Title: Dark Matter from Minimal Flavor Violation

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Abstract: Stability on cosmological time scales constitutes one of the few robust guiding principles in the formulation of a theory of dark matter. This suggests the existence of a stabilizing symmetry associated to dark matter. I will explore several examples of stabilizing symmetries beyond the canonical Z_2 parity, such as Abelian Z_N discrete gauge symmetries, Non-Abelian discrete symmetries, and flavor symmetries.

Dark Matter from Minimal Flavor Violation

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The University of Chicago

with Josef Pradler & Michael Spannowsky

JHEP 1108:038,2011 [arXiv:1105.1781]

Unravelling Dark Matter
September 23, 2011

Related work on flavored dark matter:

- Kile, Soni arXiv:1104.5239
- Kamenik, Zupan arXiv:1107.0623
- Agrawal, Blanchet, Chacko, Kilic arXiv:1109.3516

Generic phenomenological problems in BSM

- B, L violation
- Flavor, CP violation
- Electroweak precision

Impose symmetries to forbid dangerous terms!

Discrete Symmetry (e.g. R-, T-, KK- parity)

- B, L violation
- Flavor, CP violation
- Electroweak precision

Side effect: lightest odd particle stable DM candidate

Minimal Flavor Violation

Flavor symmetry broken only by SM Yukawas

- B, L violation
- **Flavor, ~~CP~~ violation**
- Electroweak precision

Can MFV provide a DM candidate?

MFV in a nutshell

D' Ambrosio et al. '02

$$-\mathcal{L}_Y \supset \bar{Q} Y_d d_R H + \bar{Q} Y_u u_R H^\dagger + \text{h.c.},$$

In the limit $Y_{u,d} \to 0$ SM quark sector exhibits large global flavor symmetry:

$$G_q = SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$$

MFV Hypothesis:

In the presence of new physics, the SM Yukawas are the only source of flavor breaking

→ Built-in protection against large FCNCs

Basic Idea: Give Dark Matter Flavor!

Add new matter multiplet χ :

- color singlet
- contains electrically neutral component
- transforms nontrivially under G_q

$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R},$$

For which reps is χ stable, if MFV is imposed?

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Flavored matter

- Manohar, Wise '06
- Grossman, Nir, Thaler, Volansky, Zupan '07
- Burgess, Trott, