Simplified models inspired by Indirect Detection

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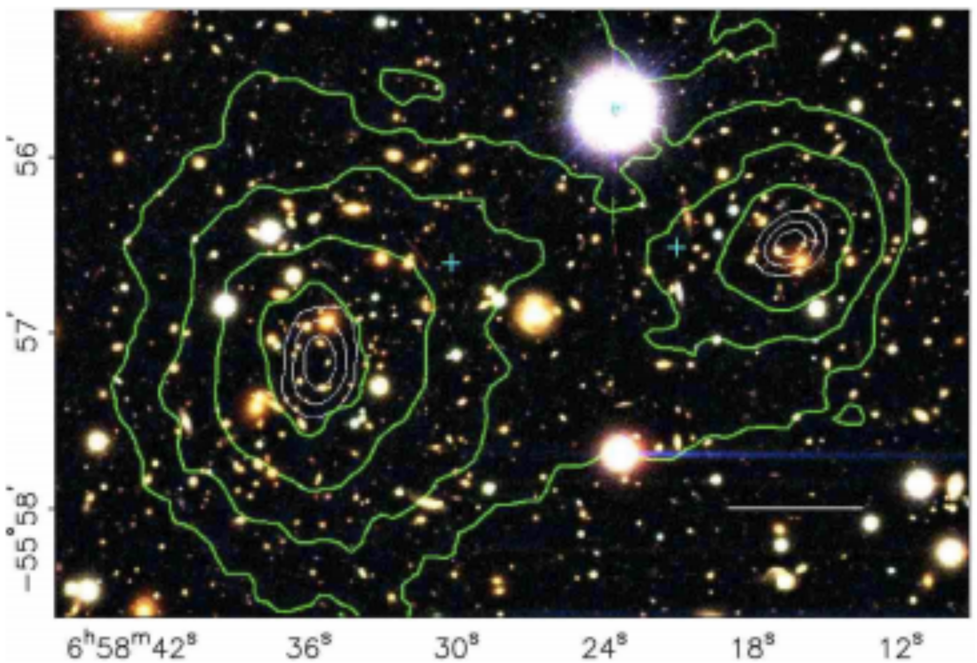
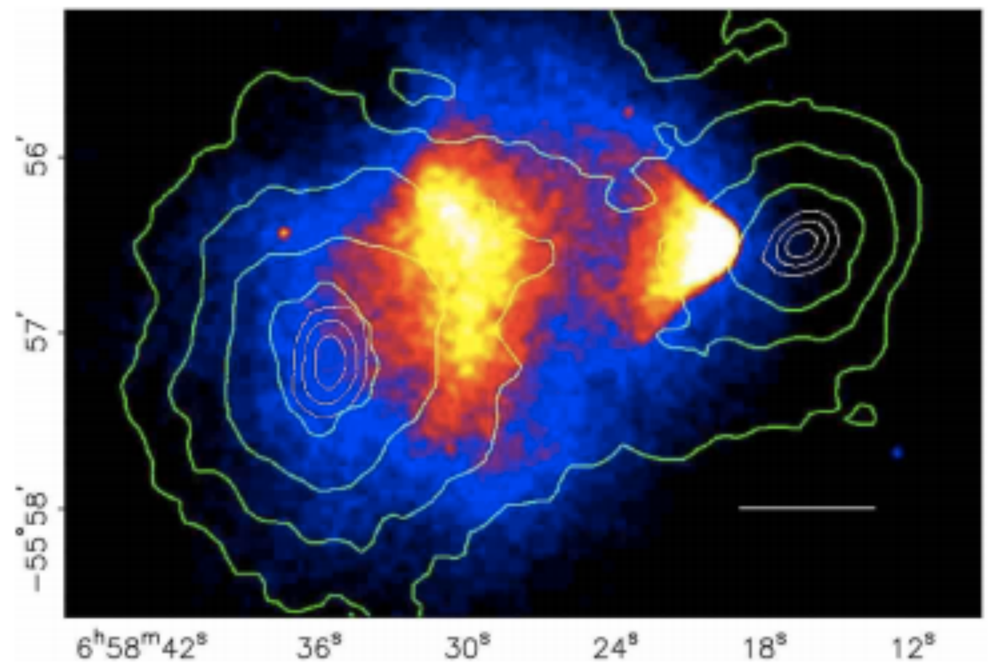
Photo credit: NASA

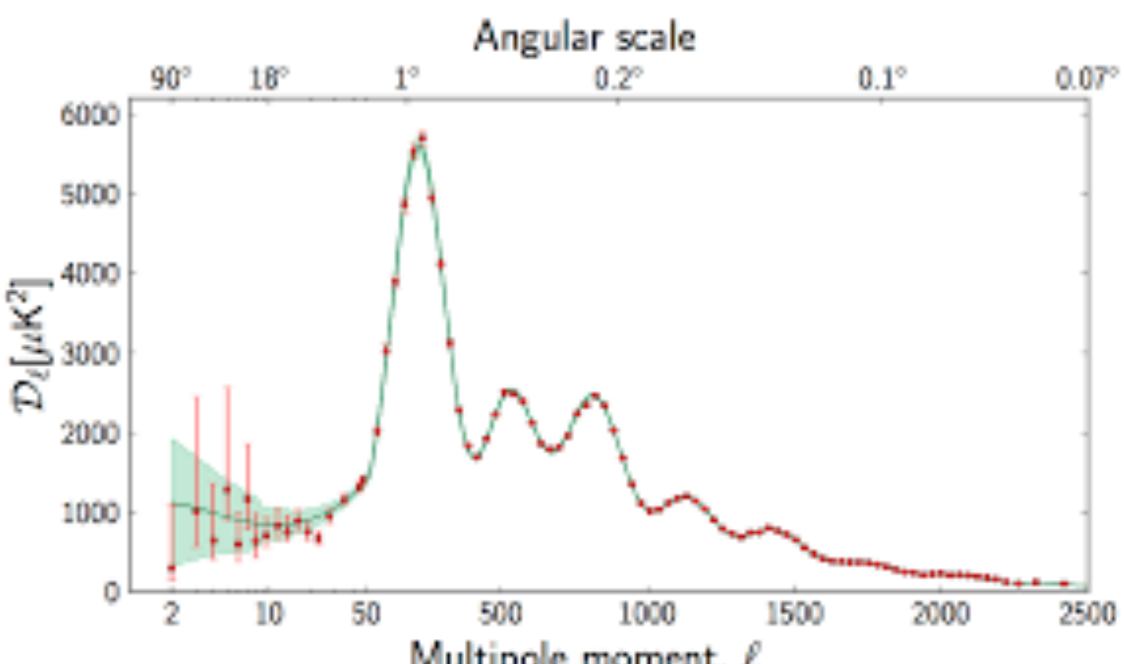
Intro

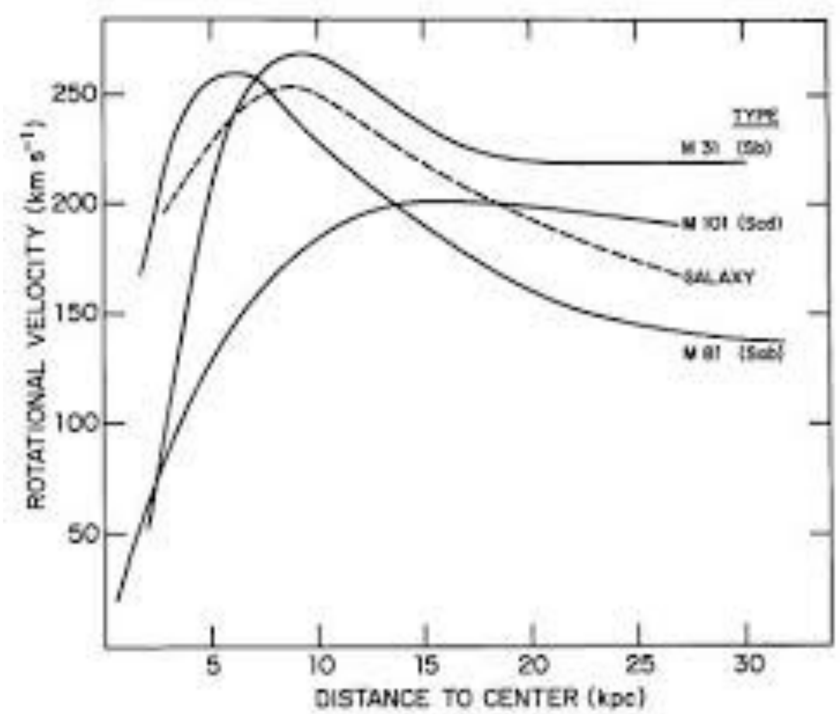
- Effective Field Theories
- Simplified Models
- Indirect Detection
- Galactic Centre Excess
- Consistent Pseudoscalar meditated Dark Matter
- New LHC Pheno

