Indirect Detection Constraints on Dark Matter Model Space

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Fermi Dwarf Analysis

Dwarf Spheroidal Galaxies large amount of DM

Low Astrophysical Background

photon flux

$$\Phi_\gamma = \frac{1}{4\pi} \sum_f \frac{\langle \sigma v \rangle_f}{2m_\chi^2} \int_{E_{\min}}^{E_{\max}} \left(\frac{dN_\gamma}{dE_\gamma} \right)_f dE_\gamma J.$$

averaged annihilation xsec

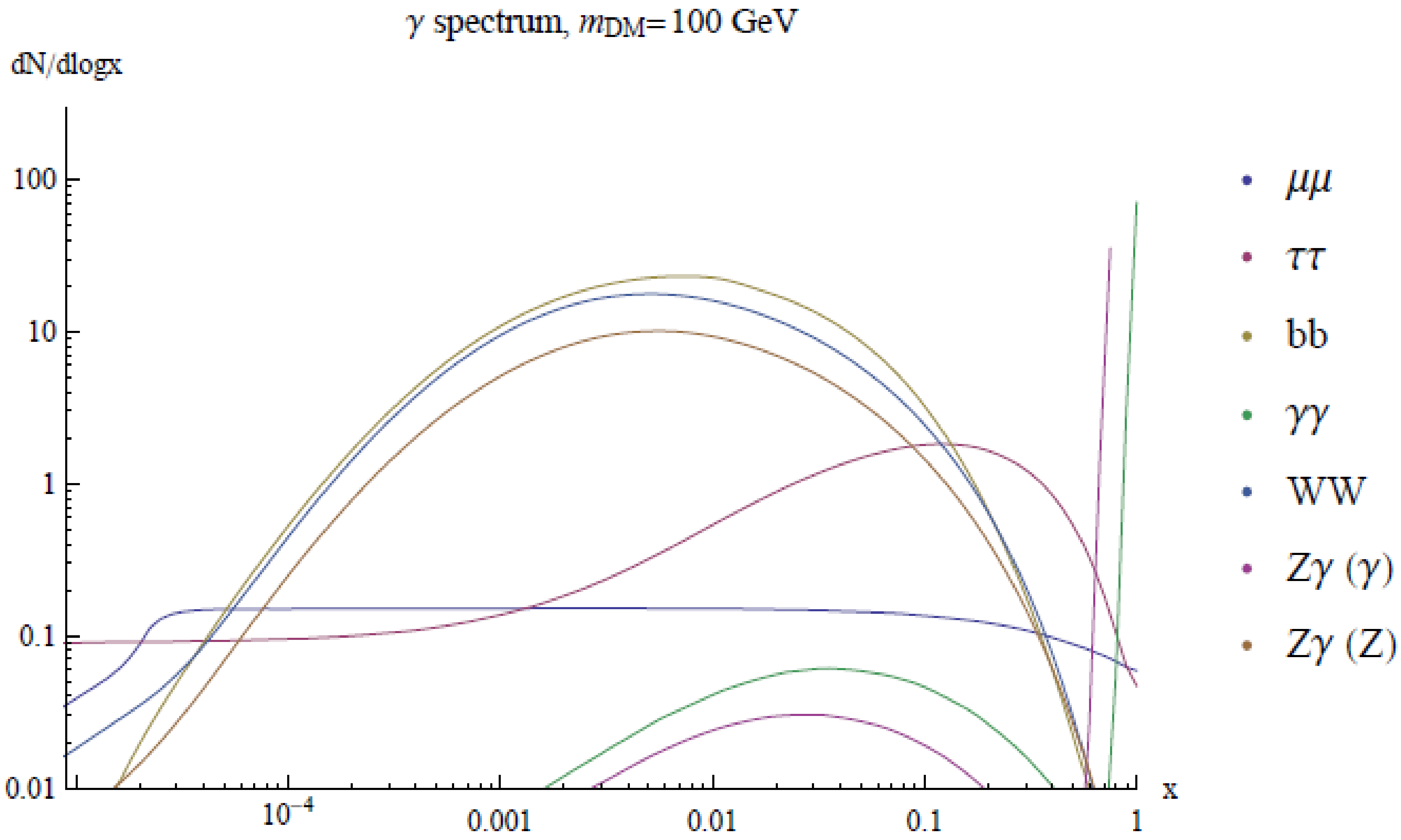
DM mass

Photon energy spectrum

Line of sight integral of DM density

$$J = \int_{\Delta\Omega} \int_{l.o.s} \rho^2(\mathbf{r}) dl d\Omega'.$$

Spectrum

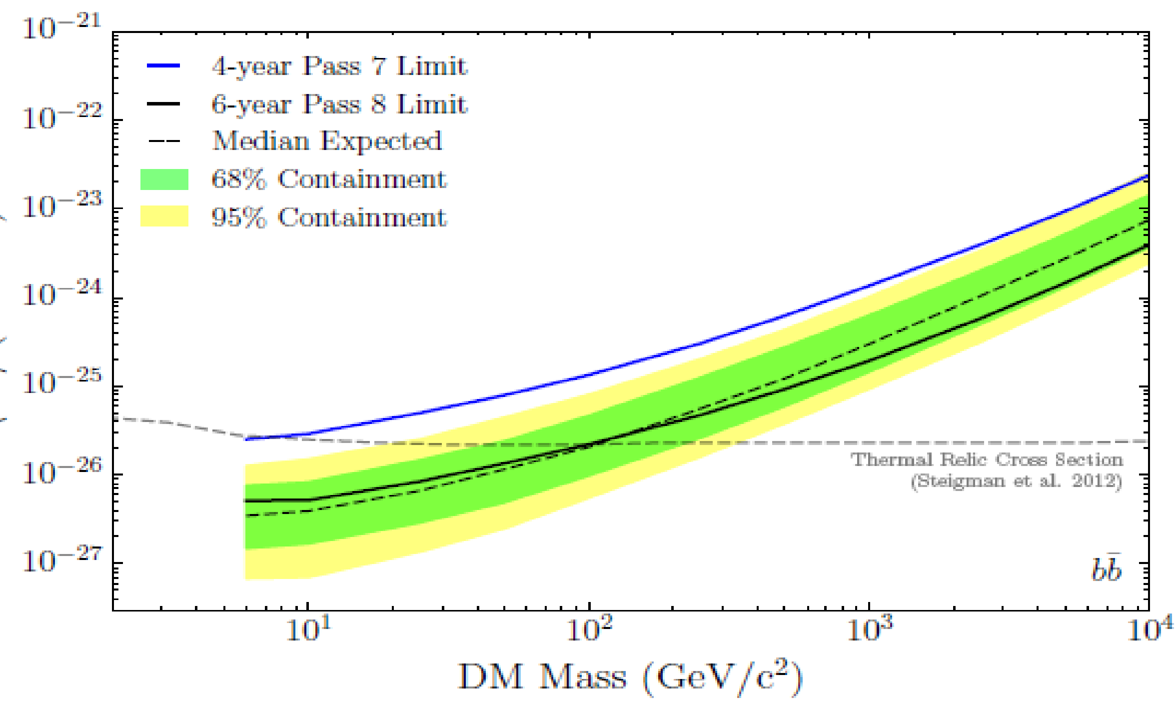


DM annihilates to various SM final states each with a characteristic photon spectrum

Fermi Analysis combine 15 dwarf's with largest J factors, set 95% c.l. upper bound assuming 100% annihilation into a single channel,e.g. b's

TABLE I. Properties of Milky Way dSphs.

