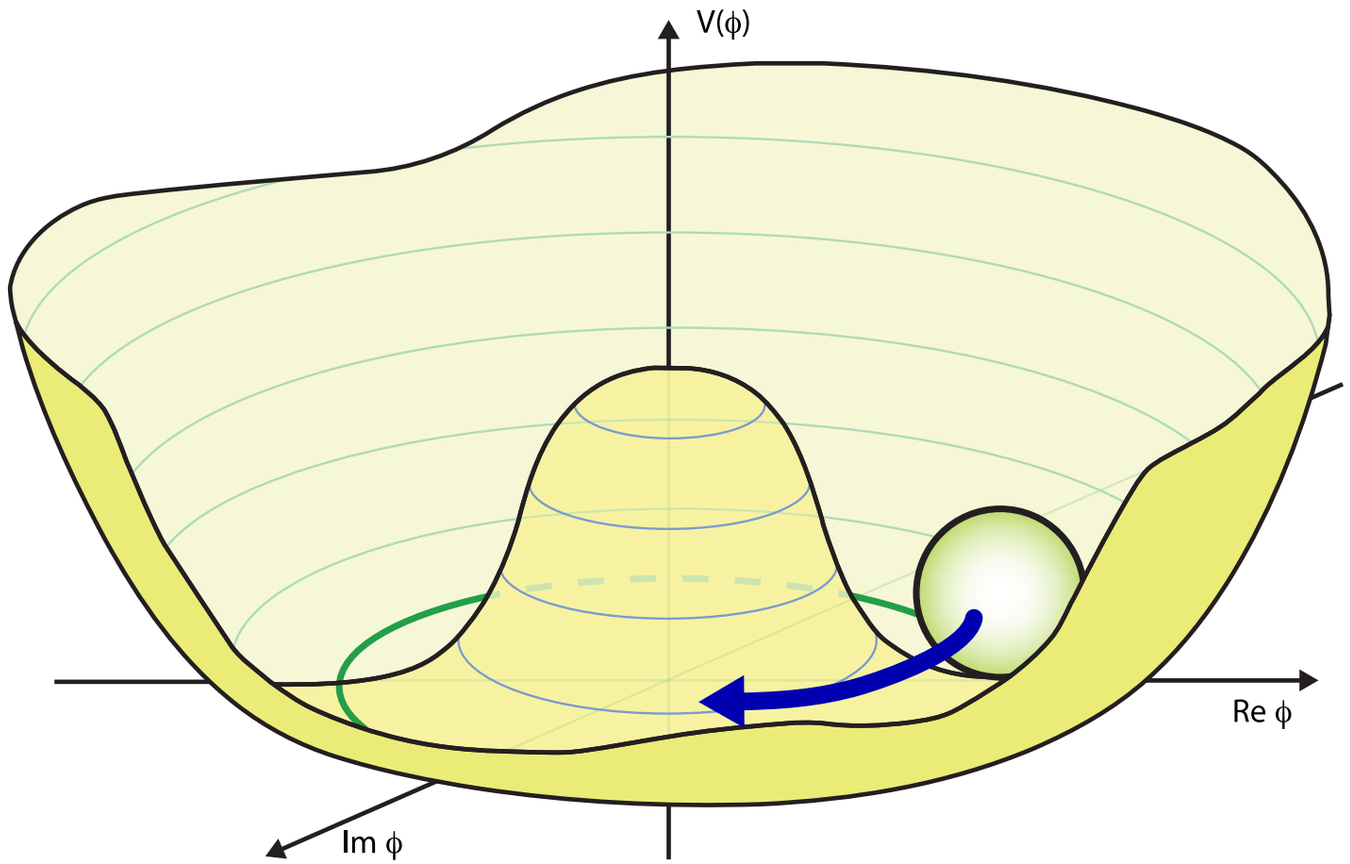
Recent UV completion through 'Higgs-portal'-portal: Ipek et al. 1404.3716

