Indirect Detection Constraints on Dark Matter Model Space

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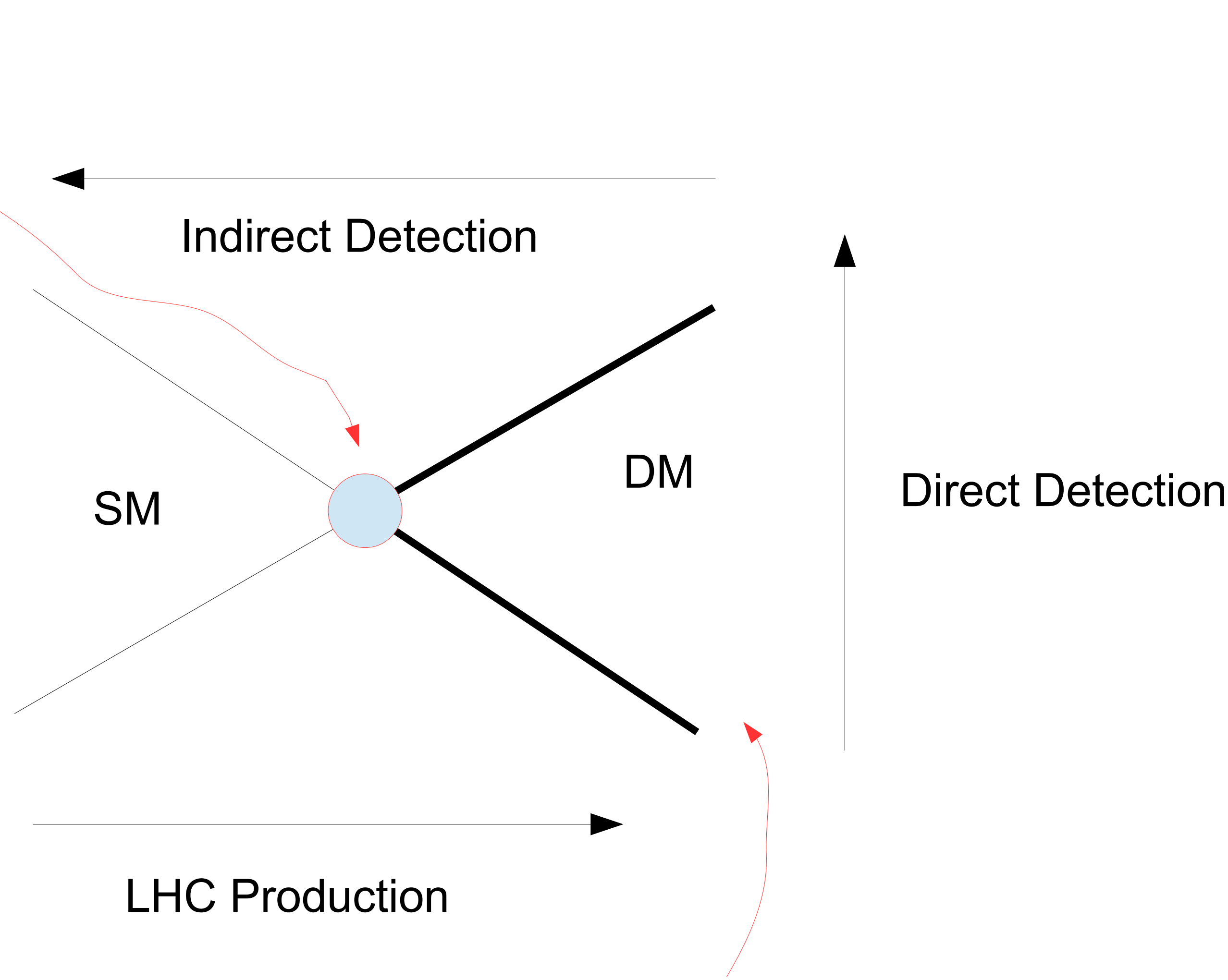
arXiv:1506.08841 With Russell Colburn Jessica Goodman and new work with Tim Linden

We may complete this picture with various mediator sectors, with much physics captured by a
Set of effective couplings between DM and the SM



Many models demand multiple final state annihilations due to gauge invariance or other
Theoretical considerations