Name	ℓ^{a} (deg)	b^{a} (deg)	Distance (kpc)	$\log_{10}(J_{obs})^{b}$ ($\log_{10}$[GeV^2 cm^{-5}])
Bootes I	358.1	69.6	66	18.8 ± 0.22
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Carina	260.1	−22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	−65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Sculptor	287.5	−83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31
Bootes II [c]	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canis Major	240.0	−8.0	7	–
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo V	261.9	58.5	178	–
Pisces II	79.2	−47.1	182	–
Sagittarius	5.6	−14.2	26	–
Segue 2	149.4	−38.1	35	–
Ursa Major I	159.4	54.4	97	18.3 ± 0.24



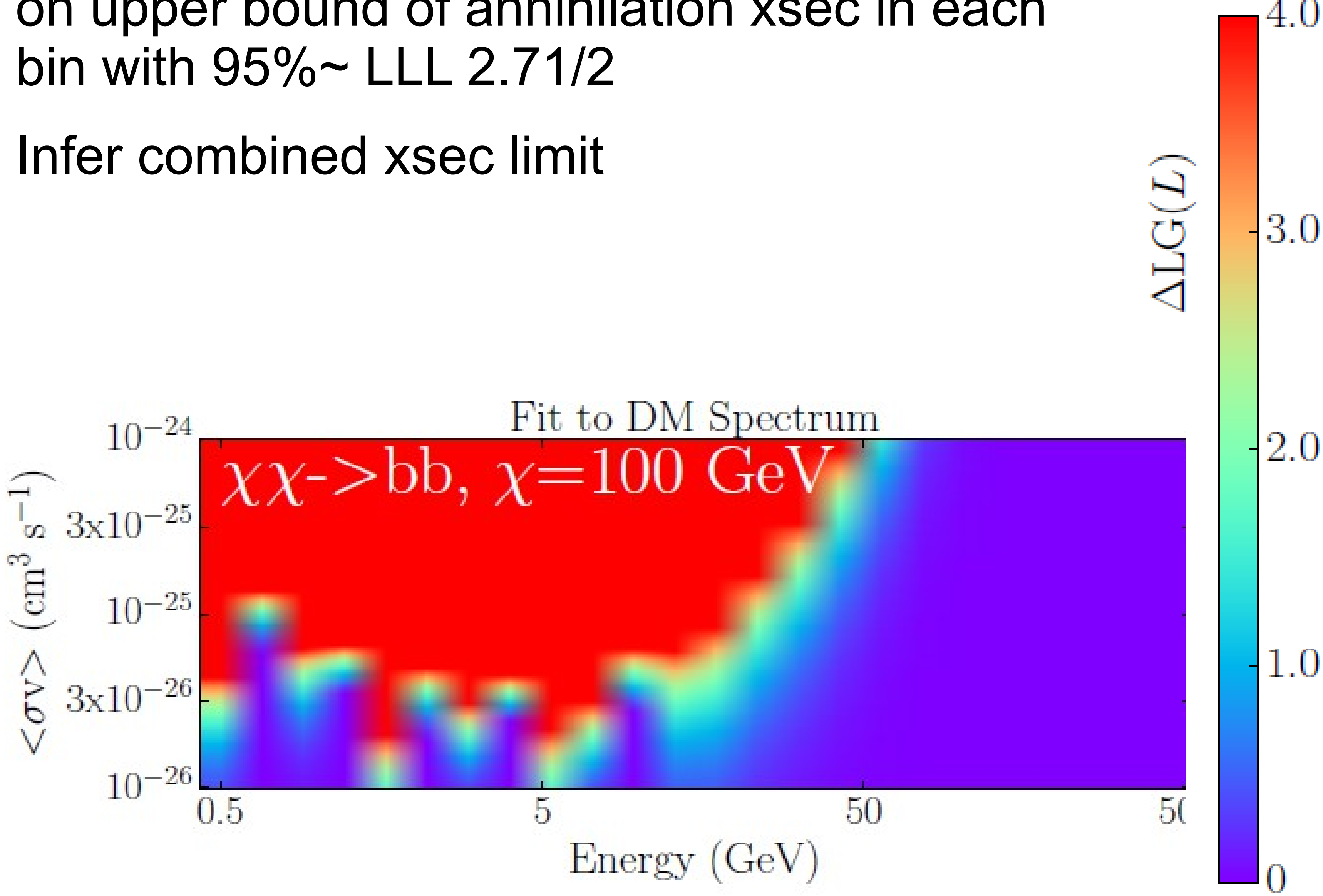
ArXiv:1503.02641

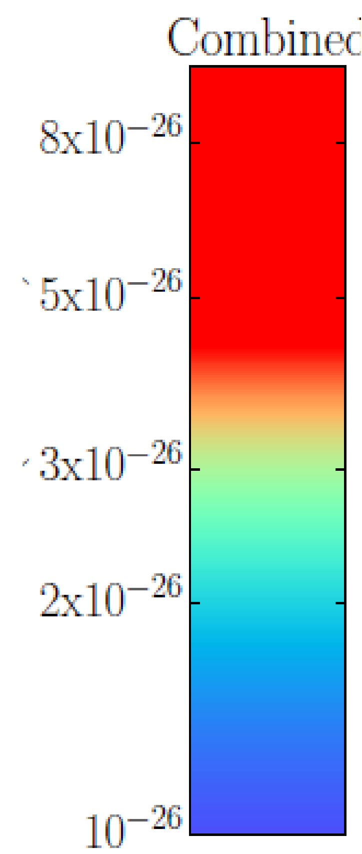
Choose DM mass and annihilation channel

Allow J factor to float with Least Log Likelihood cost $\Delta\mathrm{LG}(\mathcal{L}) = (\mathrm{J}_{bf} - \mathrm{J}_{meas})^2 \;/\; (2\sigma_J^2)$