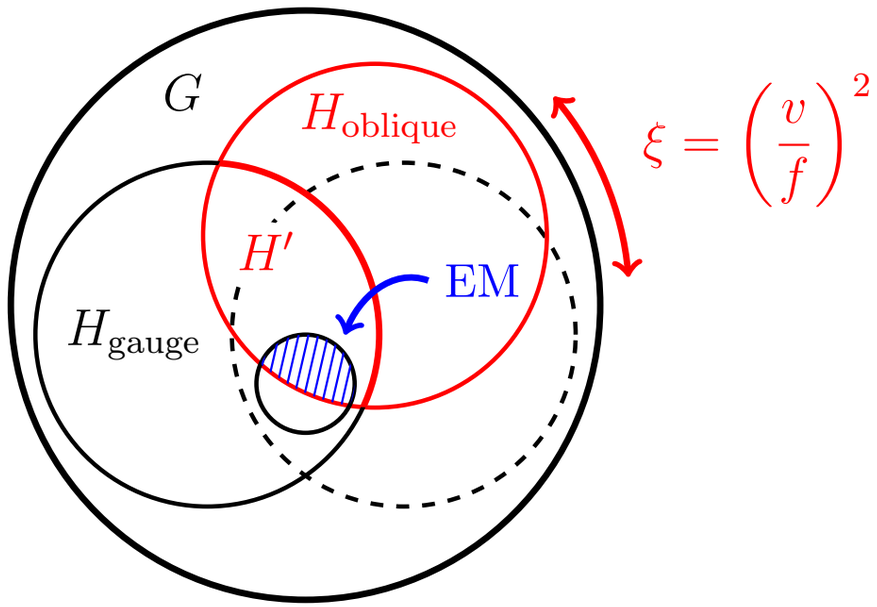


Recently: many studies mapping this to (N)MSSM, 2HDM
See also singlet scalar model, Profumo et al. 1412.1105

Pseudoscalar without the scalar





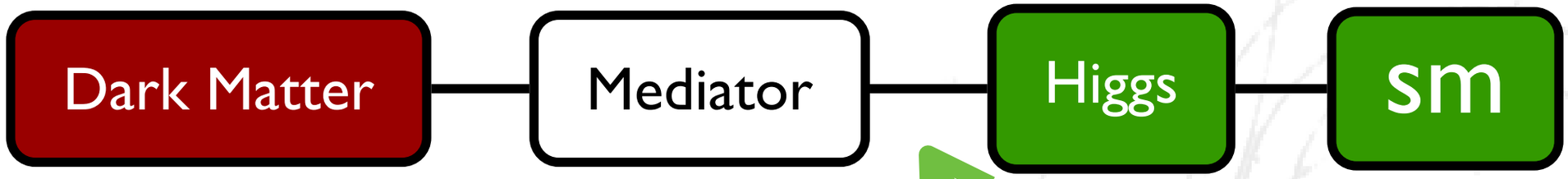


Higgs as a pNGB (composite Higgs) with non-minimal coset

analogy: π^0 vs $\pi^\pm$

Work in progress with A. Wijangco and J. Serra

Composite Mediators



New Matter
incomplete rep. adds to global symmetry breaking

SM singlet
"extra" Goldstone

These interactions are given by nonlinear sigma model and are distinct from 2HDM

Connects:

- Dark Matter
- Mediators
- EWSB

No 2HDM required!

different phenomenology and constraints

Higgs as a pNGB (composite Higgs) with non-minimal coset

Work in progress with A. Wijangco and J. Serra

Avoiding the Dwarf Bounds

Dwarf Spheroidals: mostly DM, little stellar matter

… so should to see same GeV excess as Gal. Center if it's DM annihilation

Usual assumption:

Dark Matter Annihilation → γ-ray photons

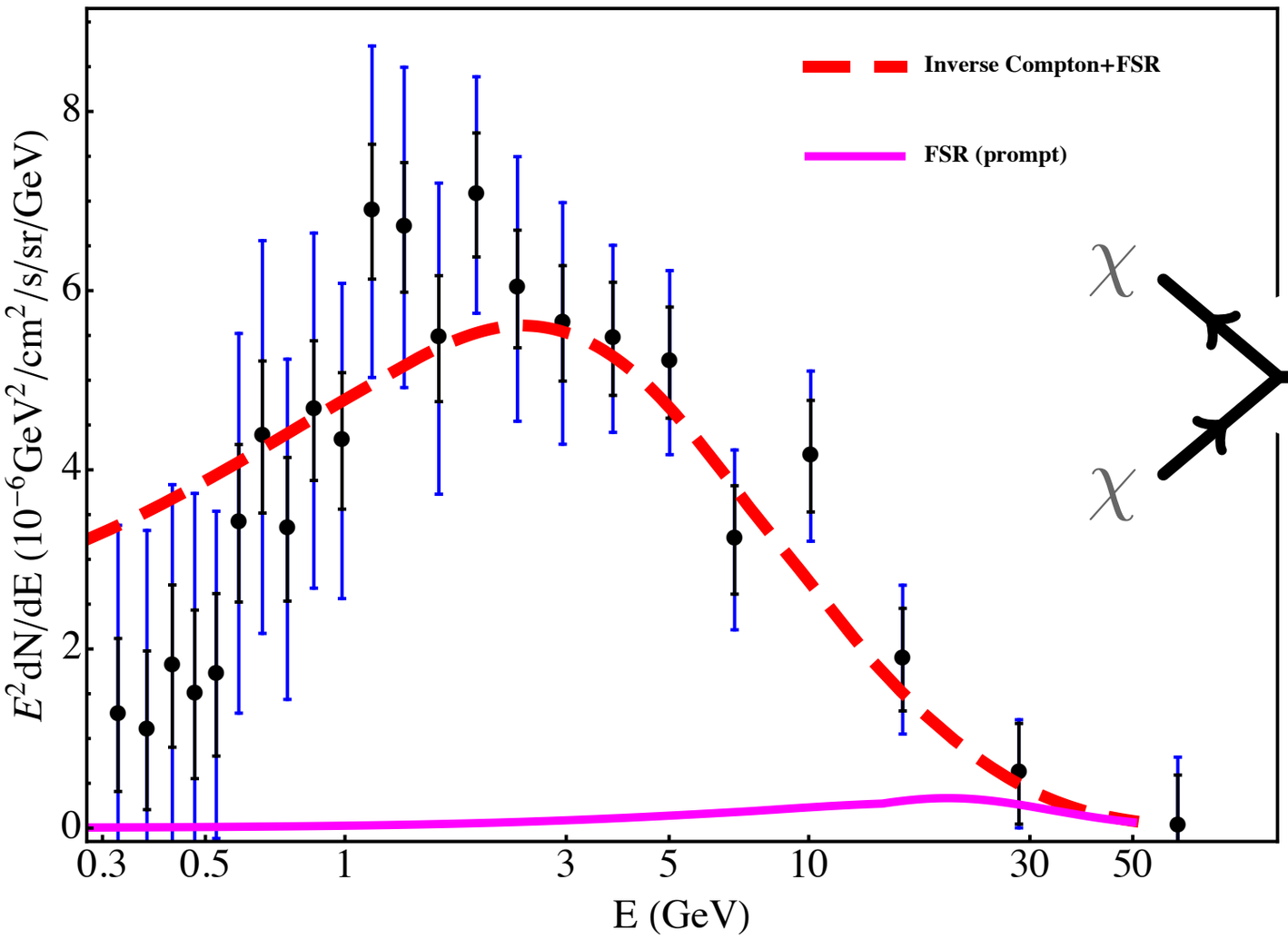
Instead, revise the relation:

Kaplinghat, Linden, Yu, 1501.03507

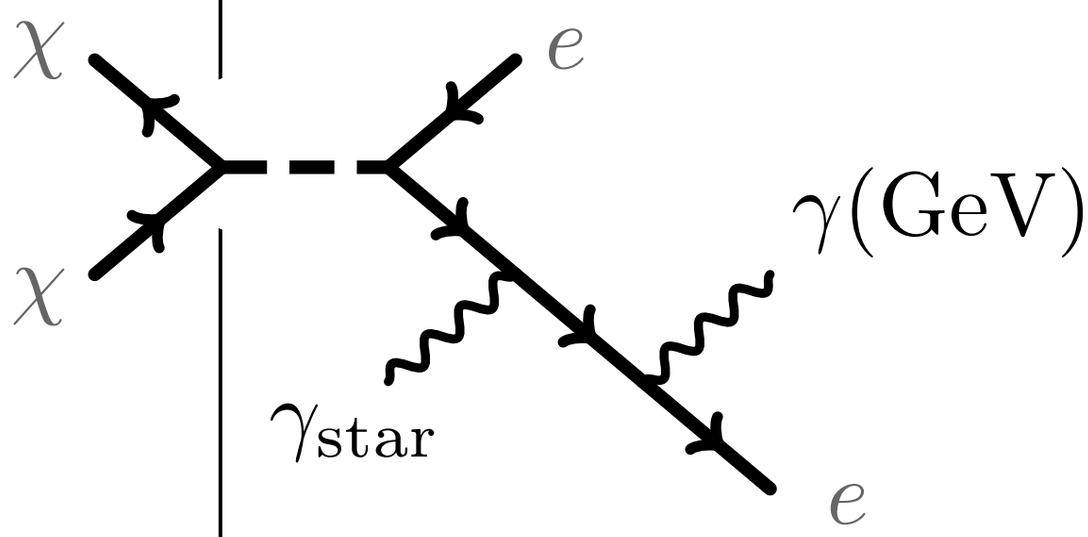
Dark Matter Annihilation **+ ambient starlight** → γ-ray photons