Evidence for DM





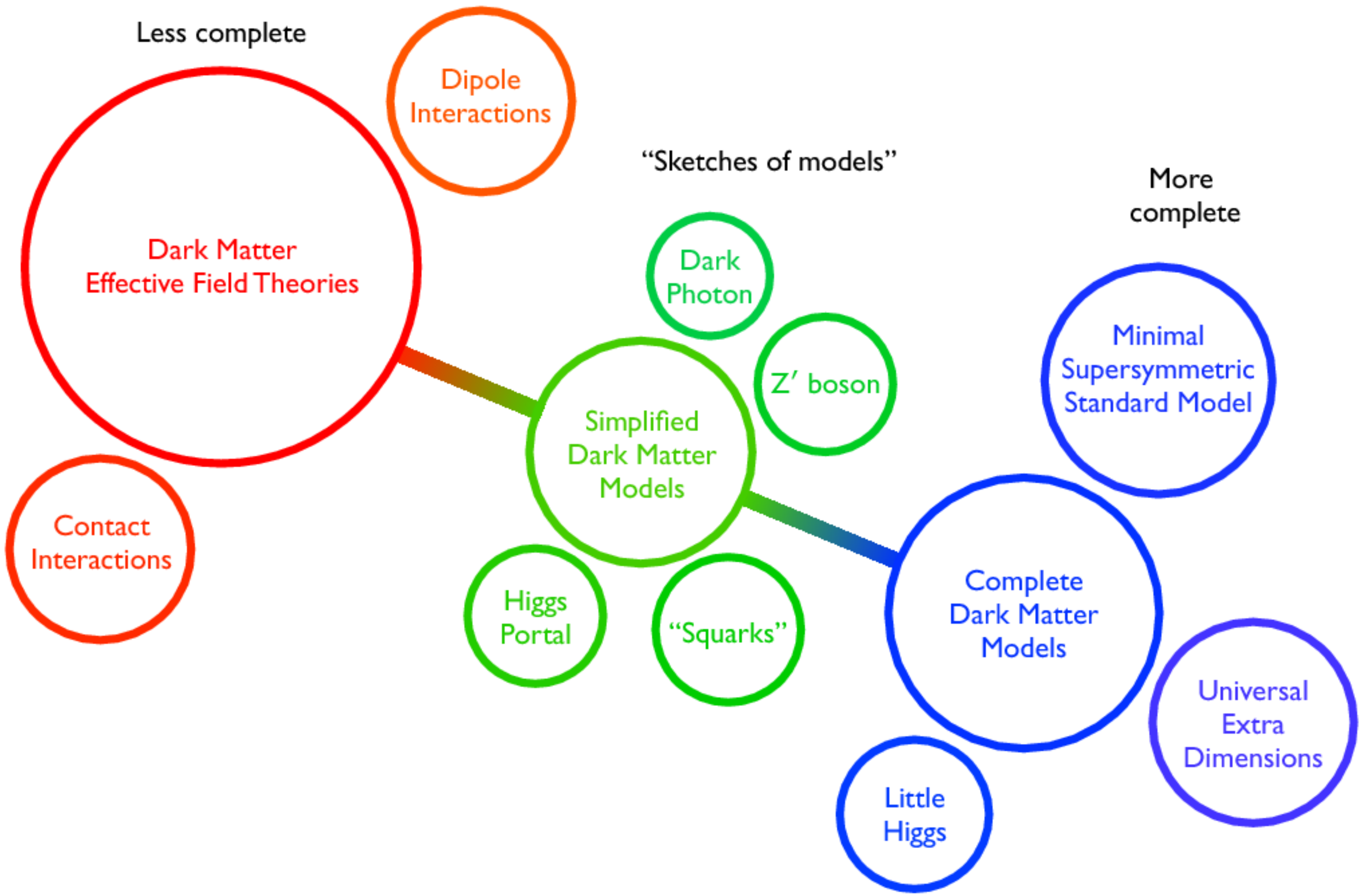




Effective Field Theories

$$\mathcal{L} = \frac{c_1}{\Lambda^2}\bar{\chi}\chi\bar{q}q + \frac{c_2}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q + ...$$

- Naively model independent
- Hidden model dependence in assuming $E < \Lambda$
- LHC may probe $E > \Lambda$



Credit: arXiv:1506.03116

Simplified Models

Solution: Introduce dynamical mediator $\phi\,,\ Z'_\mu$

$$\mathcal{L}_S = g_q\,\phi \sum_q y_q\,\bar{q}q + g_\chi\,\phi\,\chi\bar{\chi}\ ,$$

$$\mathcal{L}_P = g_q\,\phi \sum_q y_q\,\bar{q}\gamma^5 q + g_\chi\,\phi\,\chi\gamma^5\bar{\chi}\ ,$$

$$\mathcal{L}_V = g_q\,Z'_\mu \sum_q \bar{q}\gamma^\mu q + g_\chi\,Z'_\mu\,\chi\gamma^\mu\bar{\chi}\ ,$$

$$\mathcal{L}_{AV} = g_q\,Z'_\mu \sum_q \bar{q}\gamma^\mu\gamma^5 q + g_\chi\,Z'_\mu\,\chi\gamma^\mu\gamma^5\bar{\chi}$$

Indirect detection

$$\Phi = \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{dN}{dE} \frac{1}{4\pi} \int_{\text{l. o. s.}} ds\, \rho^2(s, \psi)$$