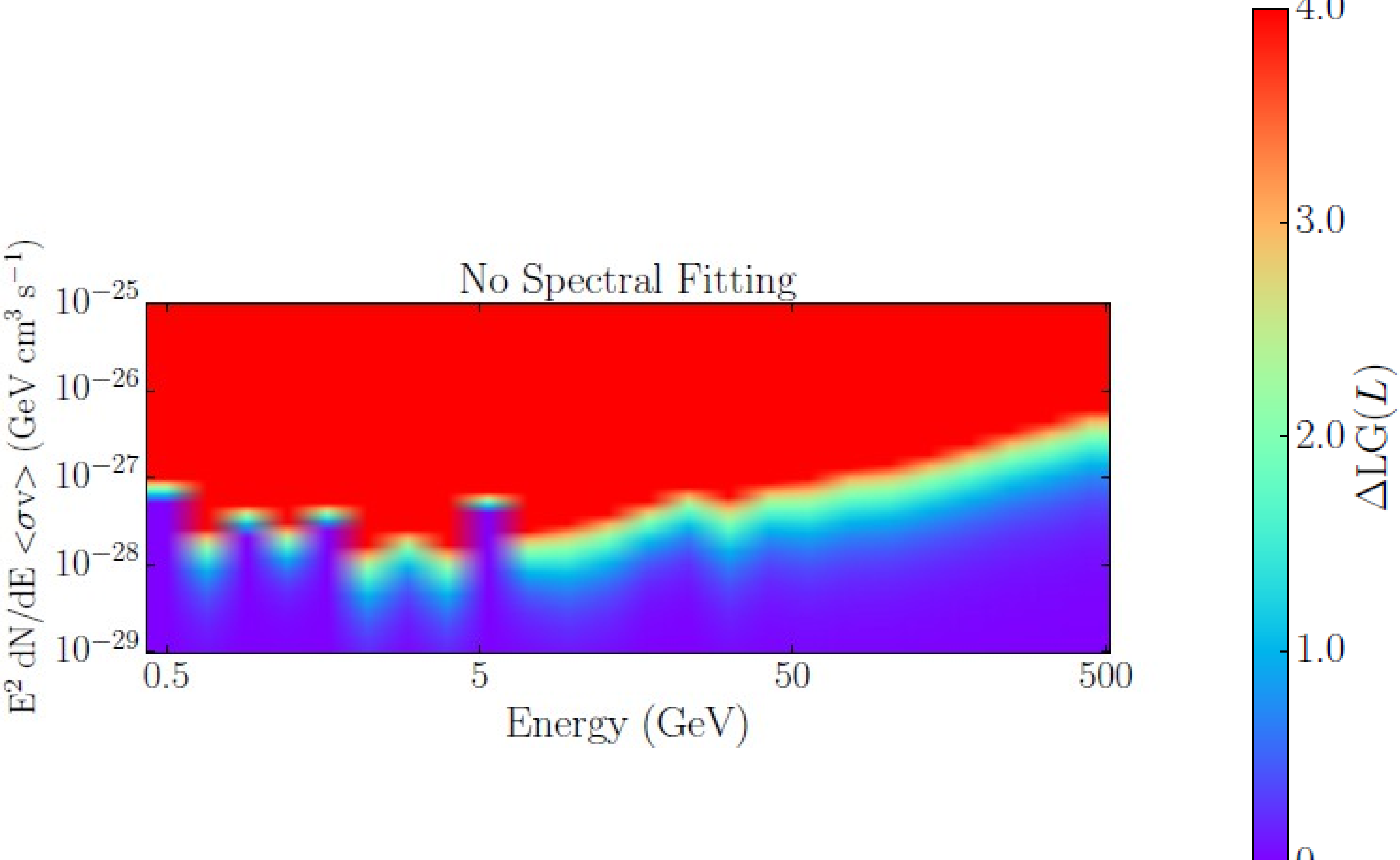
Compare to null hypothesis no DM to set limit on upper bound of annihilation xsec in each bin with 95%~ LLL 2.71/2

Infer combined xsec limit





No spectral Fitting

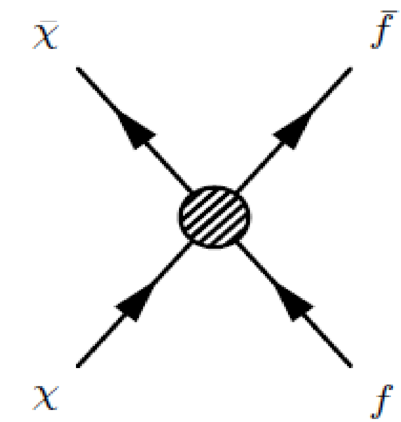


Fermion Portal

Simplest EFT model: 1 operator 1 channel

$$\mathcal{L}_{\mathrm{f}} = \cancel{\frac{\kappa_t}{\Lambda_t^2}\chi\Gamma\overline{\chi}t\Gamma\overline{t}} + \frac{\kappa_b}{\Lambda_b^2}\chi\Gamma\overline{\chi}b\Gamma\overline{b} + \frac{\kappa_\tau}{\Lambda_\tau^2}\chi\Gamma\overline{\chi}\tau\Gamma\overline{\tau} + \frac{\kappa_\nu}{\Lambda_\nu^2}\chi\Gamma\overline{\chi}\nu\Gamma\overline{\nu}.$$

Allow visible total annihilation rate below the thermal rate
Without over-closing the universe



Light DM For now consider annihilation to b, τ and invisible channel

$$\langle\sigma v\rangle_{\mathrm{tot}} = \langle\sigma v\rangle_{\mathrm{b}} + \langle\sigma v\rangle_\tau + \langle\sigma v\rangle_\nu.$$

$$\propto a\left(\kappa_b/\Lambda_b^2\right)^2 + b\left(\kappa_\tau/\Lambda_\tau^2\right)^2 + c\left(\kappa_\nu/\Lambda_\nu^2\right)^2$$