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

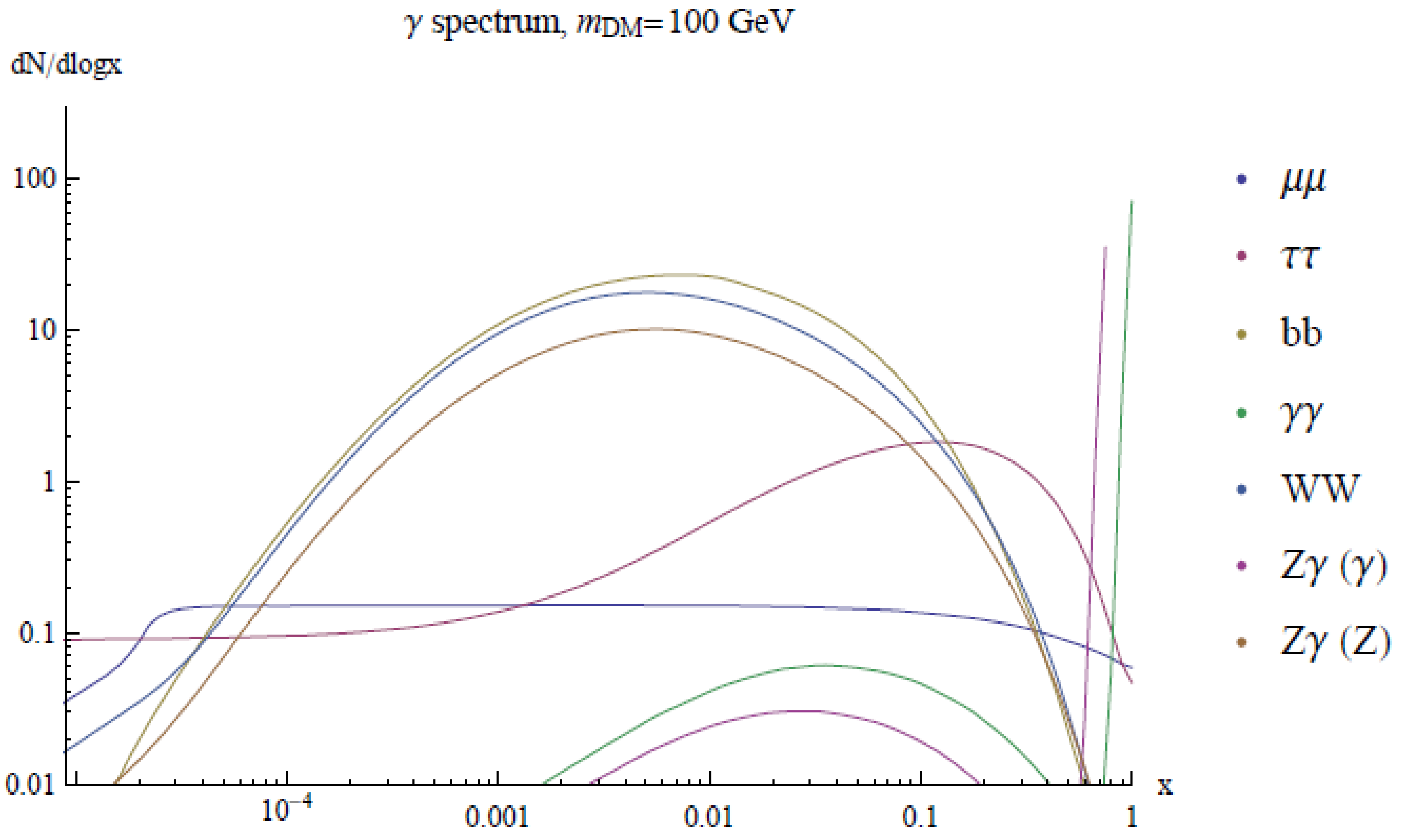
DM mass

Photon energy spectrum

Line of sight integral of DM density

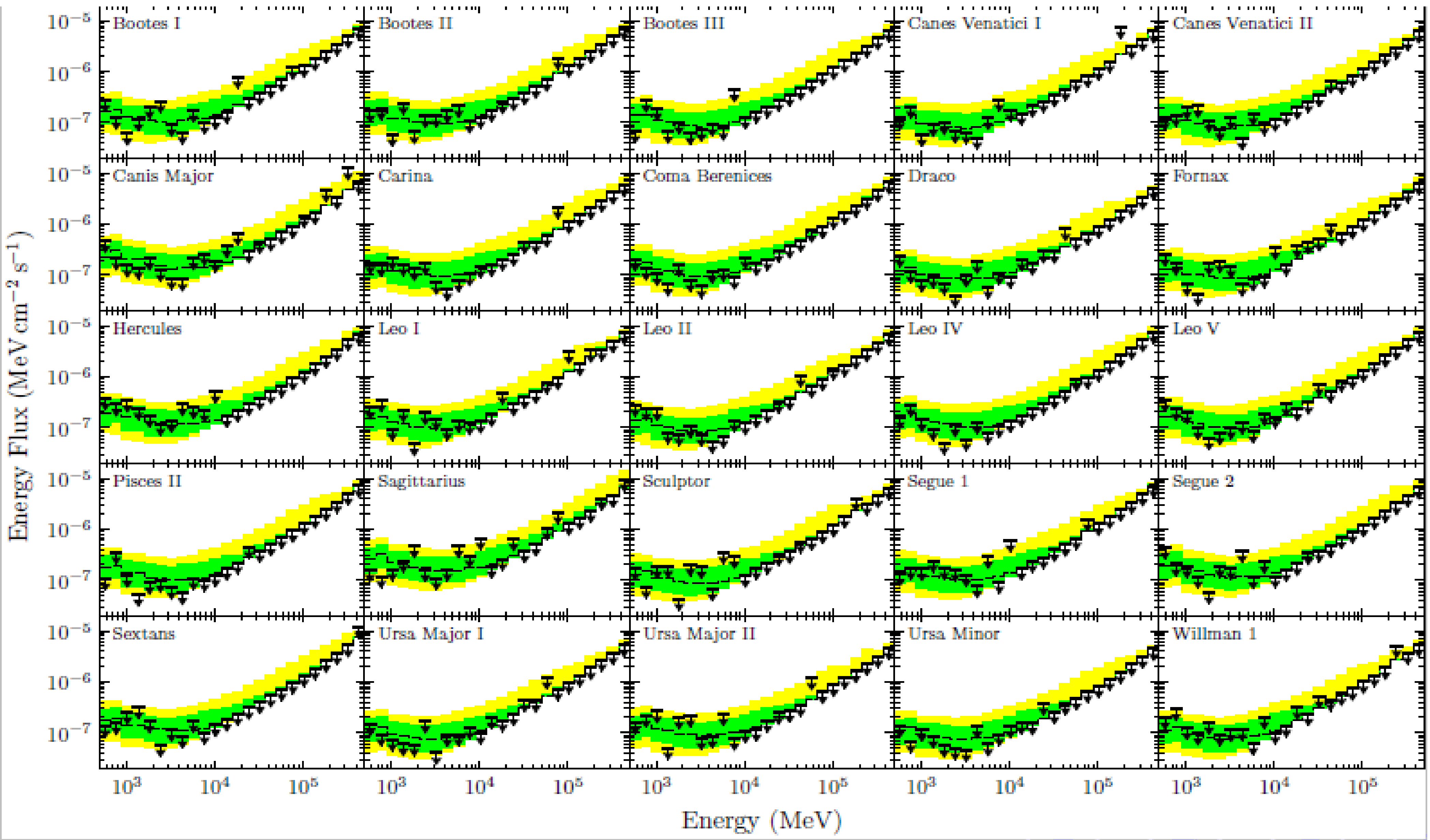
$$J = \int_{\Delta\Omega} \int_{l.o.s} \rho^2(\mathbf{r}) dl d\Omega'.$$

Spectrum

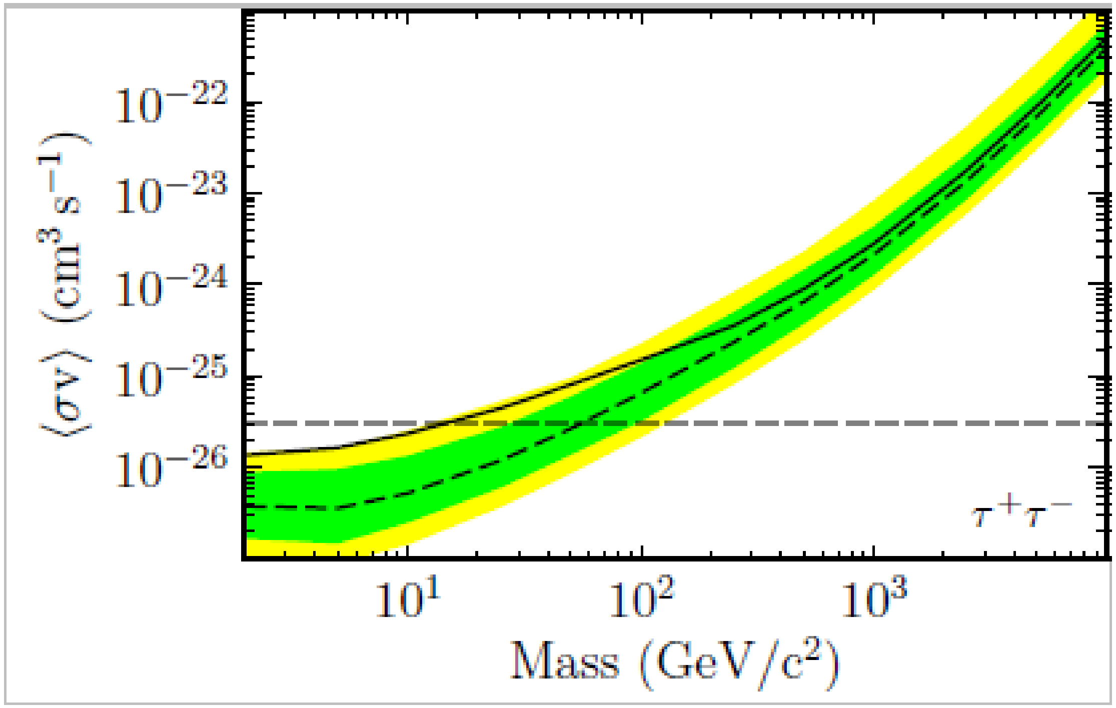


DM annihilates to various SM final states each with a characteristic photon spectrum

Pass 7- 25 Dwarfs

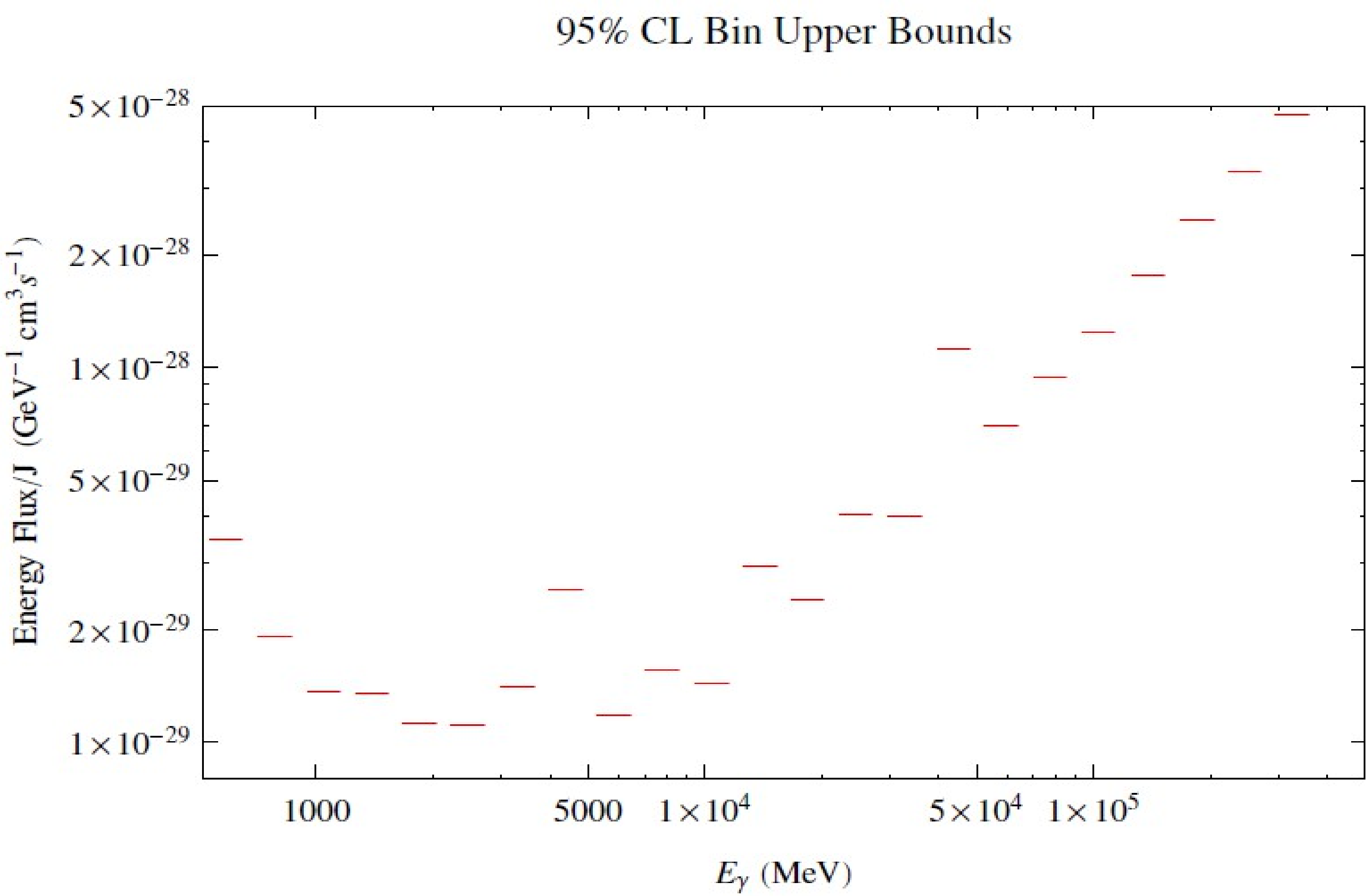


Fermi Analysis combine 15 dwarf's with largest J factors, set 95% c.l. upper bound assuming 100% annihilation into a single channel,e.g.τ's



arXiv:1310.0828

Combine Limits



Look at Dwarf's with highest J factors pick tightest bin

EFT's

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

arXiv:1008.1783 Goodman *et al*

Multiple Final State Annihilations

Simplest EFT model

$$\mathcal{L}_{\rm f} = \Sigma_i \mathcal{O}_i = \Sigma_i \frac{\kappa}{\Lambda_i^n} \chi\chi X_i X_i.$$