$$\sigma v = a + b v^2 + \ldots$$

s-wave

p-wave

$v_{\text{f.o.}}^2 \approx 10^{-1}$

$v_{\text{today}}^2 \approx 10^{-6}$

DM bilinear	***SM fermion bilinear***			
fermion DM	$\bar{f} f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\text{SI}} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\text{SD}} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\text{SI}} \sim q^2}$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\text{SD}} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\text{SI}} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\text{SD}} \sim v_\perp^2}$
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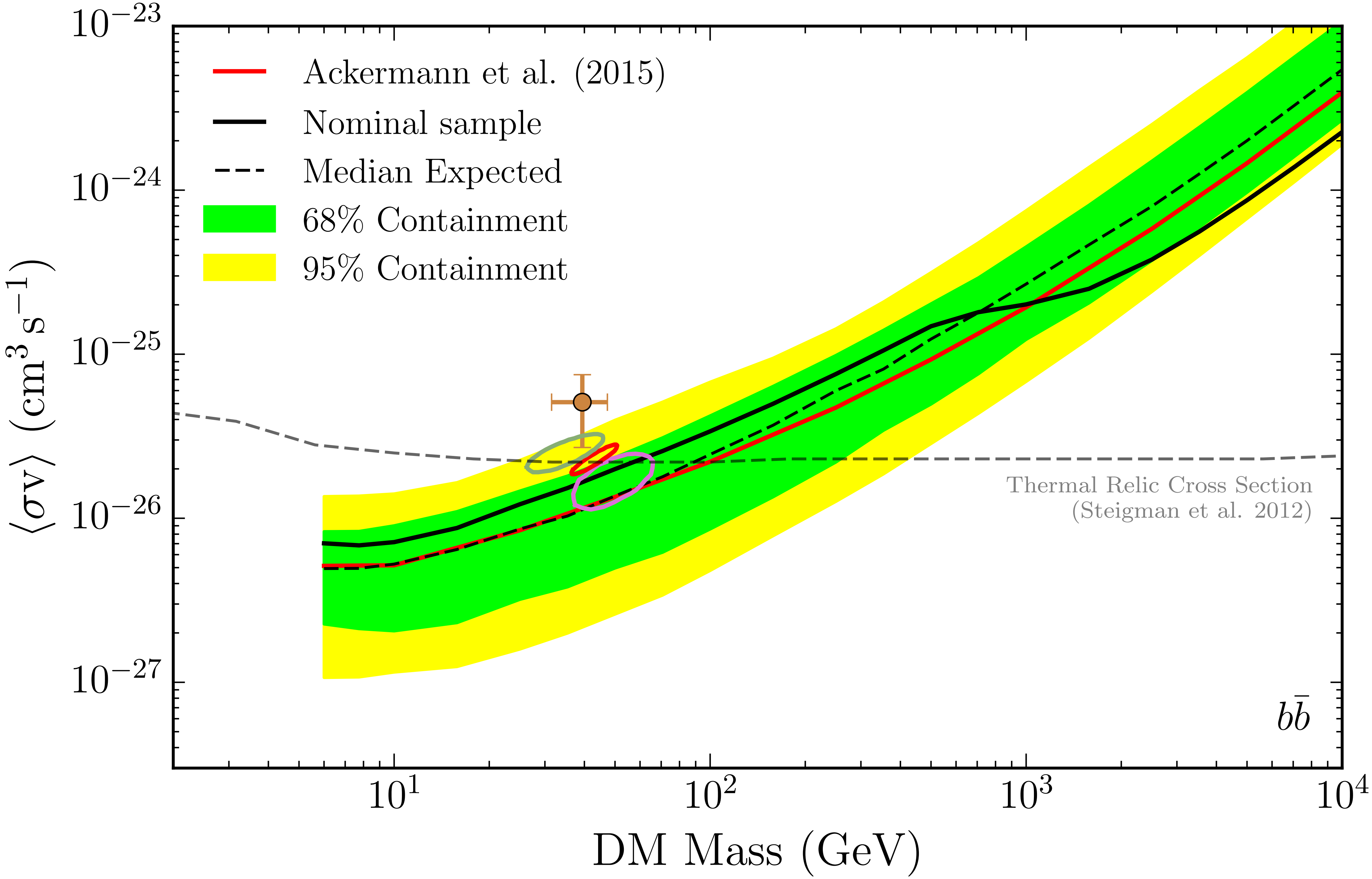
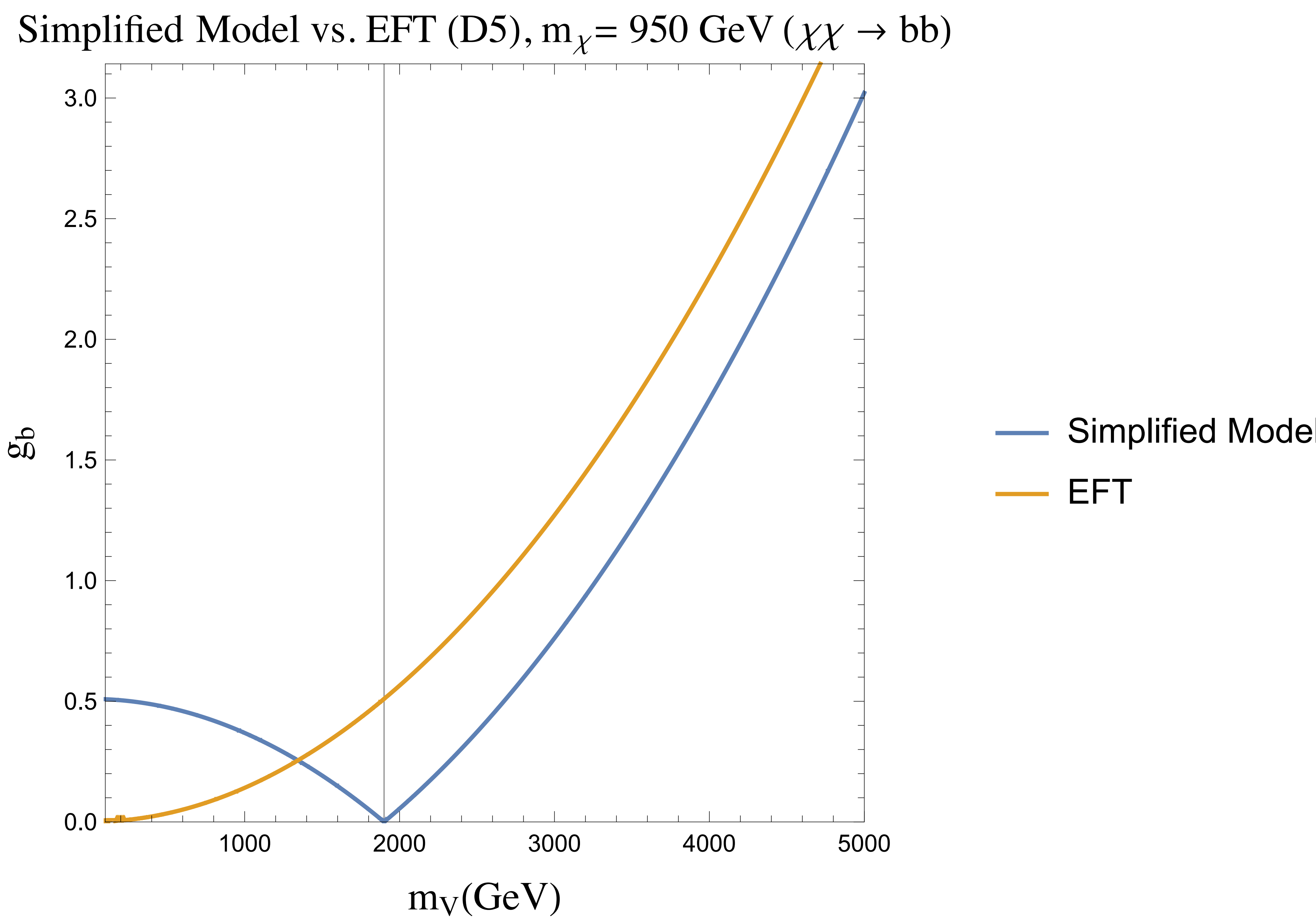
Berlin, Hooper, McDermott, arXiv:1404.0022