First Fix the Annihilation rate as desired

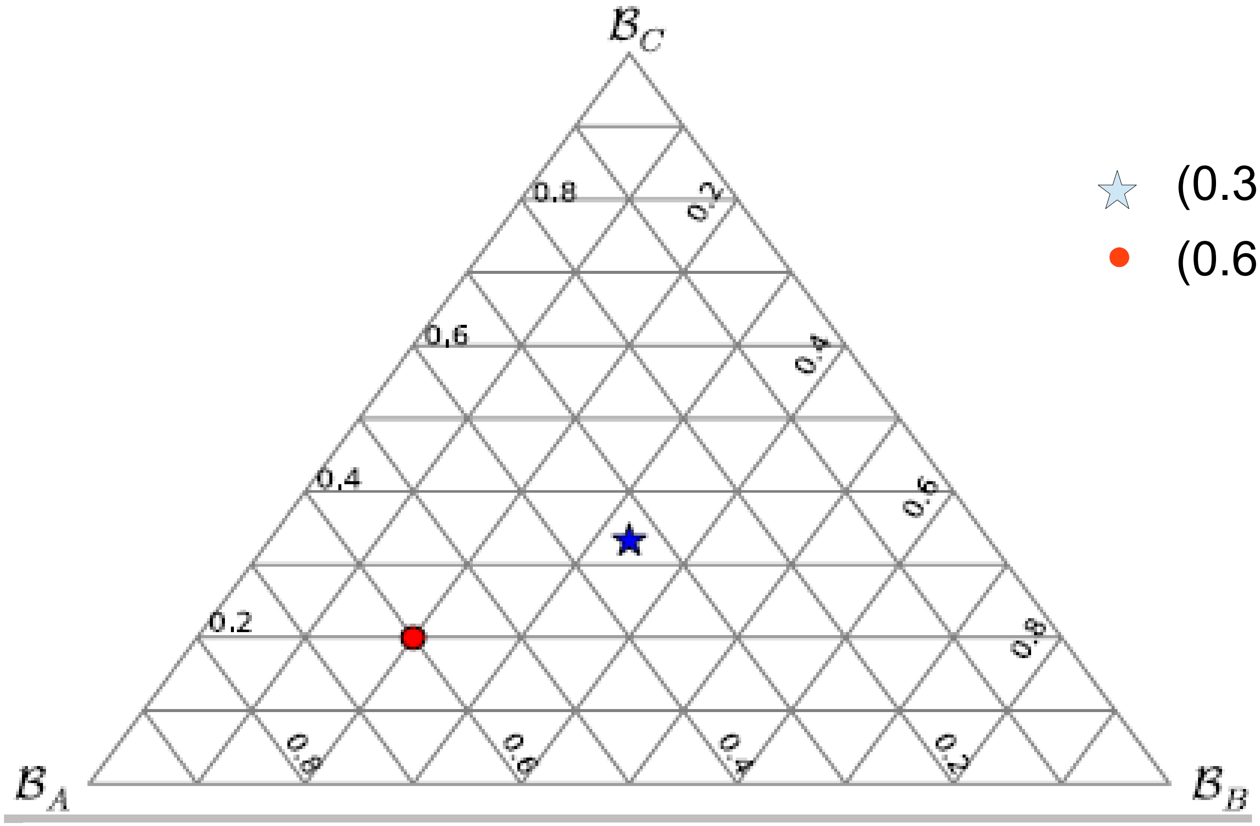
Dividing out by the total rate to define partial rate $R_i = \langle\sigma v\rangle_i/\langle\sigma v\rangle_{\mathrm{tot}}$

get a constraint between the partial annihilation rates

$$R_1 + R_2 + R_3 + \cdots = 1.$$

Three Parameters and 1 constraint may be visualized on 2-D surface as triangle

The partial rates are saturated at the corners of the triangle

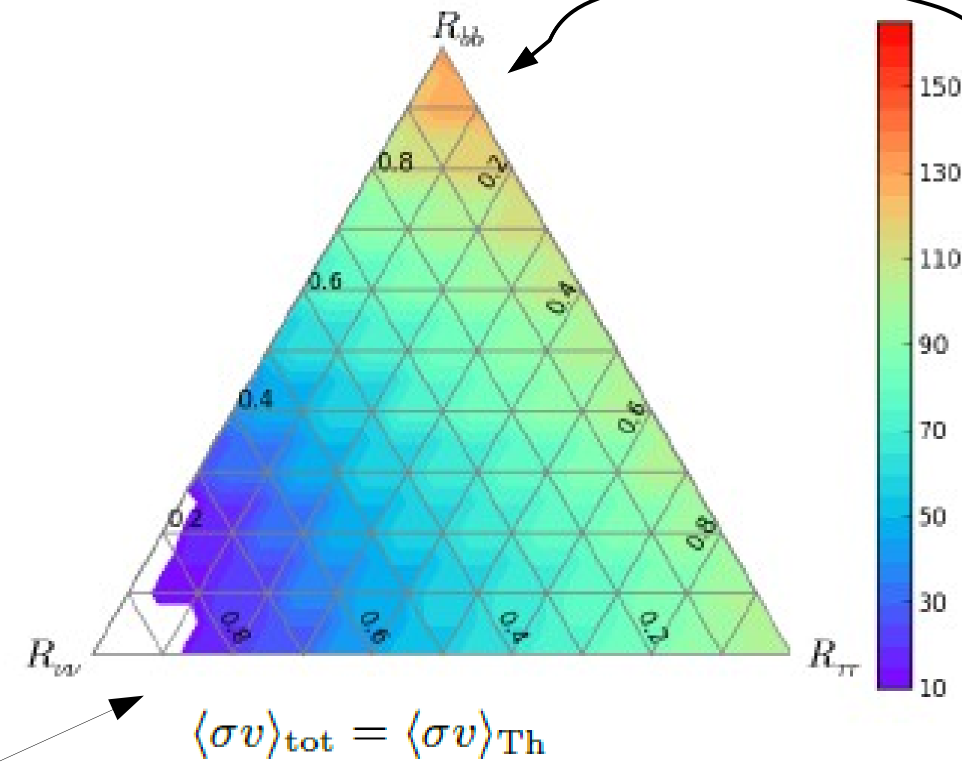


☆ (0.33, 0.33,0.33)

● (0.6, 0.2,0.2)

$$\Phi_\gamma = \frac{1}{4\pi} \sum_f \frac{\langle \sigma v \rangle_f}{2m_\chi^2} \int_{E_{\min}}^{E_{\max}} \left(\frac{dN_\gamma}{dE_\gamma} \right)_f dE_\gamma J.$$

Pass 8



Max exclusion improves by factor ~4

order 10s GeV min mass bounds even for visible annihilation rates at 30% of thermal rate