Effective cut-off DM Sum over i final states

Sum partial annihilation rates $\langle \sigma v \rangle_{\rm tot} = N \langle \sigma v \rangle_{\rm Th} = \langle \sigma v \rangle_{\mathcal{O}_1} + \langle \sigma v \rangle_{\mathcal{O}_2} + \cdots$

Dividing out by the total rate....

$$R_i = \langle \sigma v \rangle_i / \langle \sigma v \rangle_{\rm tot}$$

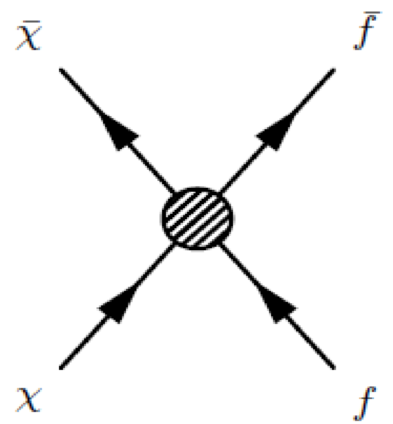
get a constraint between the partial annihilation rates

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

Fermion Portal

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

DM couples to third generation fermions



Invisible channel

Allow visible total annihilation rate bewlow the thermal rate
Without overclosing the universe

For now consider annihilation to b, τ and invisible channel

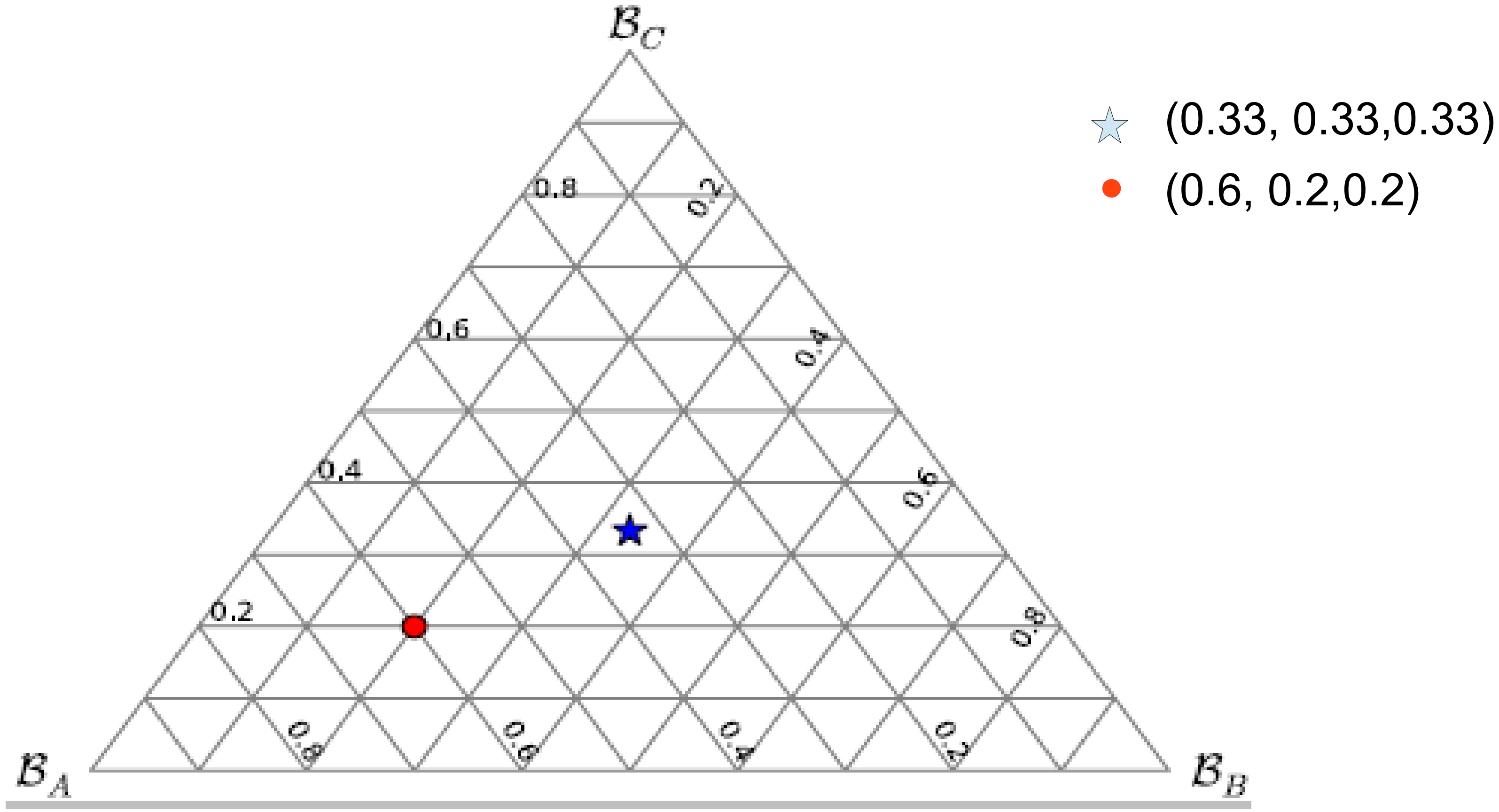
$$\langle\sigma v\rangle_{\rm tot} = \langle\sigma v\rangle_{\rm b} + \langle\sigma v\rangle_{\tau} + \langle\sigma v\rangle_{\nu}.$$