But: requires annihilation into *electrons* … spectrum doesn't fit?

Avoiding Dwarf Bounds



Photon spectrum from FSR doesn't fit
(Weiszacker-Williams)

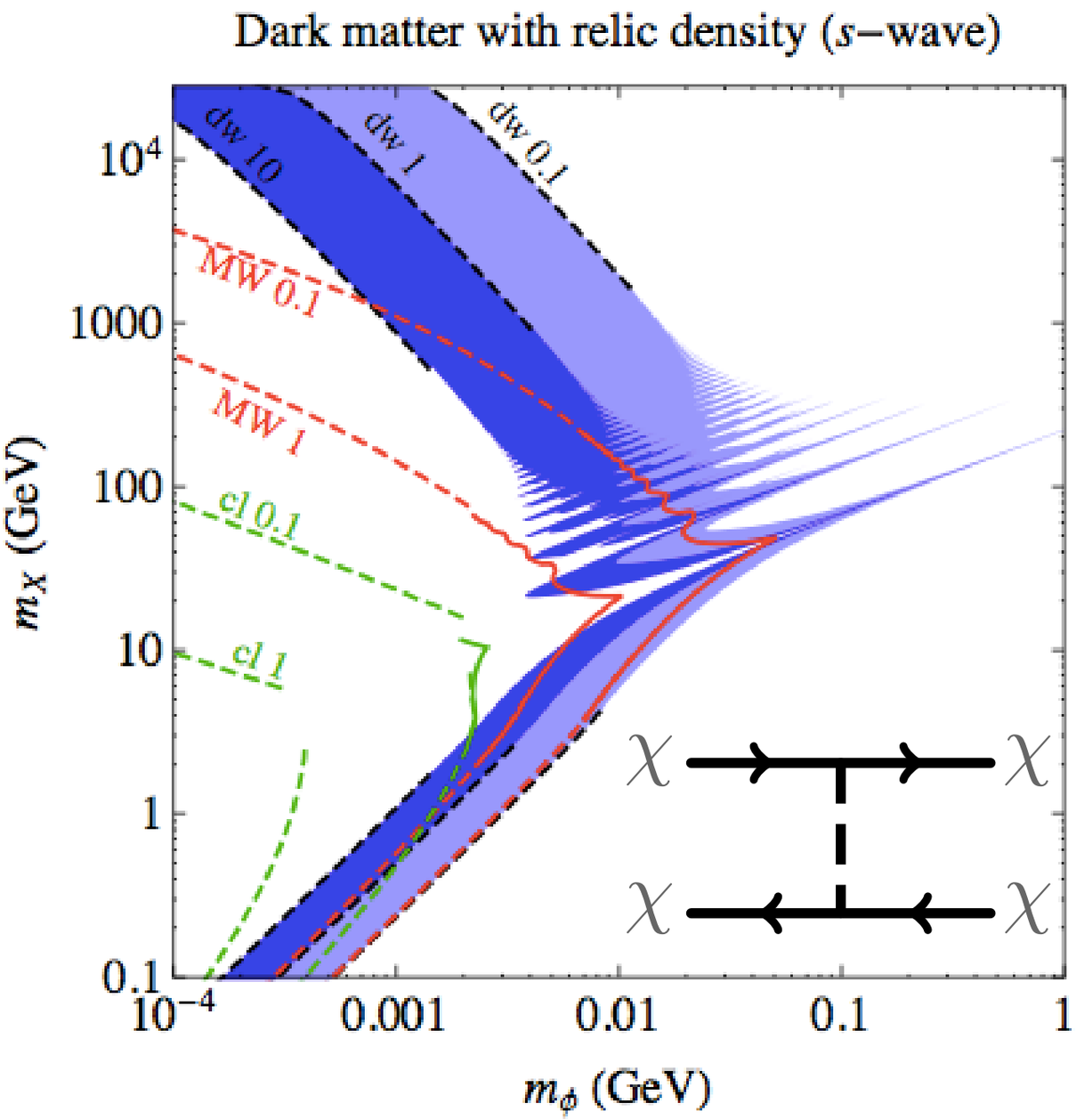


but Inverse Compton can upscatter starlight into a diffuse GeV spectrum

But: this leaves an imprint on positron fraction (PAMELA) and can be constrained by mono-photon searches at LEP