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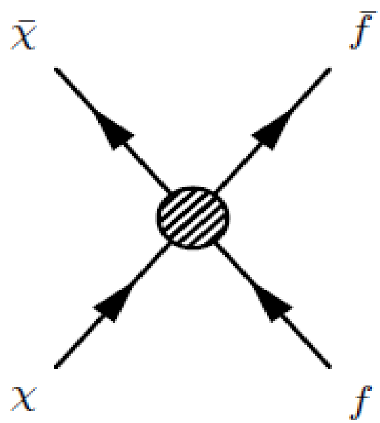
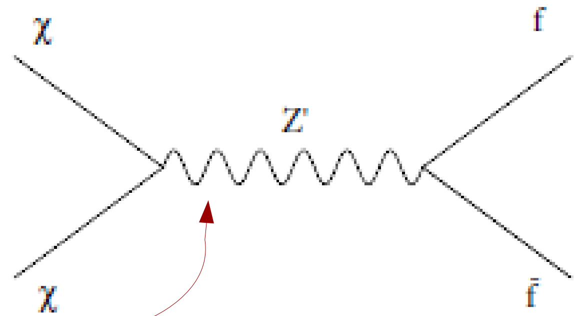
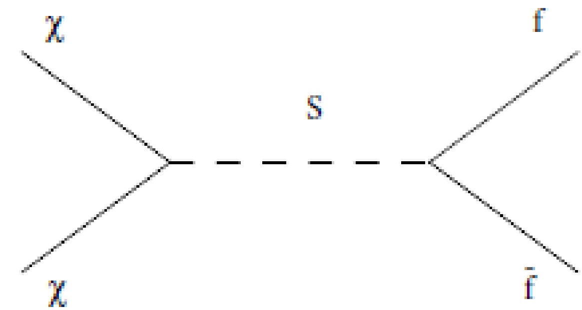
EFT to Simplified Model



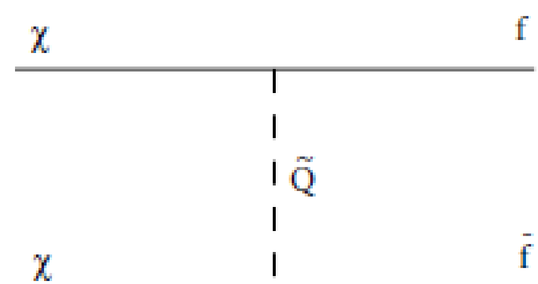
S channel vector



S channel scalar

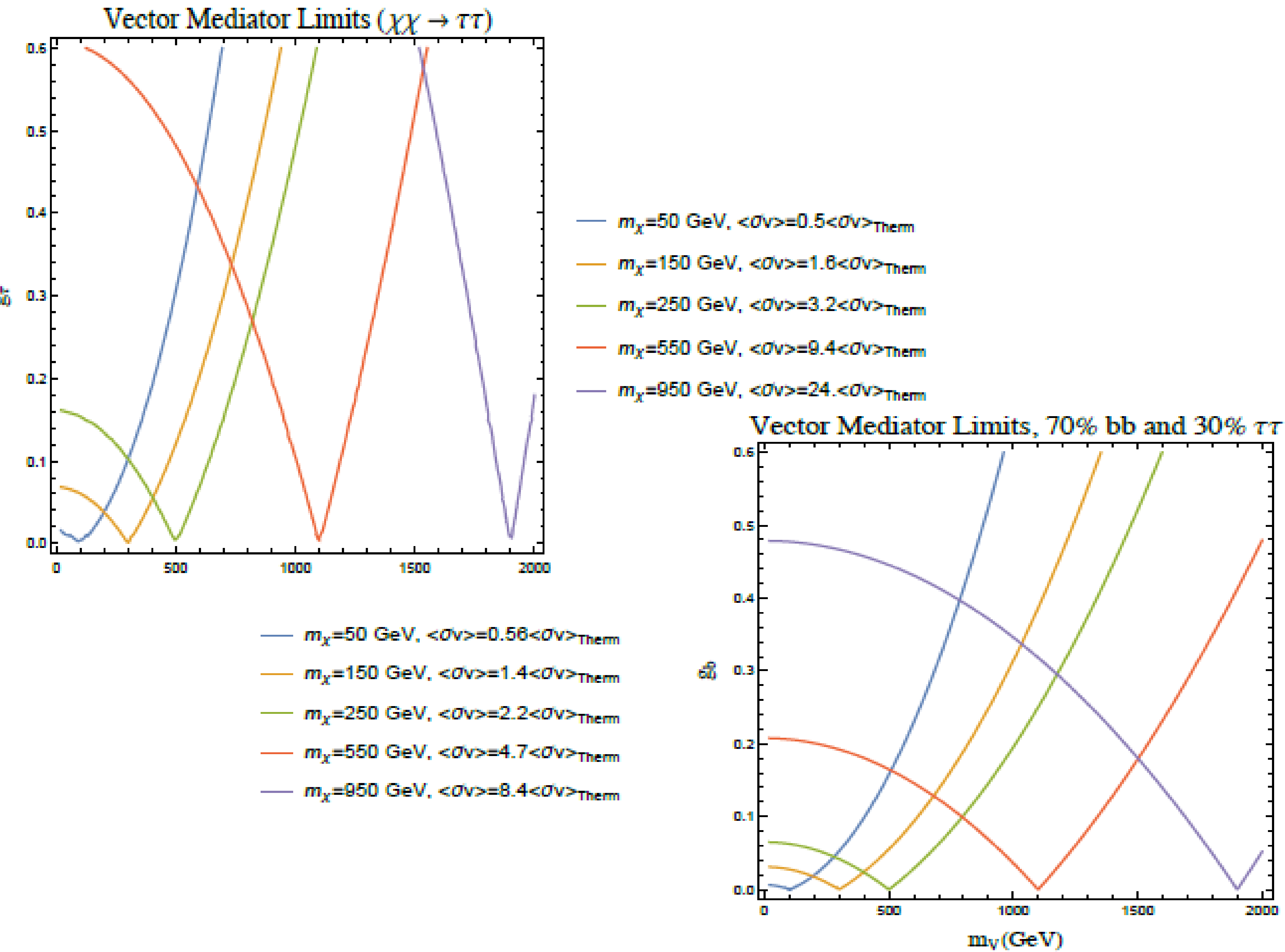


t channel scalar: 'fake SUSY'



$$\mathcal{L} = V_\mu \bar{\chi}\gamma^\mu(g_\chi^V - g_\chi^A\gamma^5)\chi + \sum_f V_\mu \bar{f}\gamma^\mu(g_f^V - g_f^A\gamma^5)f$$