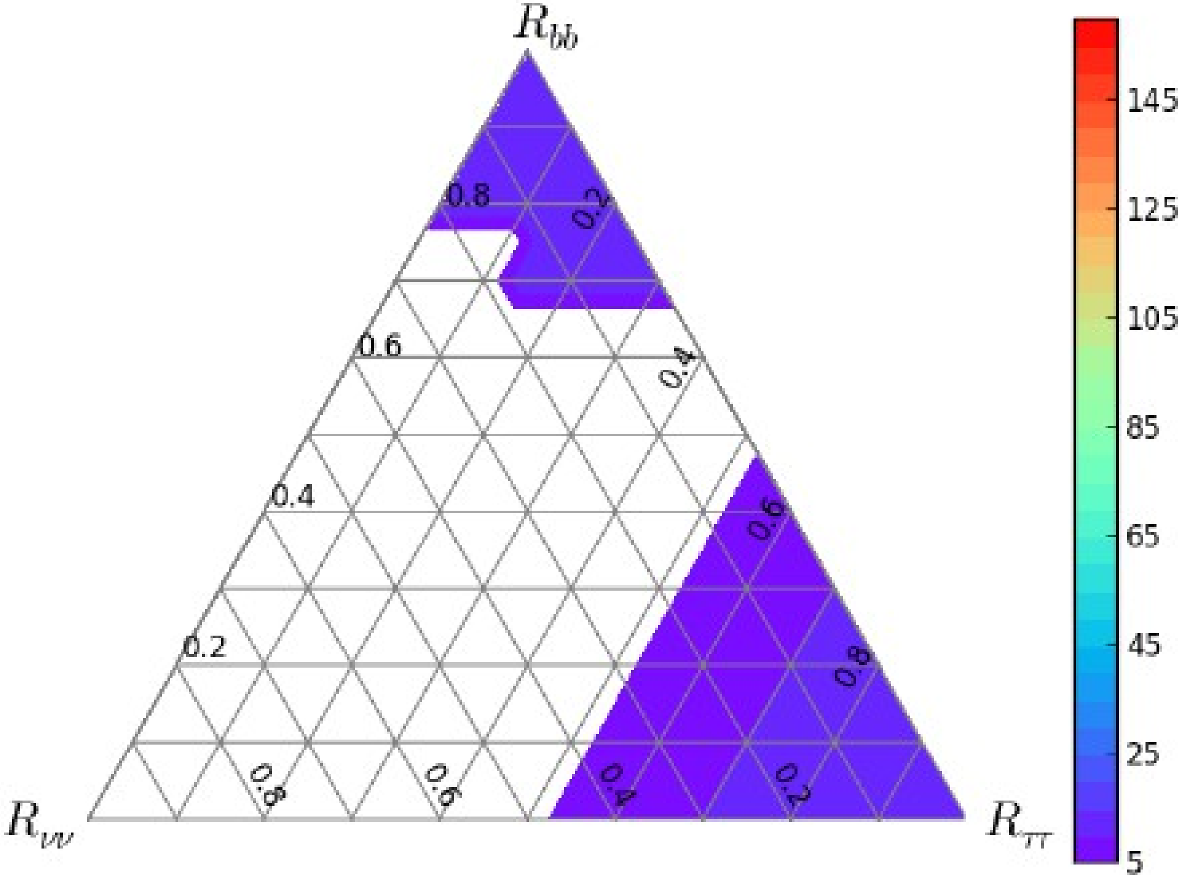
The constraint has the form

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

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

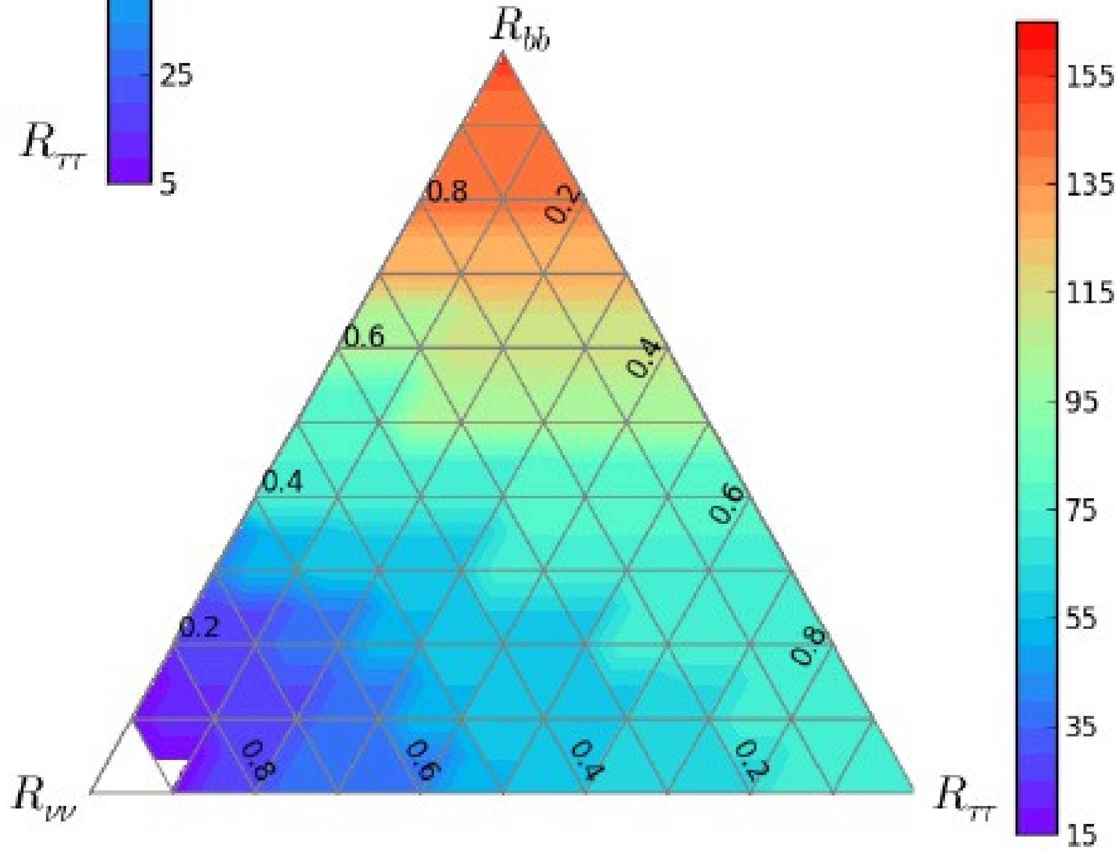
The partial rates are saturated at the corners of the triangle





DM mass lower bounds for
$\langle \sigma v \rangle_{\rm tot} = \langle \sigma v \rangle_{\rm Th}$

DM mass lower bounds for
$\langle \sigma v \rangle_{\rm tot} = 10 \langle \sigma v \rangle_{\rm Th}$