Limits from dSphs



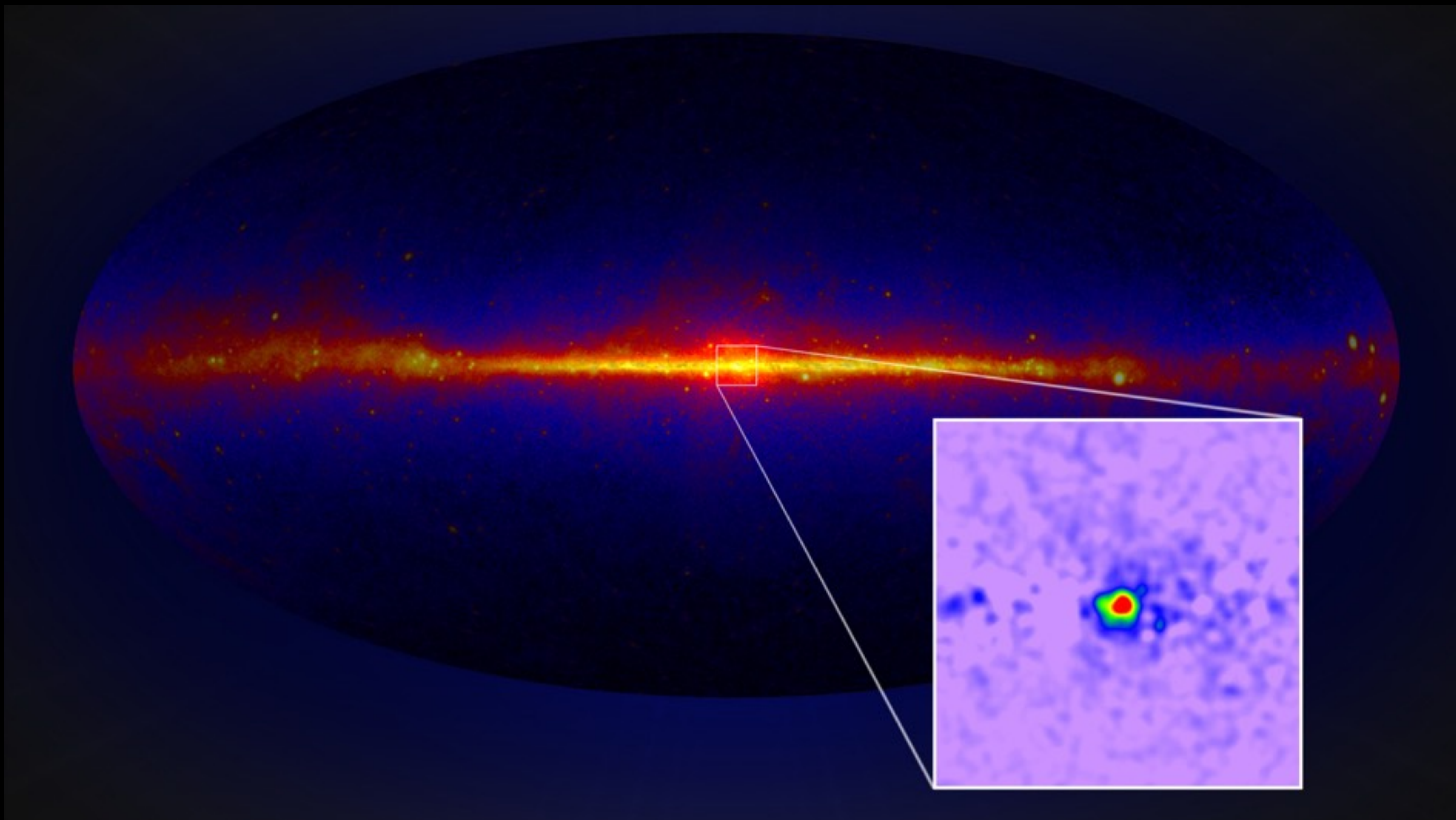
Credit: Fermi-LAT

EFT vs Simp Model



Carpenter, Colburn, Goodman, Linden arXiv:1606.04138 **Vector model, g_DM = 1**

Galactic Centre Excess



Credit: NASA/T. Linden

DM interpretation

$$m_\chi \approx 10 - 100\ GeV$$
$$\langle \sigma v \rangle \approx 0.3 - 3 \times 10^{-26}\ cm^3\ s^{-1}$$

But, now under pressure:

- Limits from dSph galaxies

  Fermi-LAT,…

- Limits looking away from the the centre of our Galaxy

  Chang, Lisanti, Mishra-Sharma, arXiv:1804.04132, …

- Unresolved point sources

Pseudoscalar mediators

DM bilinear	***SM fermion bilinear***			
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Berlin, Hooper, McDermott, arXiv:1404.0022

$$\mathcal{L} = \frac{m_{a_0}^2}{2}\, a_0^2 + m_\chi\, \bar{\chi}\chi + y_\chi\, a_0\, \bar{\chi} i\gamma^5 \chi + \sum_q y_q\, a_0\, \bar{q} i\gamma^5 q$$

Pseudoscalar mediators

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$$\mathcal{L} = \frac{m_{a_0}^2}{2}\, a_0^2 + m_\chi\, \bar{\chi}\chi + y_\chi\, a_0\, \bar{\chi} i\gamma^5\chi + \sum_q \cancel{y_q\, a_0\, \bar{q} i\gamma^5 q}$$

SU(2) X U(1) gauge invariance forbids this term

Need extended theory for consistent pseudoscalar coupling!

Ipek, McKeen & Nelson, arXiv:1404.3716
No, arXiv:1509.01110
Goncalves, Machado & No arXiv:1611.04593
Bauer, Haisch & Kahlhoefer, arXiv:1701.07427
Pani & Polesello, arXiv:1712.03874

2HDM

$$H_i = \left(\phi_i^+, (v_i + h_i + \eta_i)/\sqrt{2}\right)^T \qquad \tan\beta = \frac{v_2}{v_1}$$

Rotate to mass basis

$$A_0 = \cos\beta\,\eta_2 - \sin\beta\,\eta_1$$ **CP Odd**

$$H^\pm = \cos\beta\,\phi_2^\pm - \sin\beta\,\phi_1^\pm$$ **Charged**

$$h = \cos\alpha\,h_2 - \sin\alpha\,h_1$$ **CP Even, SM Higgs if** $\cos(\beta - \alpha) = 0$

$$H_0 = -\sin\alpha\,h_2 - \cos\alpha\,h_1$$ **CP Even**

2HDM + a

$$H_i = \left(\phi_i^+, (v_i + h_i + \eta_i)/\sqrt{2}\right)^T \qquad \tan\beta = \frac{v_2}{v_1}$$

Rotate to mass basis

$$A_0 = \cos\beta\, \eta_2 - \sin\beta\, \eta_1$$ **CP Odd**

$$H^\pm = \cos\beta\, \phi_2^\pm - \sin\beta\, \phi_1^\pm$$ **Charged**

$$h = \cos\alpha\, h_2 - \sin\alpha\, h_1$$ **CP Even, SM Higgs if** $\cos(\beta-\alpha)=0$

$$H_0 = -\sin\alpha\, h_2 - \cos\alpha\, h_1$$ **CP Even**

Mix A and a via: $V_{\rm portal} = i\, a_0\, H_1^\dagger H_2 + \text{h.c.}$

Rotate again:

$$a = c_\theta\, a_0 - s_\theta\, A_0$$

$$A = c_\theta\, A_0 + s_\theta\, a_0$$

Relic Density

s-channel a dominates for low m_a

$$\langle \sigma \mathrm{v} \rangle = \frac{y_\chi^2}{2\pi} \frac{m_\chi^2}{m_a^4} s_\theta^2 c_\theta^2 t_\beta^2 \left[\left(1 - \frac{4 m_\chi^2}{m_a^2} \right)^2 + \frac{\Gamma_a^2}{m_a^2} \right]^{-1} \times \sum_f N_C \frac{m_f^2}{v^2} \sqrt{1 - \frac{m_f^2}{m_a^2}}$$

Consistency with GCE, relic density

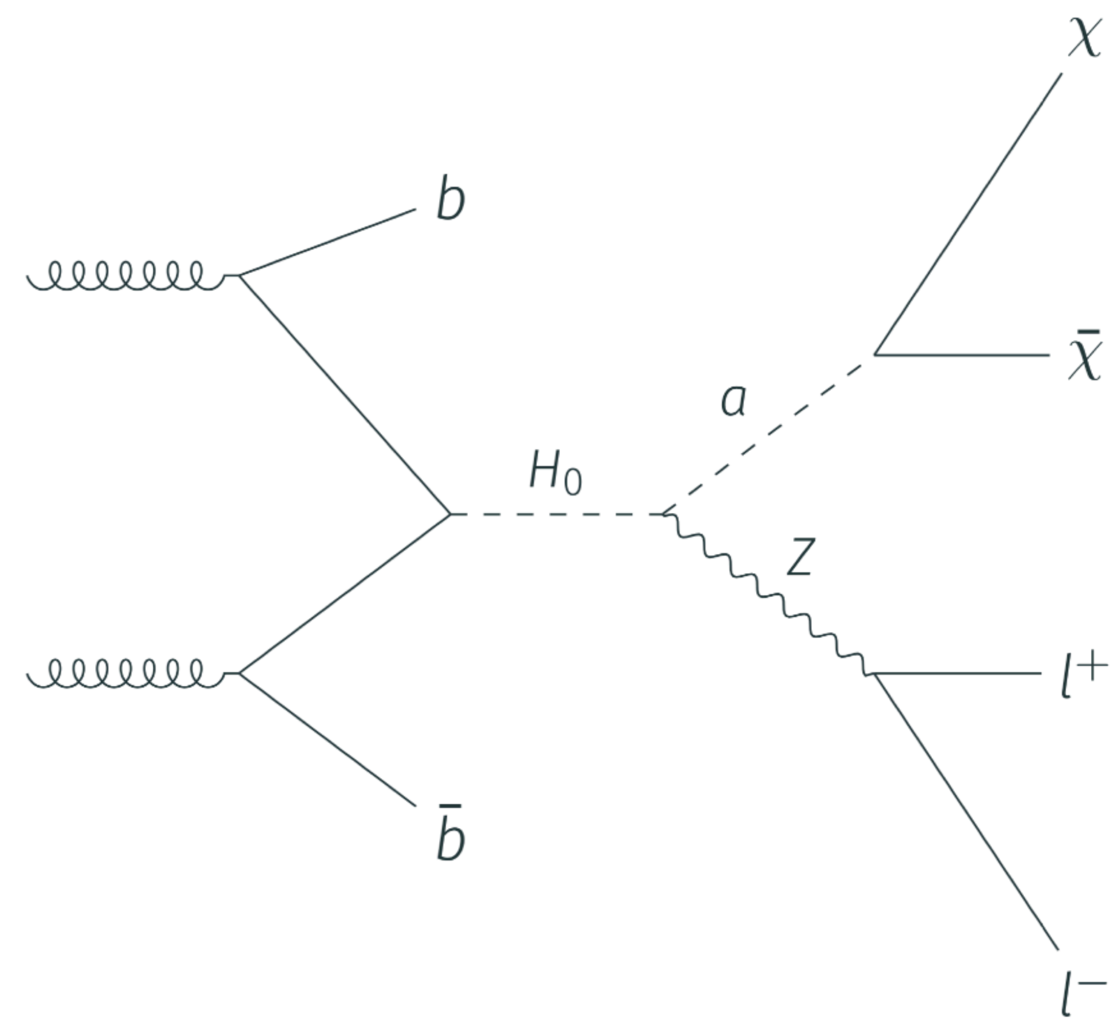
$$\langle \sigma v \rangle \approx 3 \times 10^{-26} \ cm^3 \ s^{-1}$$