$$\mathcal{L} = \sum_i g_i \phi_i^* \bar{\chi} P_R f_i + h.c.,$$

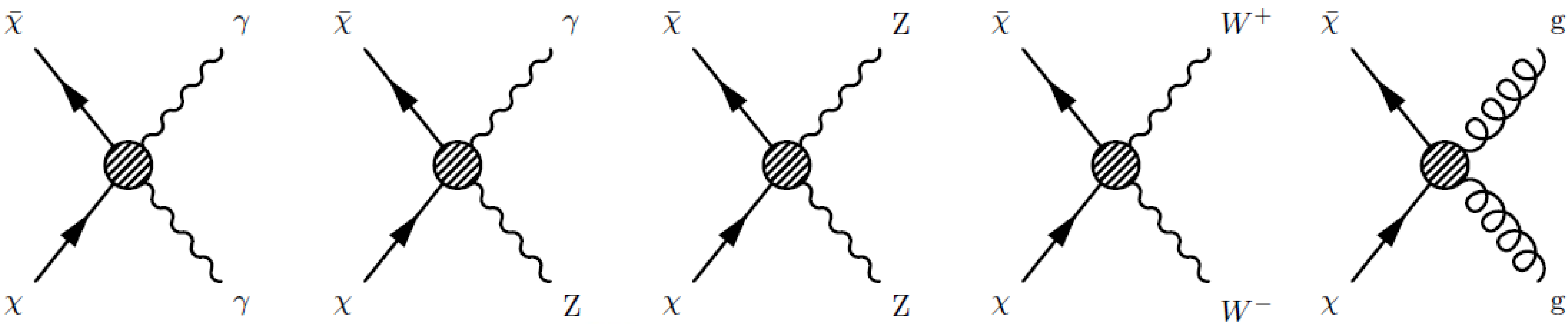


Vector Mediator Limits (χχ → ττ)
m_χ=50 GeV, <σv>=0.5<σv>_Therm
m_χ=150 GeV, <σv>=1.6<σv>_Therm
m_χ=250 GeV, <σv>=3.2<σv>_Therm
m_χ=550 GeV, <σv>=9.4<σv>_Therm
m_χ=950 GeV, <σv>=24.<σv>_Therm
Vector Mediator Limits, 70% bb and 30% ττ
m_χ=50 GeV, <σv>=0.56<σv>_Therm
m_χ=150 GeV, <σv>=1.4<σv>_Therm
m_χ=250 GeV, <σv>=2.2<σv>_Therm
m_χ=550 GeV, <σv>=4.7<σv>_Therm
m_χ=950 GeV, <σv>=8.4<σv>_Therm
m_V (GeV)

Models with Interfering Channels

Gauge Boson Portal Models

$$\mathcal{L} = \frac{\kappa_1}{\Lambda^3}\bar{\chi}\gamma^5\chi B_{\mu\nu}B^{\mu\nu} + \frac{\kappa_2}{\Lambda^3}\bar{\chi}\gamma^5\chi W^i_{\mu\nu}W_i^{\mu\nu} + \frac{\kappa_3}{\Lambda^3}\bar{\chi}\gamma^5\chi G^a_{\mu\nu}G_a^{\mu\nu}$$



$$\langle \sigma v_{rel} \rangle_{WW} = \frac{\kappa_2^2}{4\pi\Lambda^6}\sqrt{1-\frac{m_W^2}{m_\chi^2}}(16m_\chi^4 - 16m_W^2 m_\chi^2 + 6m_W^4)$$

$$\langle \sigma v_{rel} \rangle_{ZZ} = \frac{(\kappa_1 s_w^2 + \kappa_2 c_w^2)^2}{8\pi\Lambda^6}\sqrt{1-\frac{m_Z^2}{m_\chi^2}}(16m_\chi^4 - 16m_Z^2 m_\chi^2 + 6m_Z^4)$$

$$\langle \sigma v_{rel} \rangle_{Z\gamma} = \frac{s_w^2 c_w^2(\kappa_2 - \kappa_1)^2}{16\pi m_\chi^2\Lambda^6}(4m_\chi^2 - m_Z^2)^3$$

$$\langle \sigma v_{rel} \rangle_{\gamma\gamma} = \frac{4(\kappa_1 c_w^2 + \kappa_2 s_w^2)^2}{2\pi\Lambda^6}m_\chi^4$$

$$\langle \sigma v_{rel} \rangle_{gg} = \frac{16\kappa_3^2}{\pi\Lambda^6}m_\chi^4$$

Defining effective cut-ff

$$(k_i = \kappa_i/\Lambda^3)$$

The constraint has the form

$$(ak_1^2 + bk_2^2)^2 + ck_3^2 = \langle\sigma v\rangle_{tot}$$

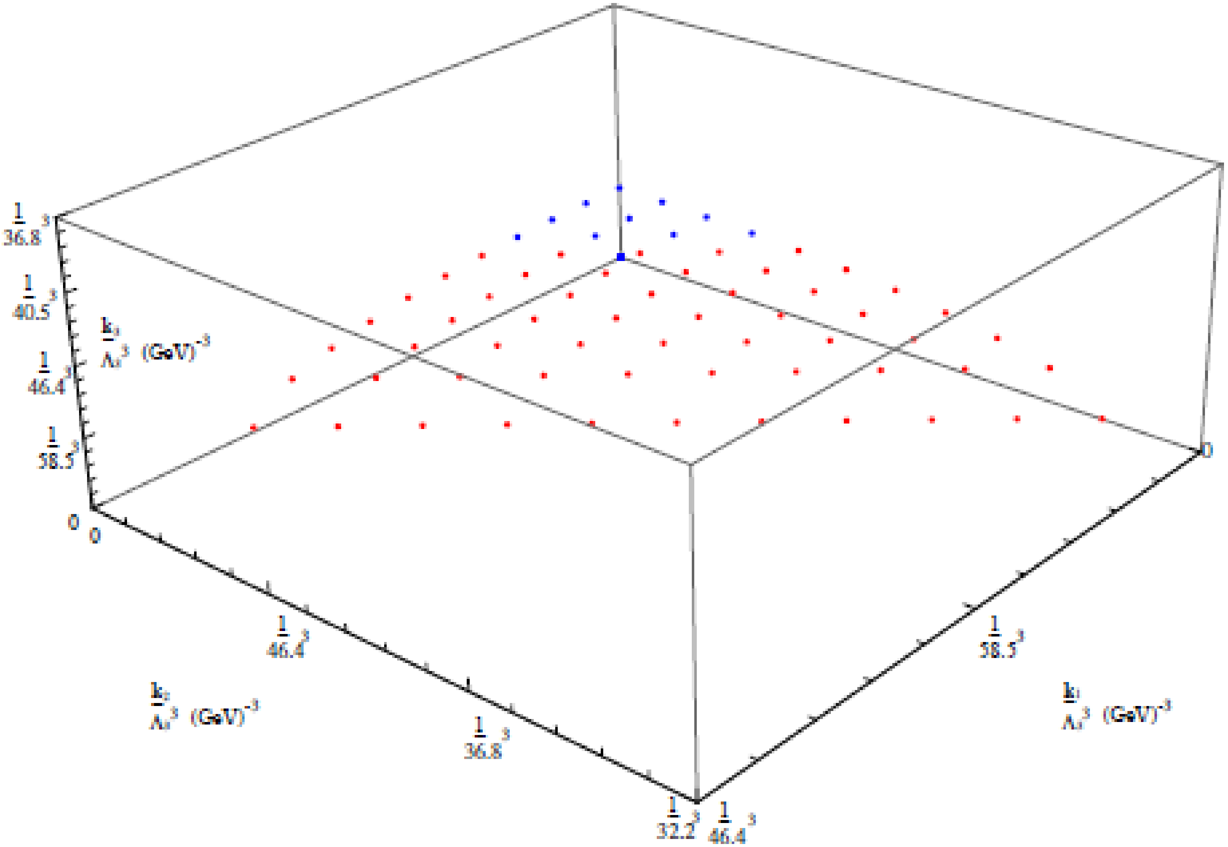
Fixing $\langle\sigma v\rangle_{tot}$ the coefficients sit on a hypersurface