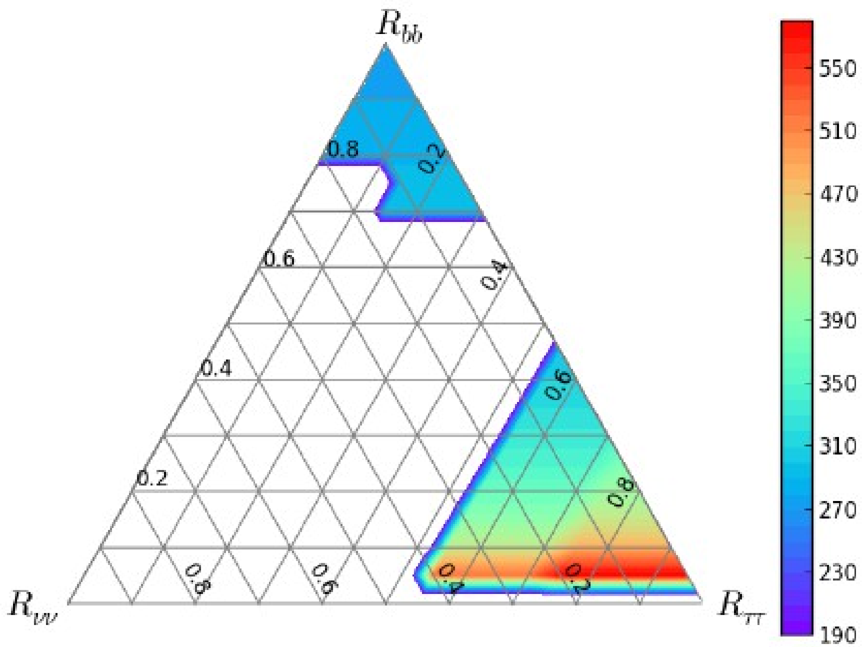


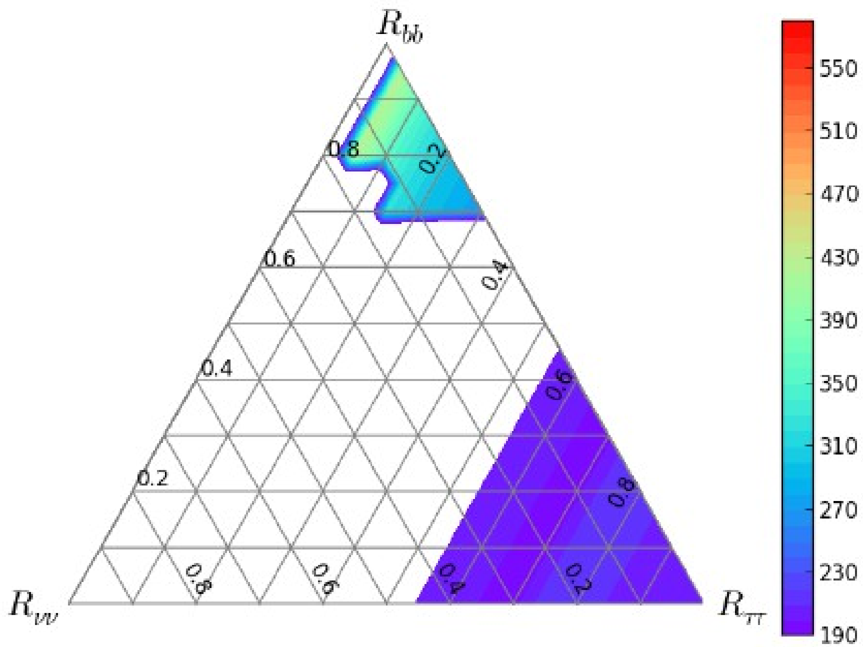
Specify a form for effective operators

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

Re-define the effective cut-off

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

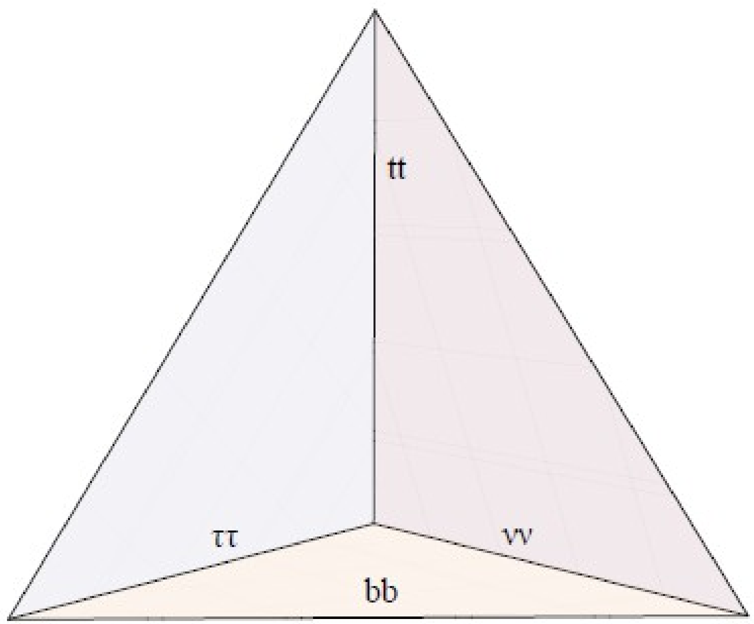




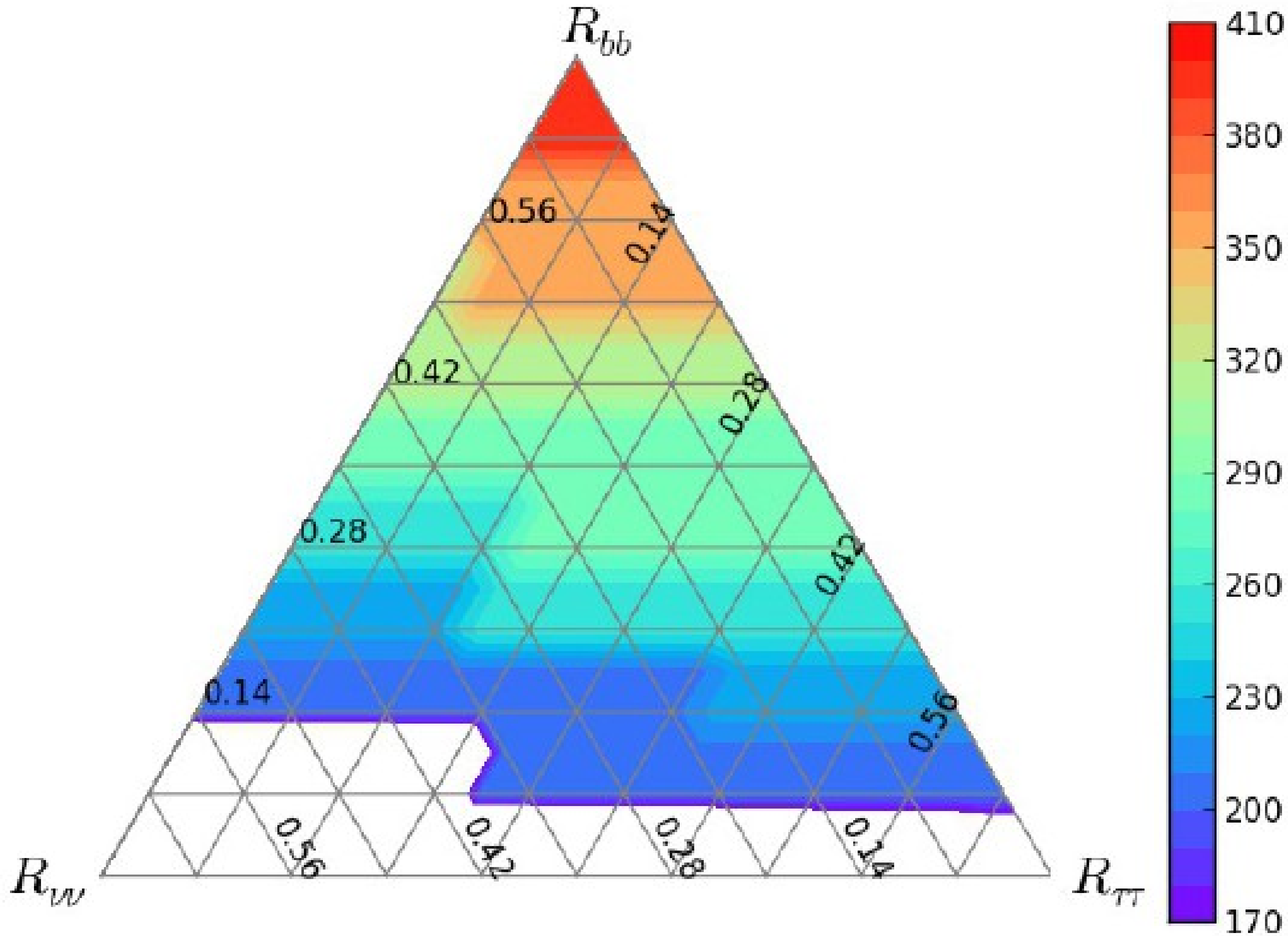
4 independent channels

$$\begin{aligned}\langle\sigma v\rangle_{\rm tot} - \langle\sigma v\rangle_{\rm t} &= \langle\sigma v\rangle_{\rm b} + \langle\sigma v\rangle_{\tau} + \langle\sigma v\rangle_{\nu} \\ (1 - R_t) &= R_b + R_\tau + R_\nu \,.\end{aligned}$$

Add the annihilation to tops



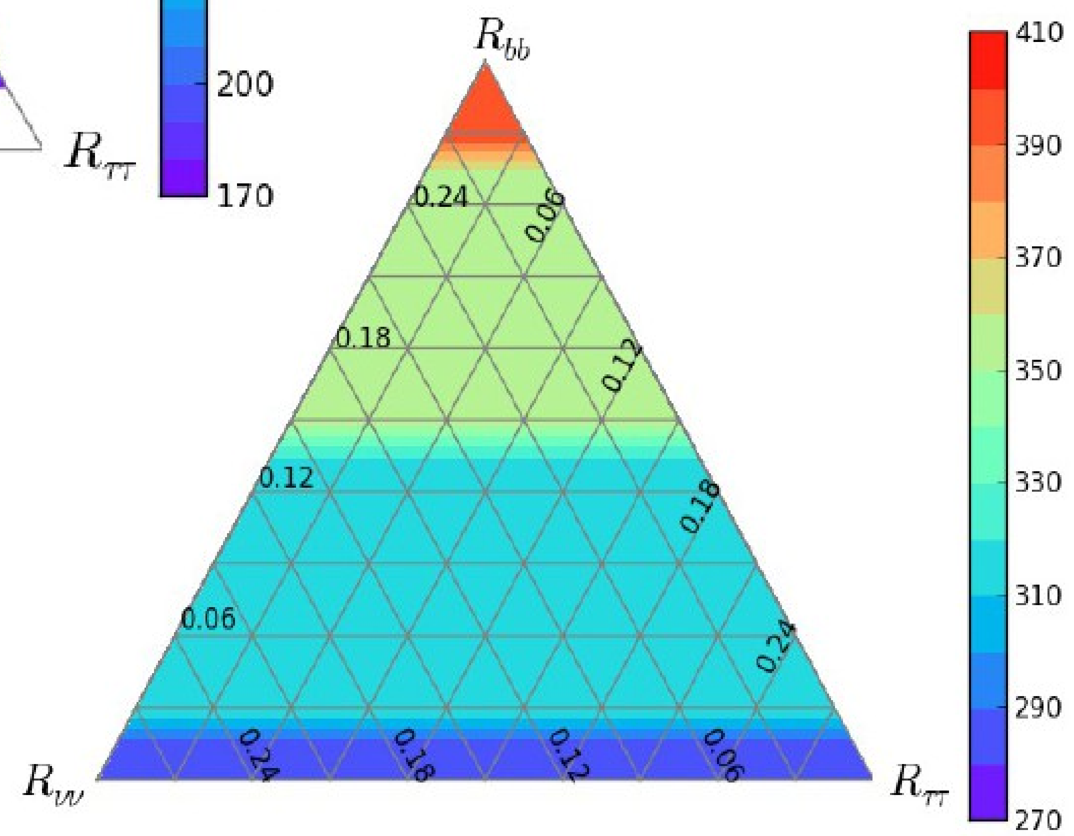
The constraint defines a tetrahedron of which we may take slices