Kaplinghat, Linden, Yu, 1501.03507

Self-Interacting Dark Matter



Free feature: *e* final state allows very light mediator, natural for self-interactions.

Long range self-interactions can address small scale structure anomalies (e.g. core vs. cusp).

Open question: SIDM target space for pseudoscalars, which generate a singular potential.

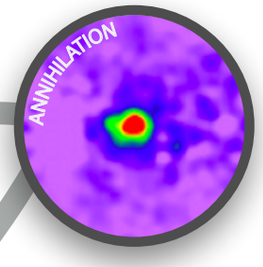
Bellazzini, Cliche, FT 1307.1129

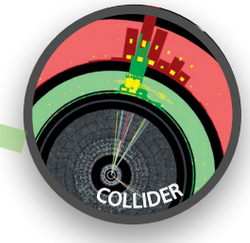
Tulin et al. 1302.3898

Flavor Violating Modes

Consider: lepton-flavor-violating decay of φ

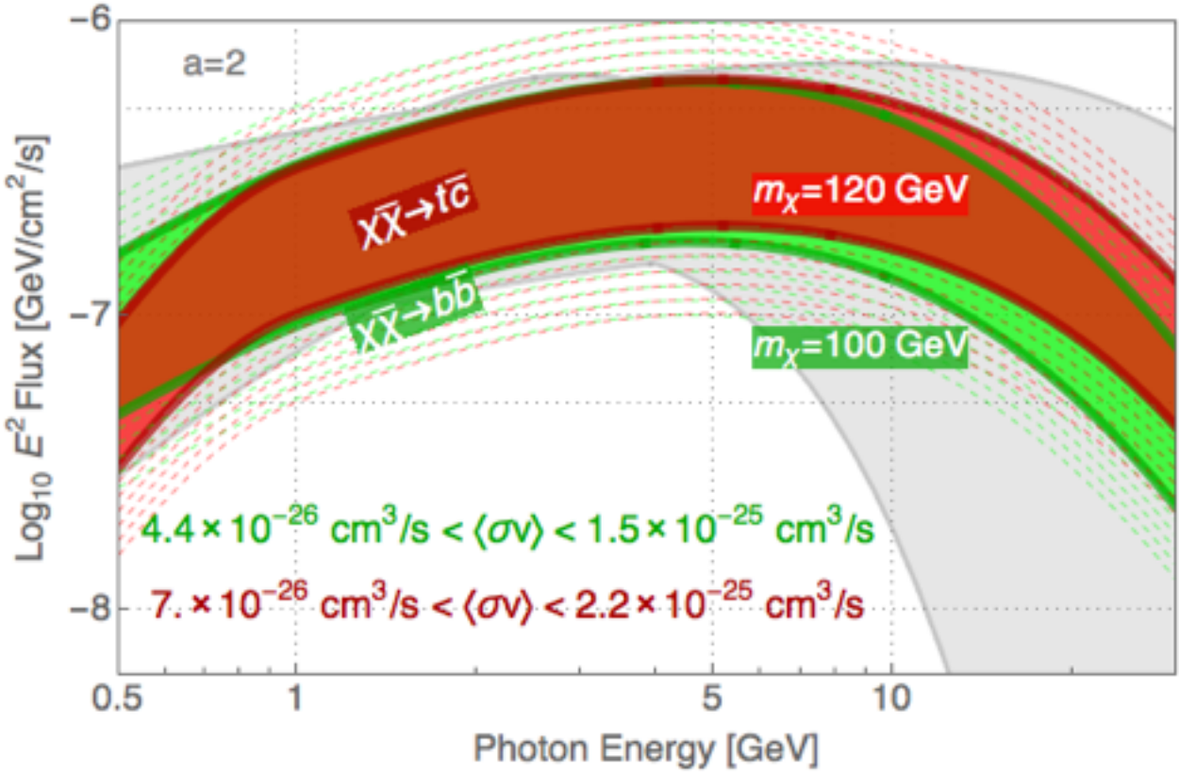
- φ into off shell μ smears out e^+ spectrum, avoid bumps?
- Also helps avoid collider, (g-2), etc. bounds
- Achieve: SIDM, Galactic Center, avoid Dwarfs
- Froggat-Nielsen mechanism naturally does this and simultaneously suppresses φ—Higgs mixing.
- No direct detection