$$m_\chi \approx 45 \ GeV$$

Flavour, EWP require $m_A, \, m_{H_0}, \, m_{H^\pm} \gtrsim 500 \ GeV$

Unitarity requires $m_A \leq 1.4 \ TeV, \ m_{H_0} \leq 1 \ TeV$

Episode IV: A new search



Major background: tt decaying leptonically

Cuts:

$m_{\ell\ell} \in [76, 106]$ ⟵ **ll pair from Z**

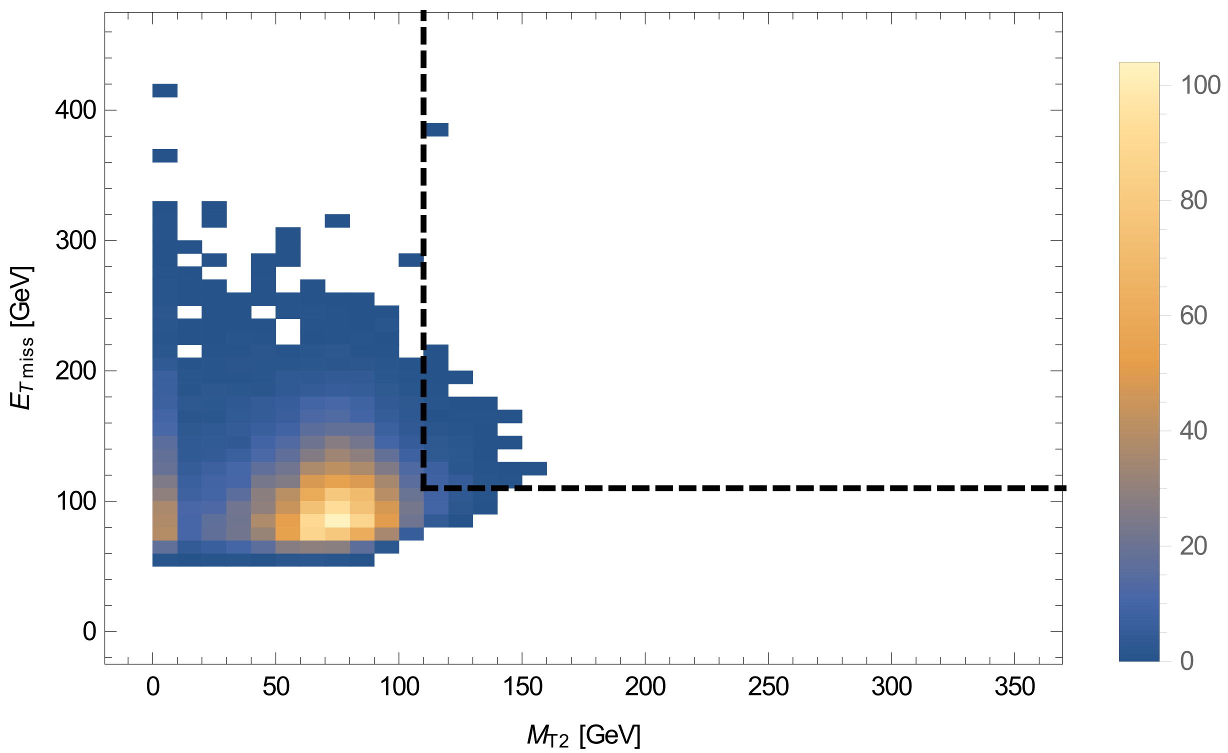
$|p_T^{\ell\ell} - \not{E}_T|/p_T^{\ell\ell} < 0.5$ ⟵ **Z and a back to back**