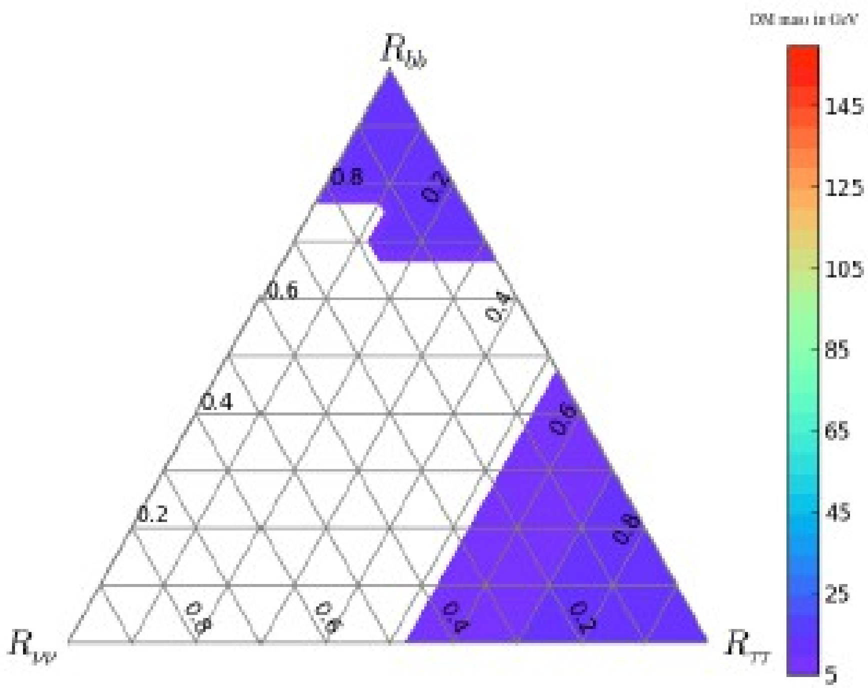
$R_t = .3$

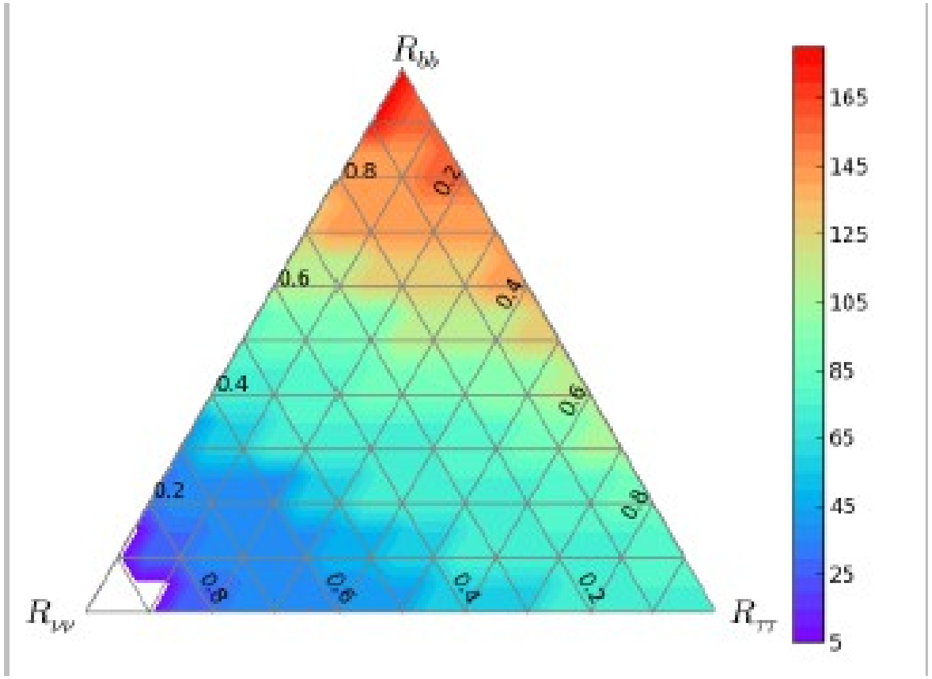
Two slices with

$R_t = .7$



Pass 7 → Pass 8

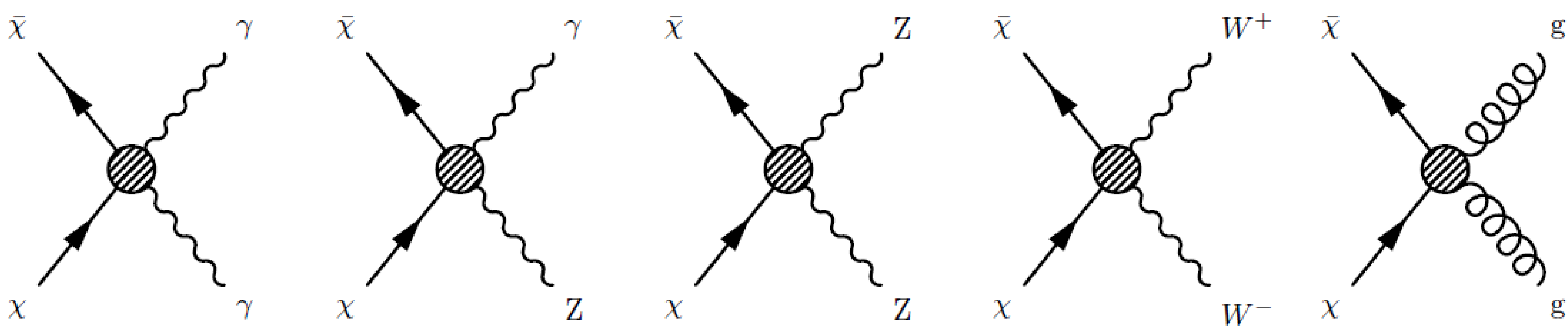

DM mass in GeV
R_{bb}
$R_{\nu\nu}$
$R_{\tau\tau}$
0.2
0.4
0.6
0.8
5
25
45
65
85
105
125
145


R_{bb}
$R_{\nu\nu}$
$R_{\tau\tau}$
0.2
0.4
0.6
0.8
5
25
45
65
85
105
125
145
165

Models with Interfering Channels

Gauge Boson Portal Models

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



5-annihilation channels given by 3 parameters

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

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

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

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

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

Defining effective cut-ff

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

The constraint has the form

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

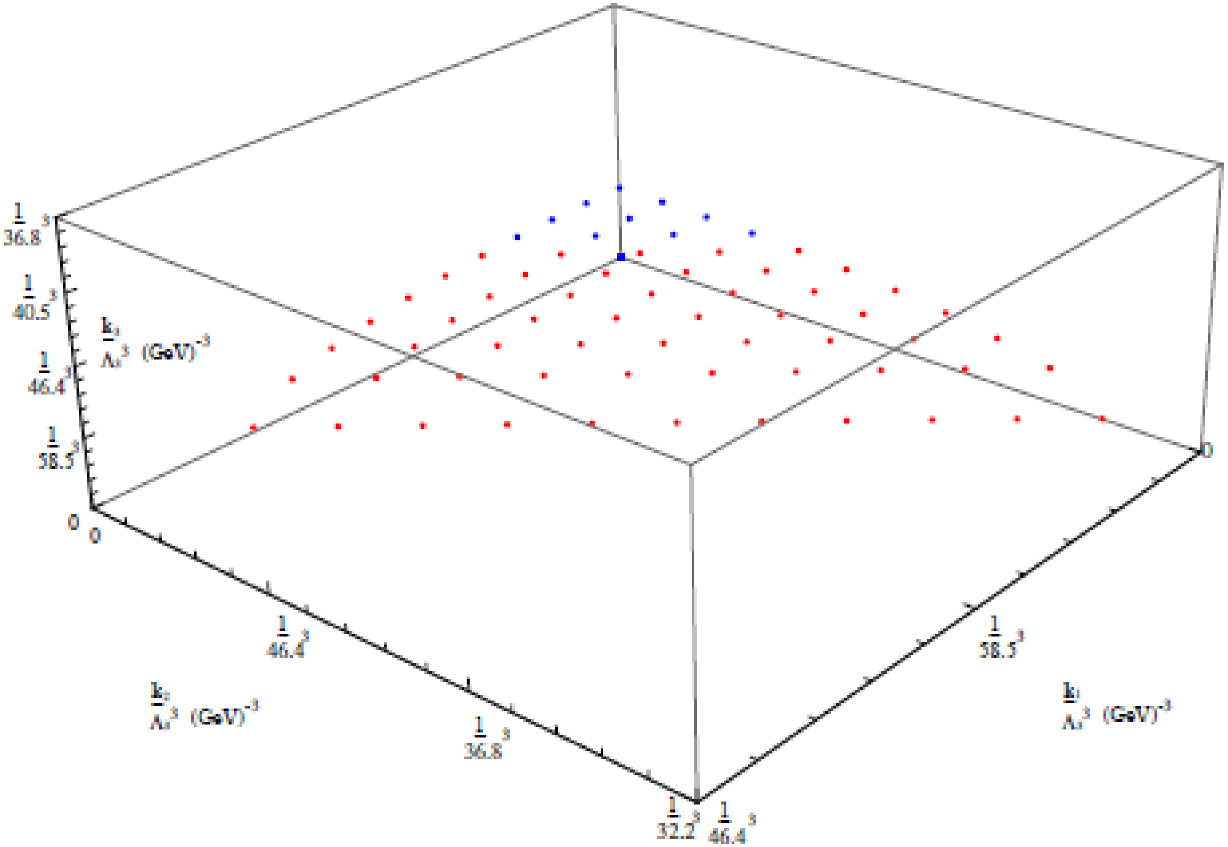
Fixing $\langle \sigma v \rangle_{tot}$ the coefficients sit on a hypersurface

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.