Also: quark flavor decays

- top — charm mode is accessible

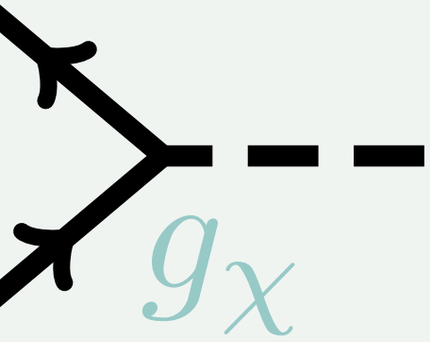


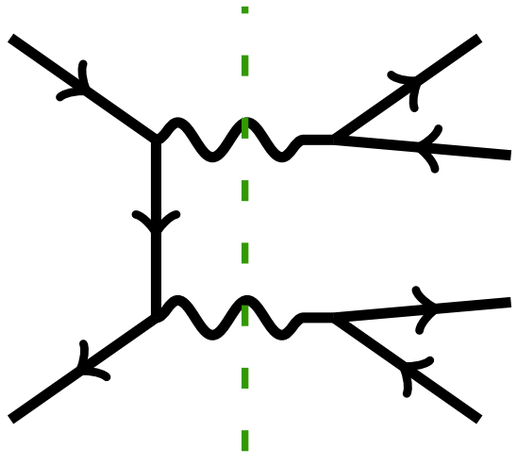
Agrawal et al. 1405.6709, 1404.1373, 1402.7369