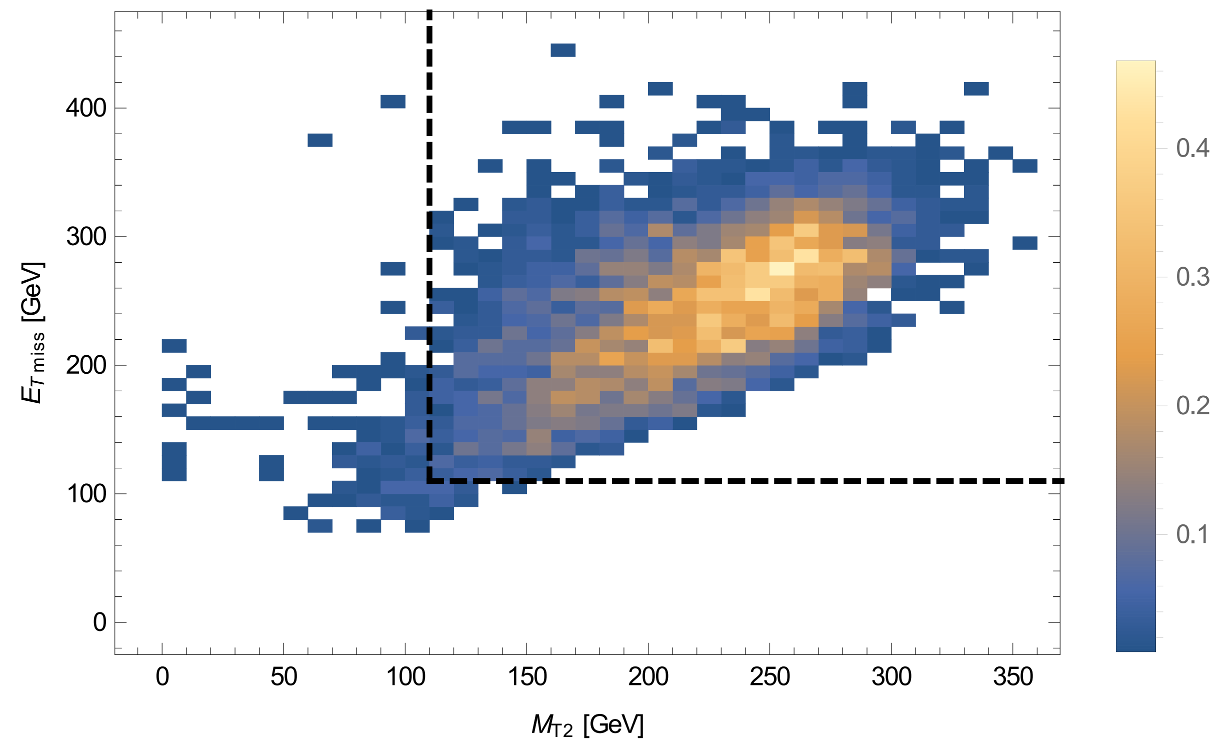
$\not{E}_T > 110\ GeV$

$m_{T2} > 110\ \mathrm{GeV}$

Next slide

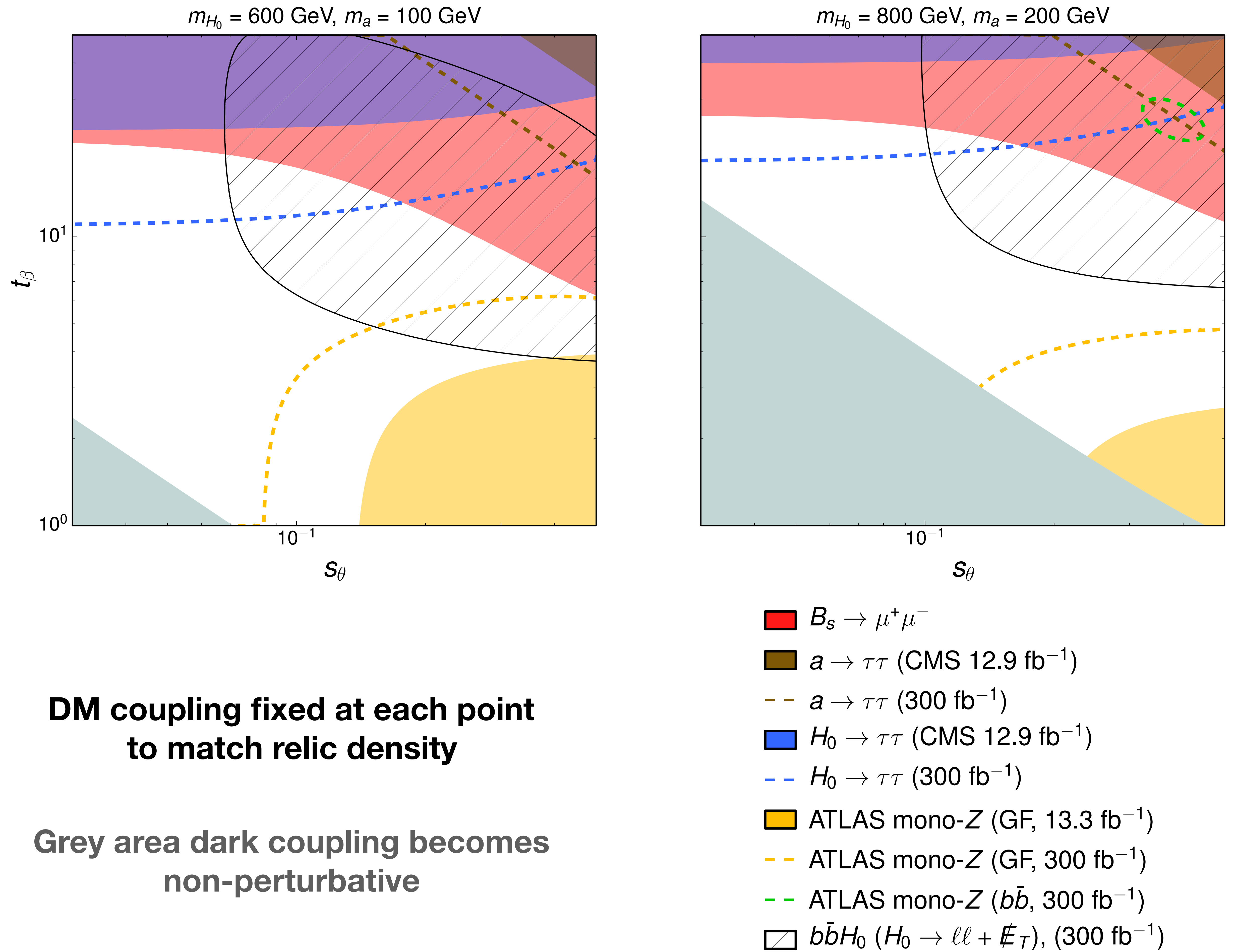
Background suppression





tt background

signal



DM coupling fixed at each point to match relic density

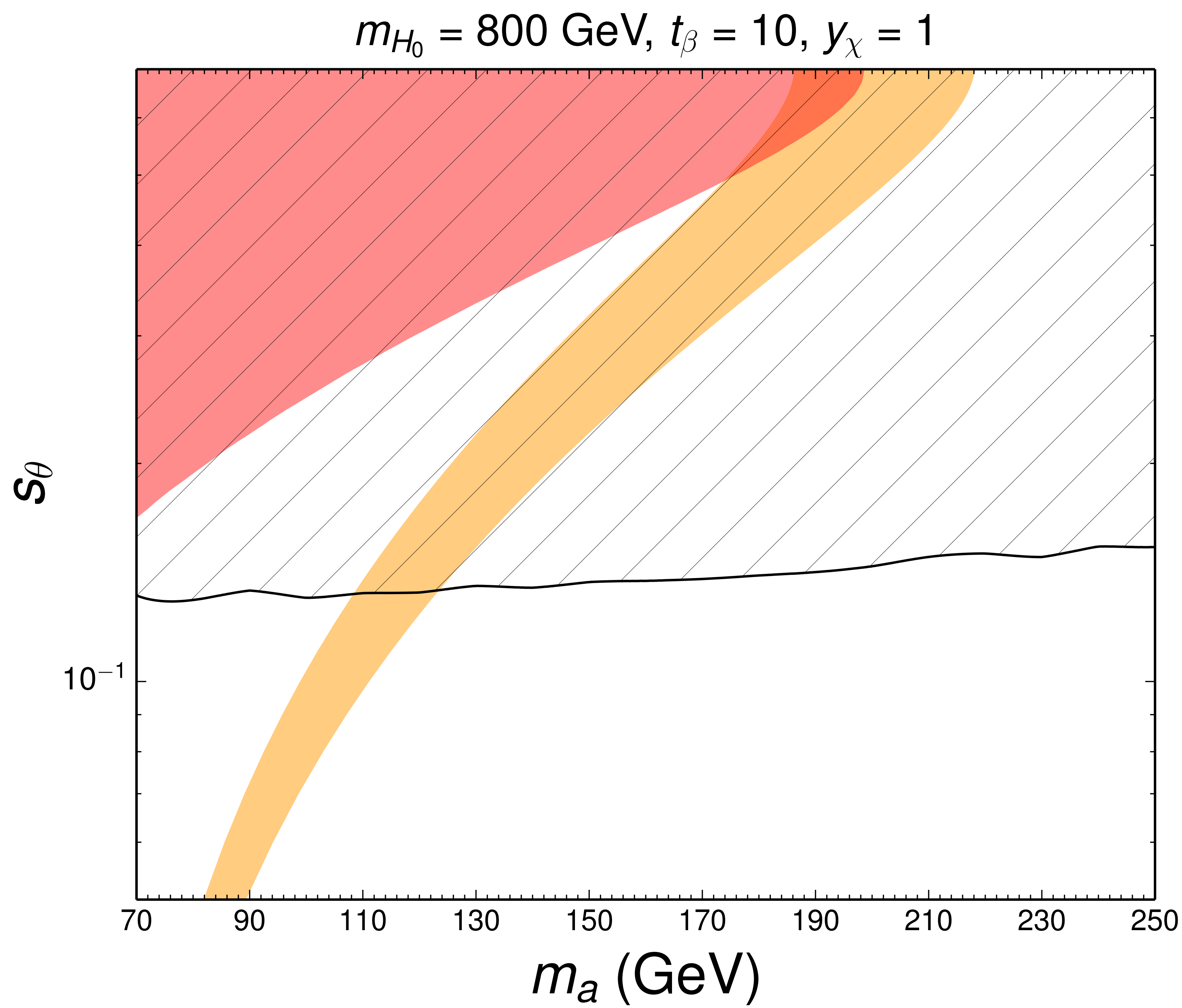
Grey area dark coupling becomes non-perturbative

Relic density requirement relaxed

Orange shows points with good relic density (+GCE)