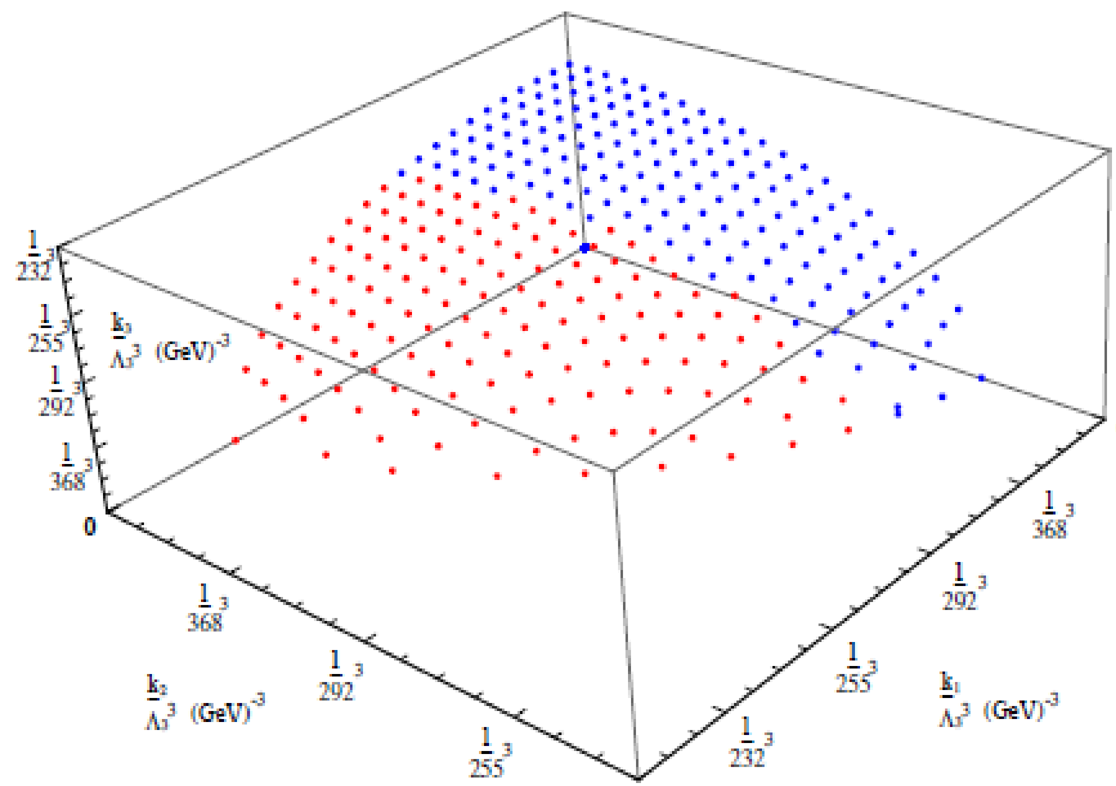
DM mass = 10 GeV
Rate constraint is saturated
By low effective cut-offs

at low DM mass only g and γ
channels kinematically accessible

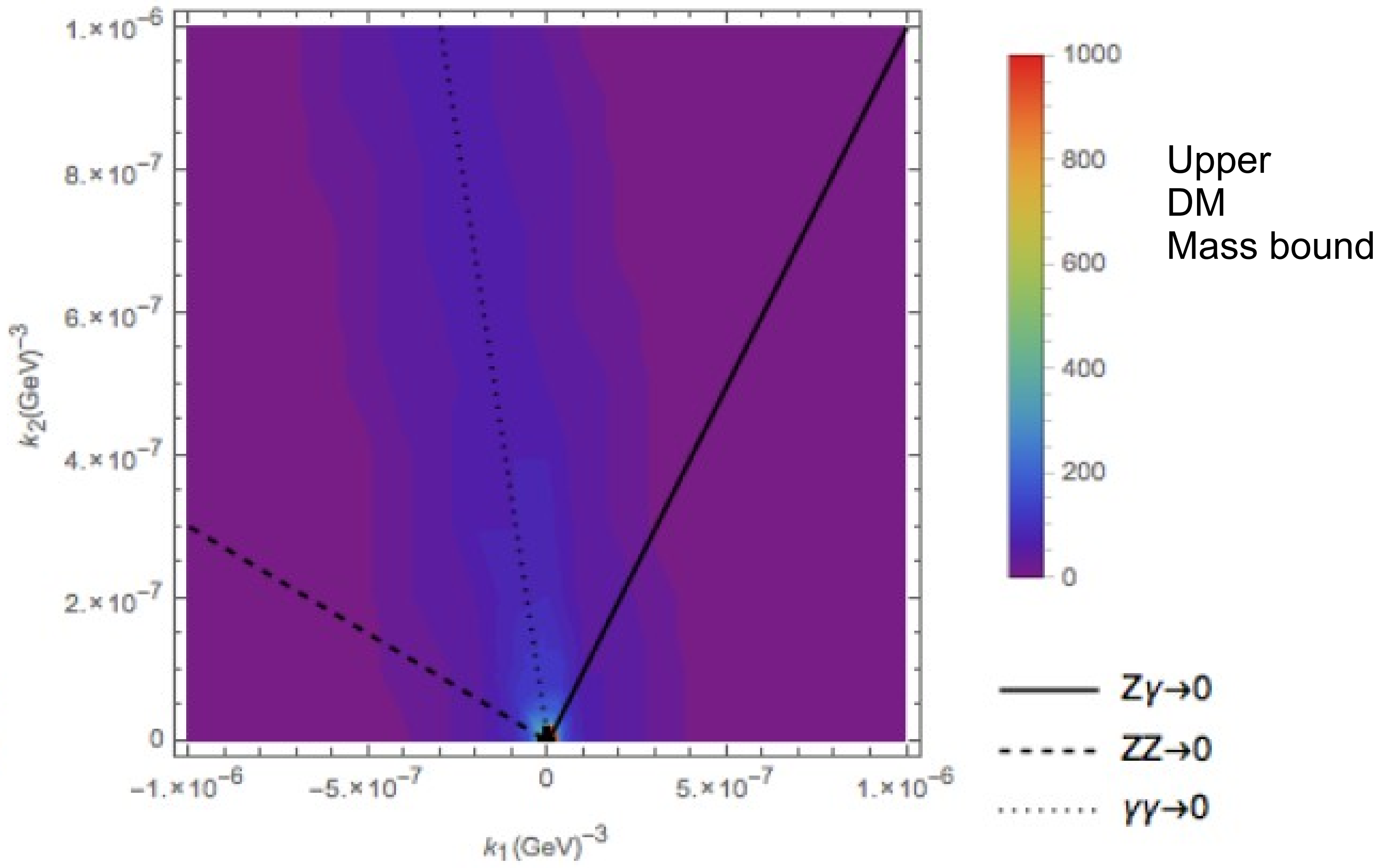
Surfaces in effective cut off space
Red points ruled out
Total annihilation rate 10x's thermal

DM mass = 150 GeV

Rate constraint is saturated
By higher effective cut-offs

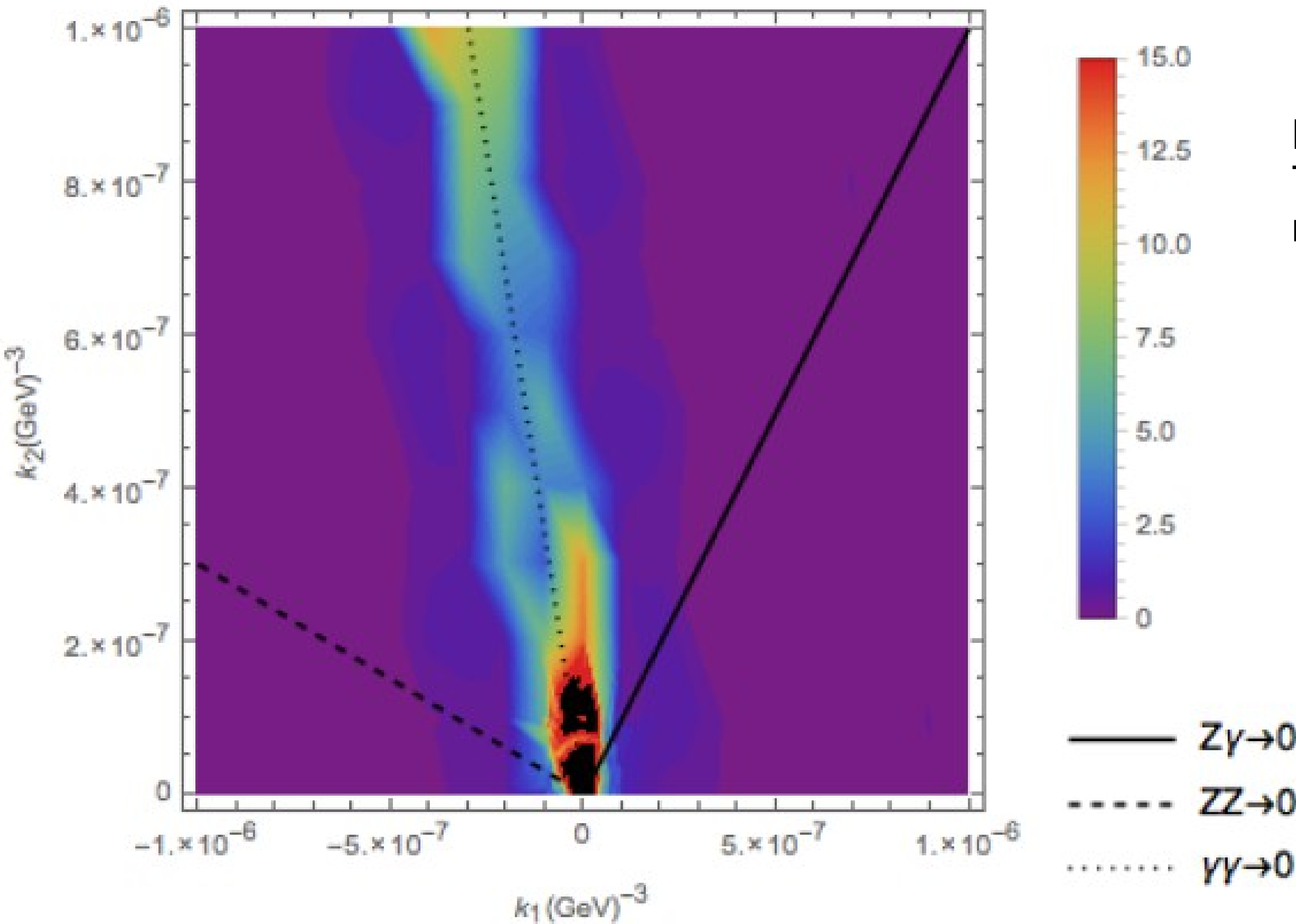


Now let the total rate float



Fraction of total rate to gluons fixed at 30%

Each point gives total annihilation rate



N times Thermal annih. rate

Fraction of total rate to gluons fixed at 30%

EFT Validity

Expect that a messenger sector mediated DM coupling to SM. EFT validity is in the regime where $\sqrt{s} < 2M_{\text{mess}}$. or $m_\chi < M_{\text{mess}}$.