The constraint no longer factorizes multiple operators contribute to a single channel

A single operator coefficient contributes to multiple channels

To visualize parameter space we can fix total annihilation xsec. We can vary DM mass
And look at the hypersurface in effective coefficient space where the constrain is satisfies

Each point in parameter space has specific admixture of partial annihilation rates into 5 channels
We add up the total flux and see if the point is excluded.

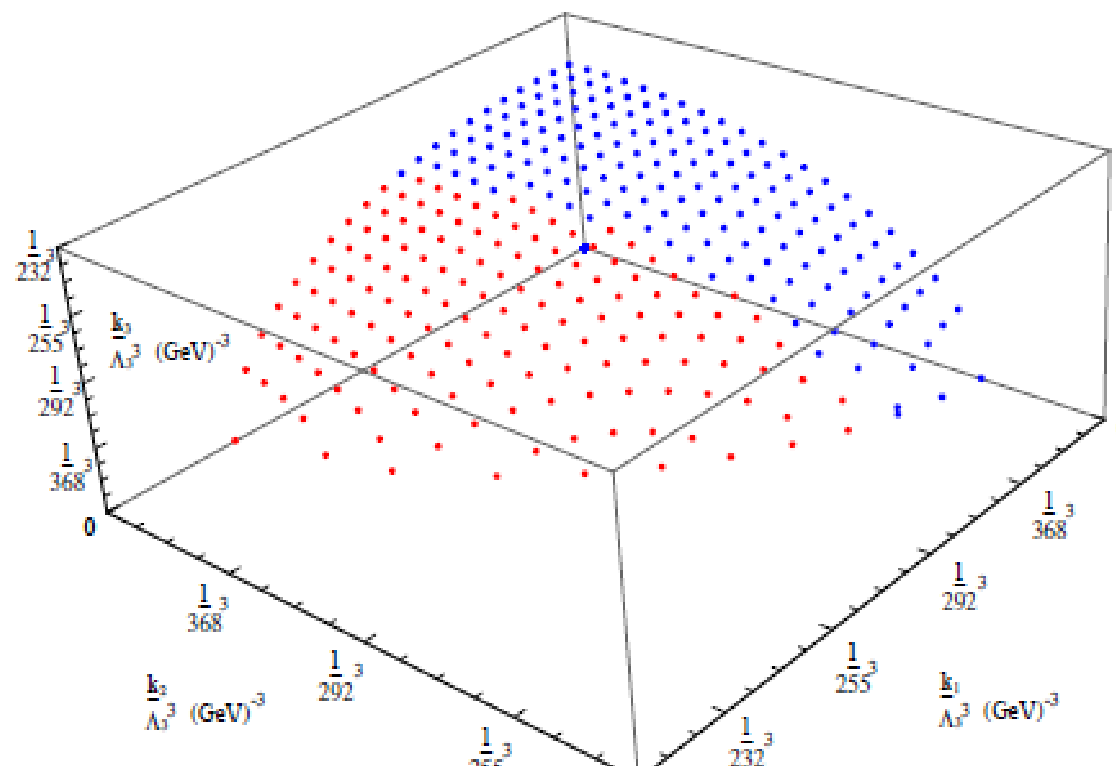


DM mass = 10 GeV
Rate constraint is saturated
By low effective cut-offs

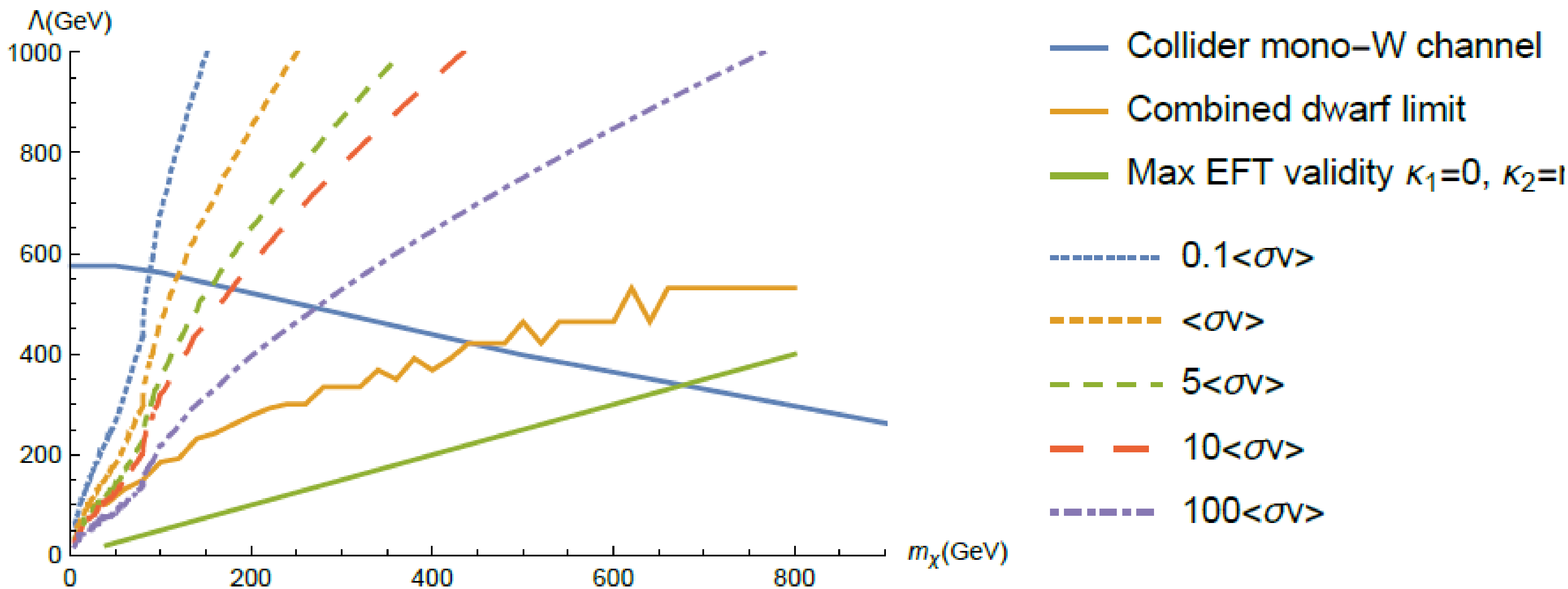
at low DM mass only g and γ
channels kinematically accessible