Red is again flavour bound
$B_s \to \mu^+\mu^-$

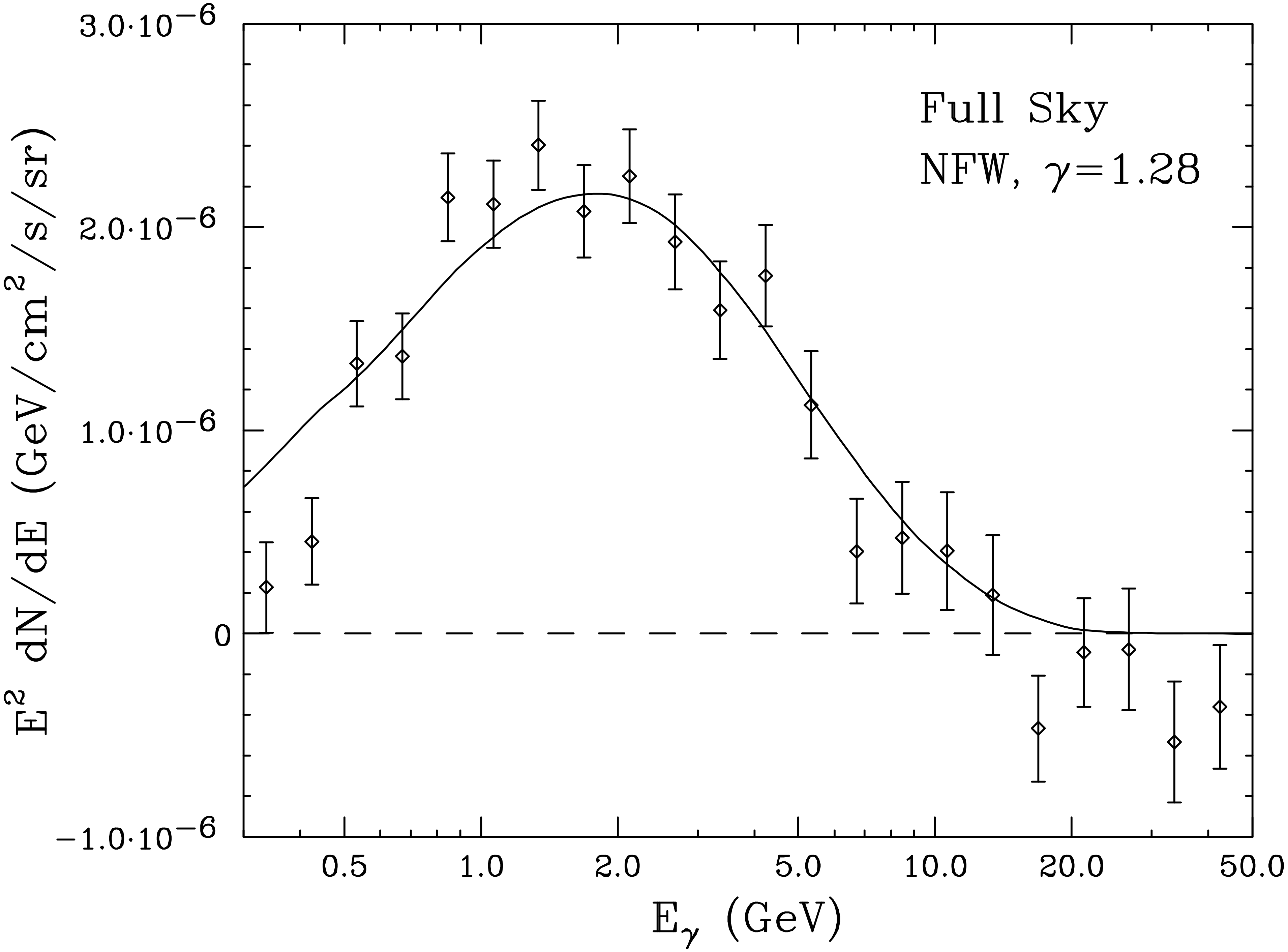
Other constraints don't reach this far!



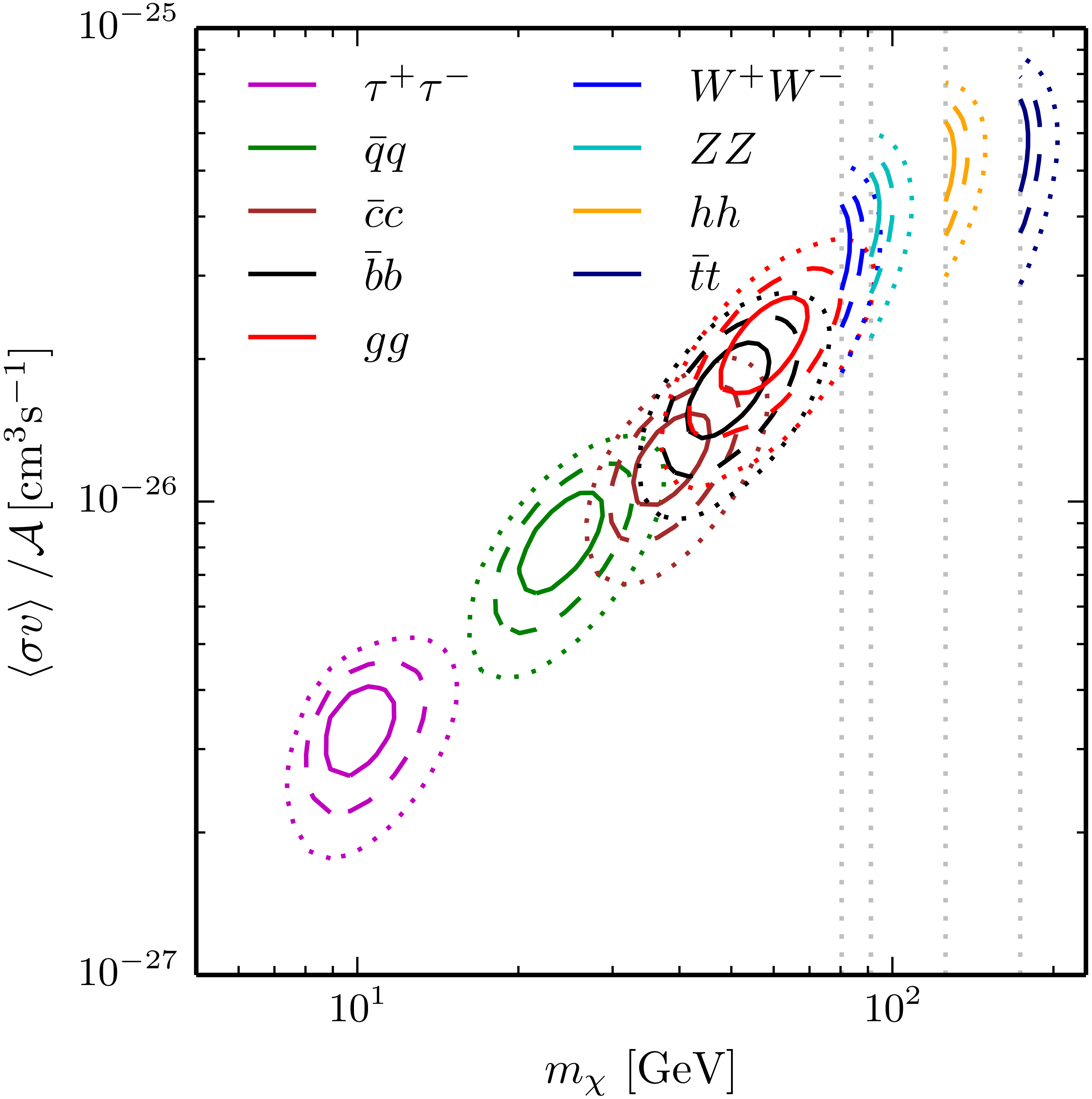
Summary

- Simplified models show resonant annihilation over EFTs
- GCE may not be dark matter but can help model build
- New LHC pheno is exciting regardless of initial motivation (GCE or gauge-invariance)