Work in Progress with I. Galon; FT, Smolinsky & Rajaraman arXiv:1503.05919

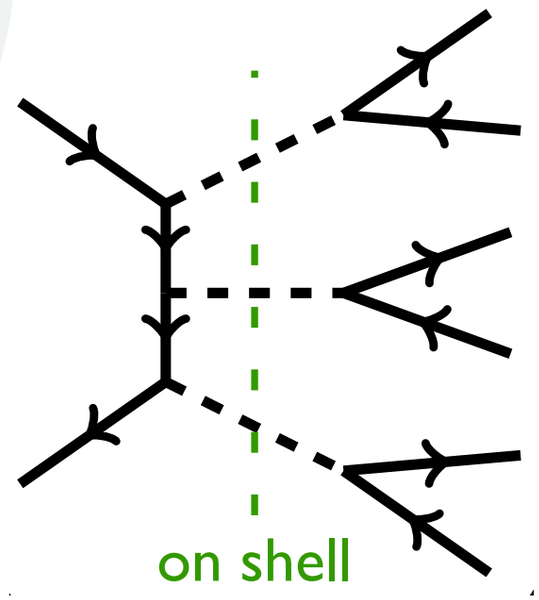
Summary

mediator

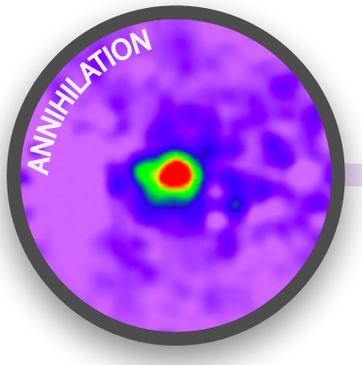


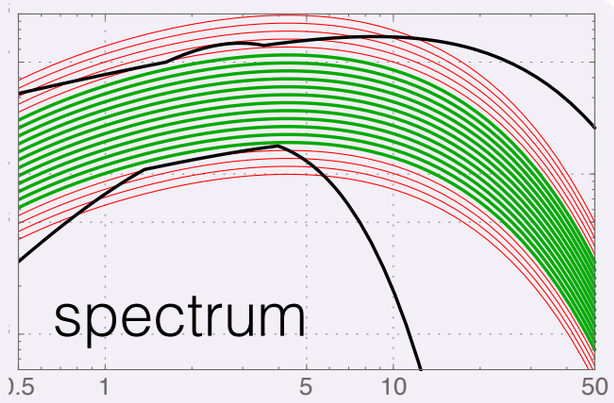


on shell



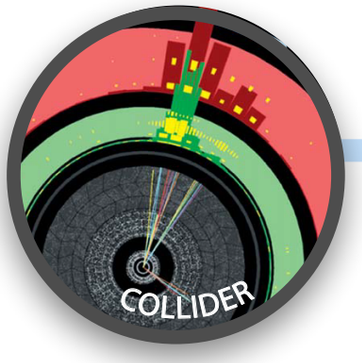
on shell

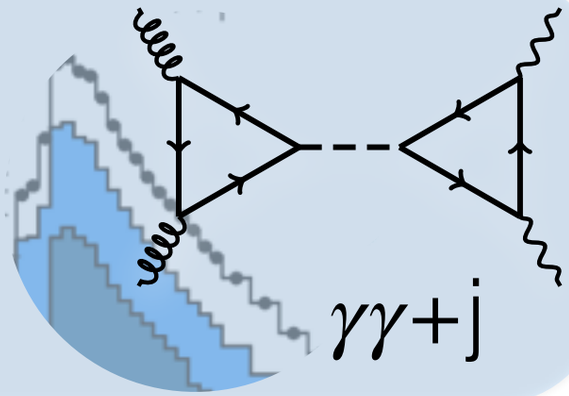




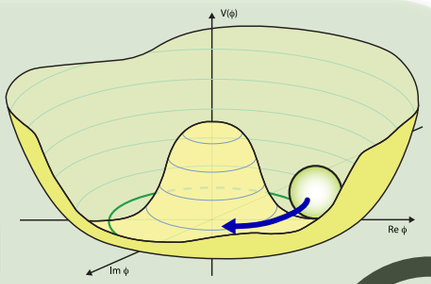
LFV μ e

SIDM χ χ χ χ

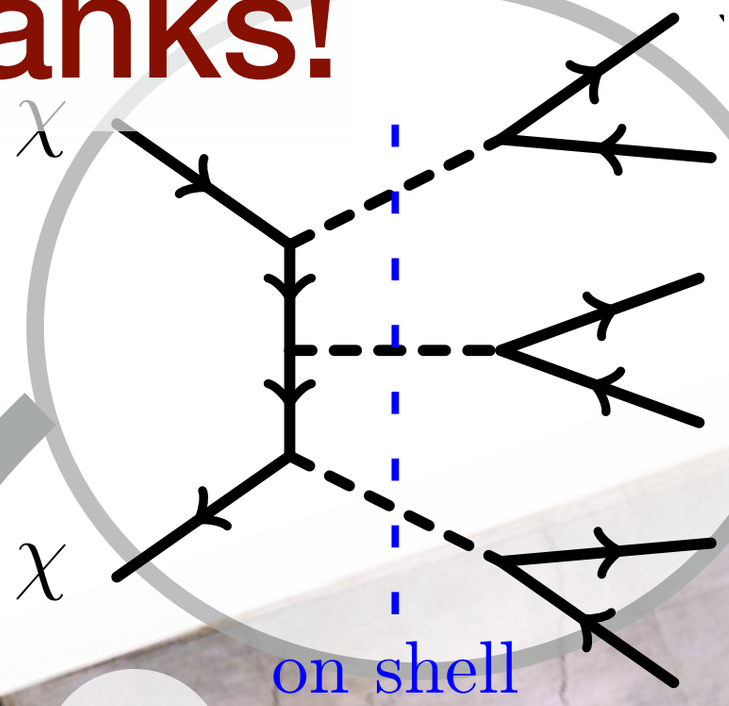




Not 2HDM



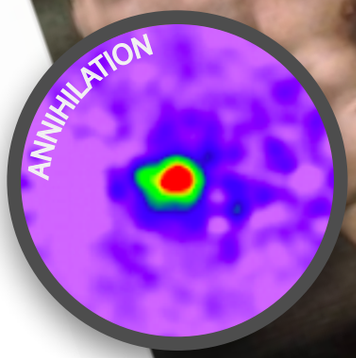
Thanks!