Assuming the EFT is completed by a loop

$$k_i/\Lambda^3 \sim f\alpha_i g_\chi^2/M_{\text{mess}}^3.$$

or

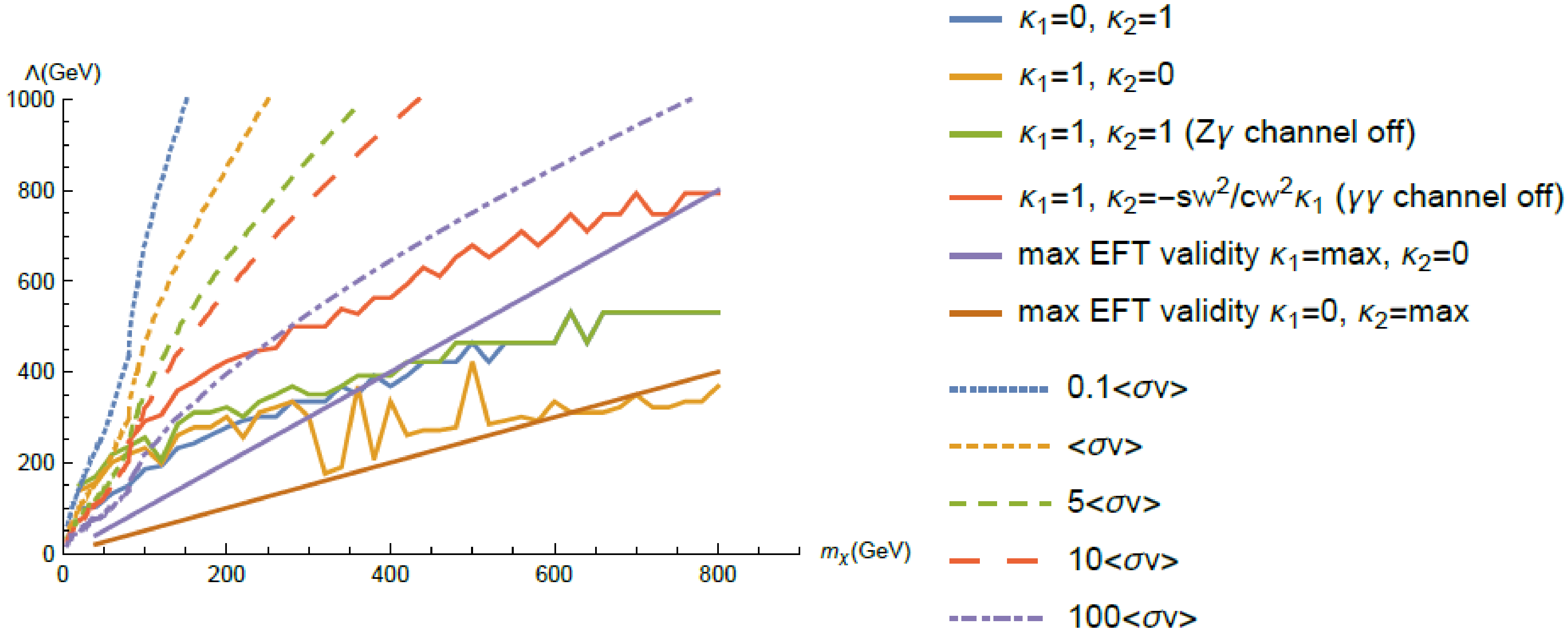
$$M_{mess} \to \Lambda \left(f\alpha_i 16\pi^2\right)^{-1/3}$$

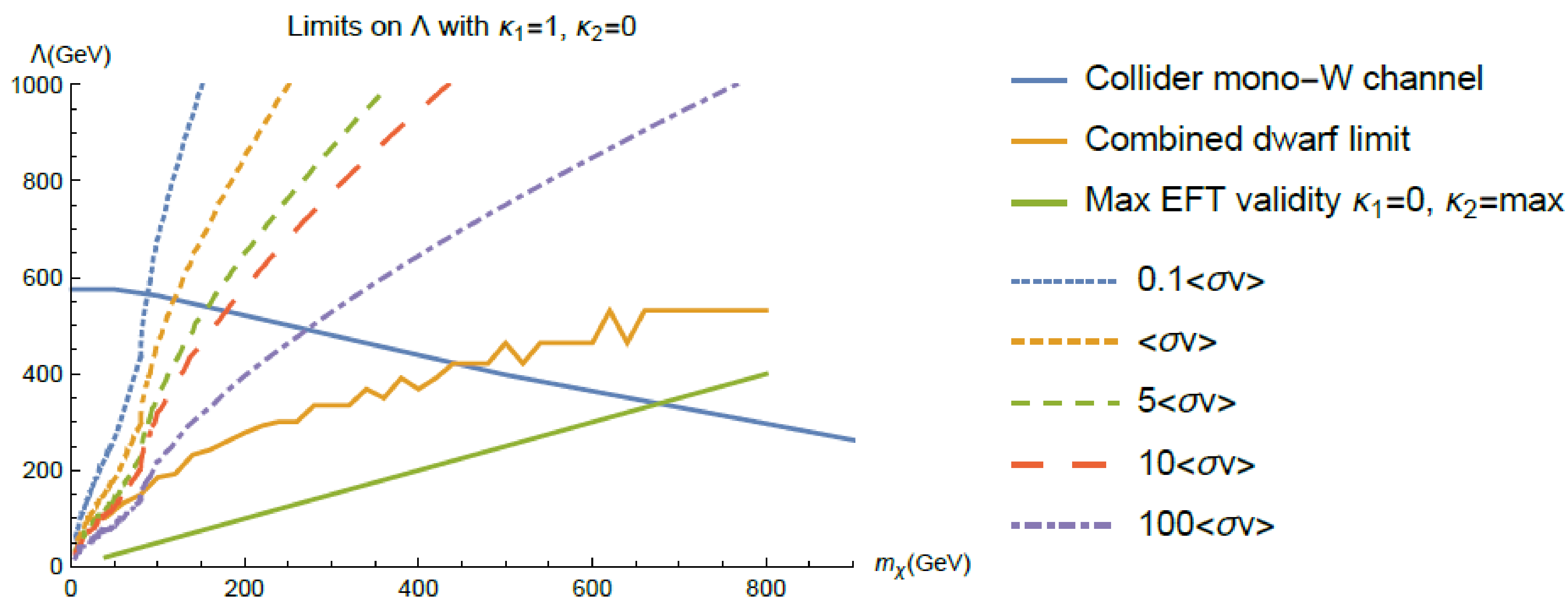
The range of validity is

$$m_\chi < \Lambda;$$

For collider validity $\sqrt{s} < 2M_{\text{mess}}$. ATLAS procedure is to set the rage of maximal validity $M_{mess} \to \Lambda \left(f\alpha_i 16\pi^2\right)^{-1/3}$ and truncate all events for which $\sqrt{s} < 2M_{\text{mess}}$. Is violated. This weakens the parameter space exclusion

Indirect and LHC Constraints





Limits on Λ with κ1=1, κ2=0
Λ(GeV)
1000
800
600
400
200
0
0
200
400
600
800
mχ(GeV)
Collider mono–W channel
Combined dwarf limit
Max EFT validity κ1=0, κ2=max
0.1<σv>
<σv>
5<σv>
10<σv>
100<σv>

High DM masses Fermi constraints place the tightest bounds

At low DM masses LHC mono-boson searches place bounds, however EFT is marginally valid.

Conclusions

We have constrained models where DM annihilates to multiple final states using Fermi dwarf galaxy analysis

We present results for EFT models where DM annihilated to fermions and also pairs of gauge bosons

We may visualize constraints on models with independent channels on triangles

We present results for gauge boson portal models on a hypersurface, as well as in parameter space with floating total annihilation rate

We find the for gauge boson portal models the dwarf analysis provides the strongest bound on models for high mass DM, and may be the best probe regions of low effective cut-off where LHC searches are invalid

Future Directions

Analysis with pass 8 data is in process

We find much stronger constraints testing fermionic EFTs

we are moving on to test well motivated models with multiple annihilation states including sets of Z' models and SUSY models with t-channel sparticles