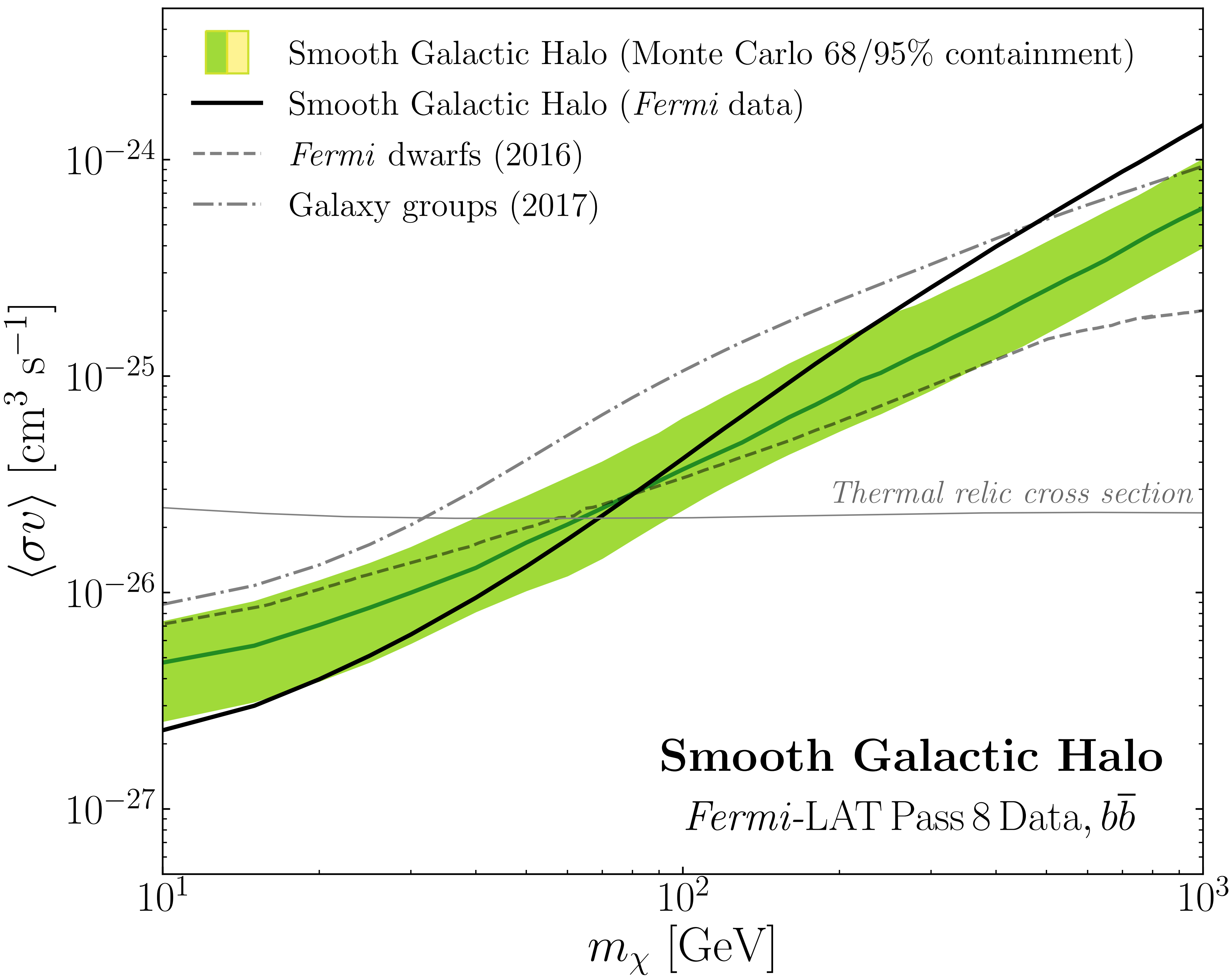
BACKUP



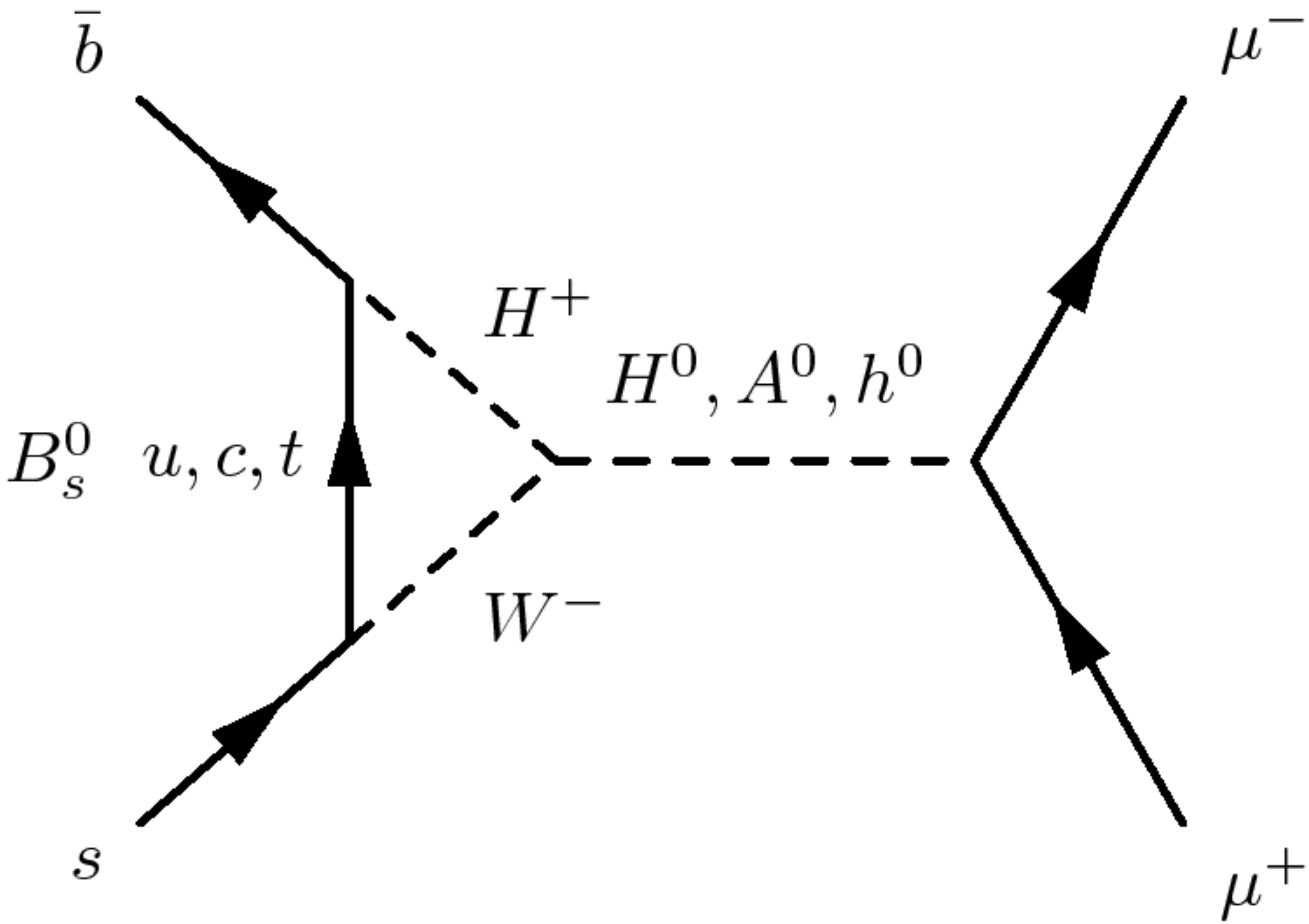
arXiv:1402.6703



arXiv:1411.4647



arXiv:1804.04132


$\bar{b}$
μ^-
H^+
H^0, A^0, h^0
B_s^0
u, c, t
W^-
s
μ^+

We calculate m_{T2} as

$$m_{T2}^2 \equiv \min_{\vec{k_T}+\vec{q_T}=\vec{\not{p}_T}} \left\{ \max \left[m_T^2(\vec{p_T^{\ell+}}, \vec{k_T}), m_T^2(\vec{p_T^{\ell-}}, \vec{q_T}) \right] \right\} \tag{1}$$

where the minimisation is over all possible vectors $\vec{k_T}$ and $\vec{q_T}$ that satisfy $\vec{k_T} + \vec{q_T} = \vec{\not{p}_T}$

Evolution from EFTs through simplified models to ... ?