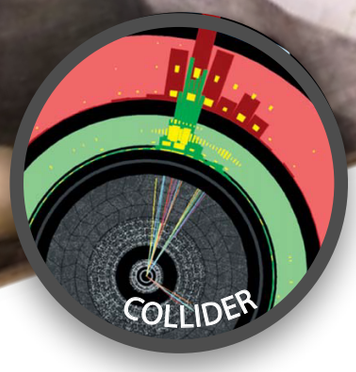


Nature

UV Models

Simplified Models





Experiments

Michelangelo Buonarroti,
“Creation of Adam” (1510)

Other interesting directions

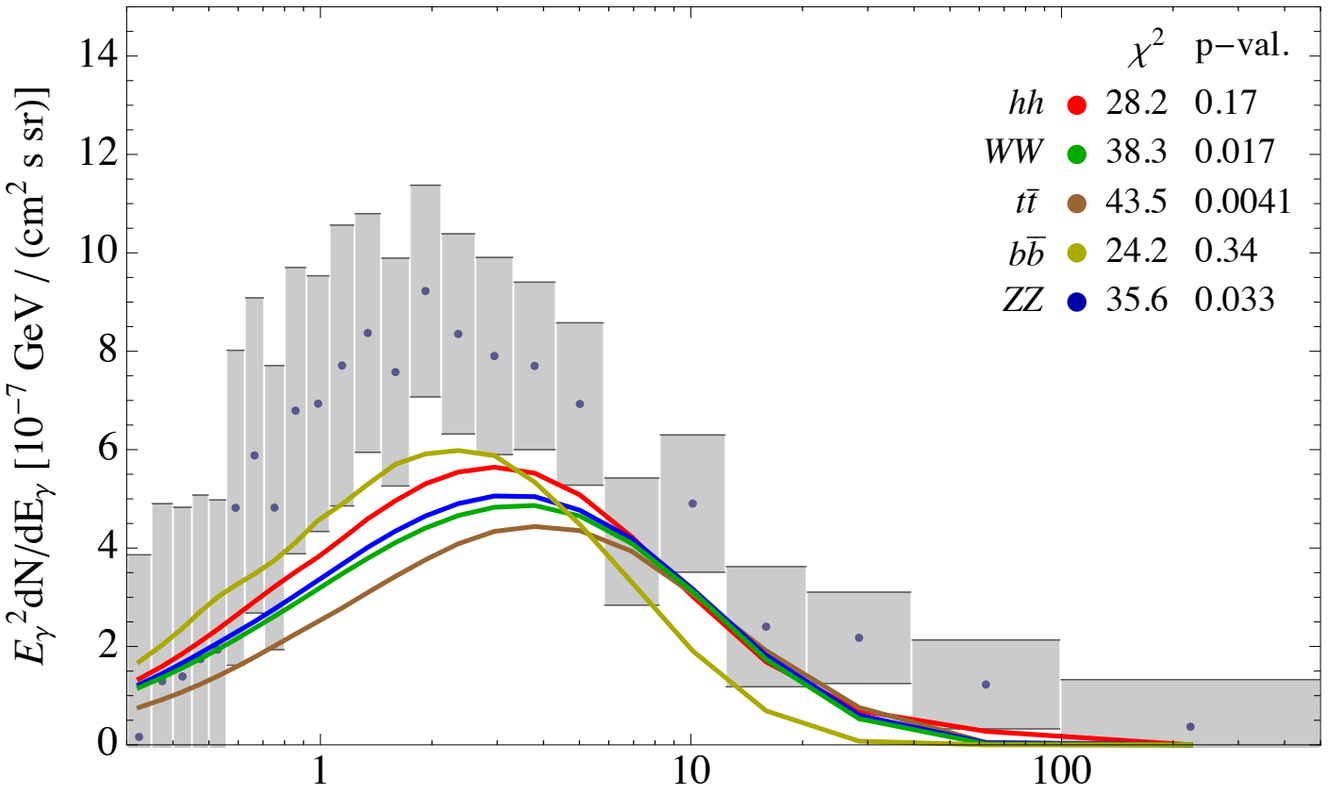
- Morphology: black hole distortion of DM profile in dwarfs (Profumo et al. 1406.2424) and the galactic center (Fields et al. 1406.4856)

- Planck bounds on mediator—SM coupling

- "Gluperon:" $m_{med} < \Lambda_{QCD}$, mediator decays to light hadrons: (Weiner et al. 1412.1485). Simplified model + chiral Lagrangian.

CCW v. FERMI

Agrawal et al. 1411.2592
w/ uncertainties from
Calore et al. 1409.0042.



Simona Murgia
Fermi Collaboration
Fermi Symposium ‘14