Surfaces in effective cut off space
Red points ruled out
Total annihilation rate 10x's thermal

DM mass = 150 GeV
Rate constraint is saturated
By higher effective cut-offs



Compare LHC search to Indirect limit



Extra Slides

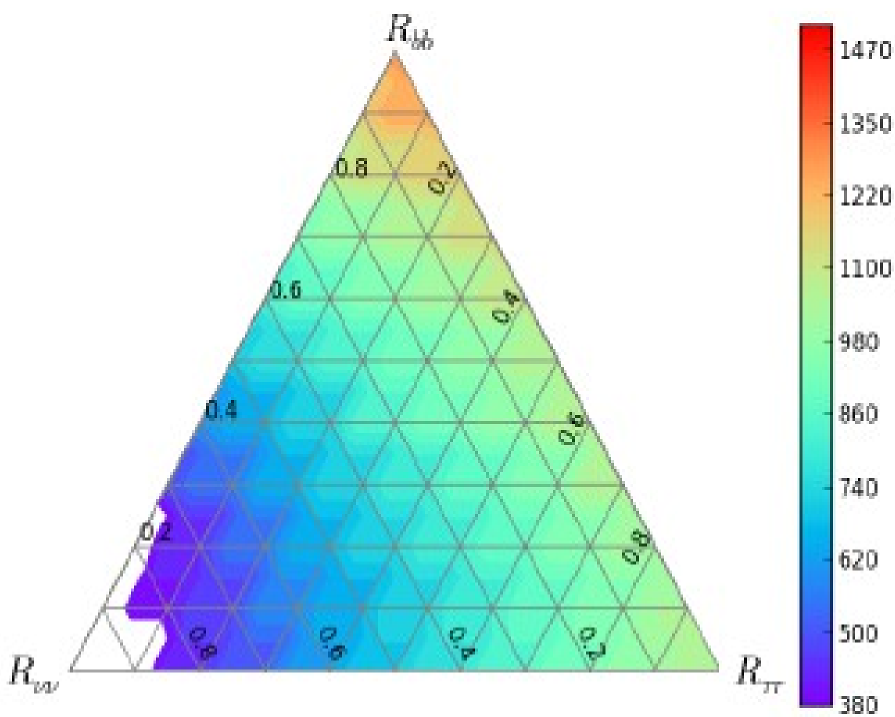
Specify a form for effective operators

$$\mathcal{L}_{\mathrm{f}} = \frac{\kappa_f}{\Lambda_f^2}\chi\gamma^\mu\overline{\chi}f\gamma_\mu\overline{f}$$

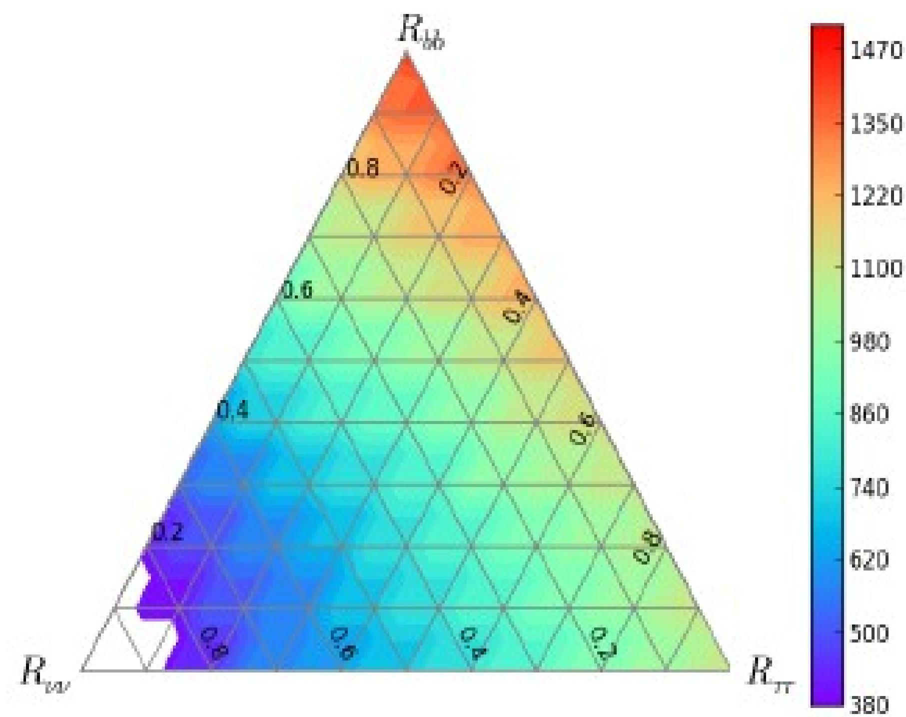
Re-define the effective cut-off

$$\Lambda_i^* = \sqrt{\kappa_i}/\Lambda_i$$

Λ_b^*



Λ_τ^*



Vector Mediator

$$\mathcal{L} = V_\mu \bar{\chi}\gamma^\mu(g_\chi^V - g_\chi^A\gamma^5)\chi + \sum_f V_\mu \bar{f}\gamma^\mu(g_f^V - g_f^A\gamma^5)f$$

$$\langle\sigma v\rangle(\chi\bar{\chi} \to V \to f\bar{f}) = \frac{N_c^f m_\chi^2}{2\pi[(M_V^2 - 4m_\chi^2)^2 + \Gamma_V^2 M_V^2]}\left(1 - \frac{m_f^2}{m_\chi^2}\right)^{1/2}$$
$$\times\left\{|g_\chi^V|^2\left[|g_f^V|^2\left(2 + \frac{m_f^2}{m_\chi^2}\right) + 2|g_f^A|^2\left(1 - \frac{m_f^2}{m_\chi^2}\right)\right] + |g_\chi^A|^2|g_f^A|^2\frac{m_f^2}{m_\chi^2}\left(1 - \frac{4m_\chi^2}{M_V^2}\right)^2\right\}$$

Decay width $\Gamma_V = \frac{M_V}{12\pi}\sum_i N_c^i\left(1 - \frac{4m_i^2}{M_V^2}\right)^{1/2}\left(|g_i^V|^2 + |g_i^A|^2 + \frac{m_i^2}{M_V^2}\{2|g_i^V|^2 - 4|g_i^A|^2\}\right)$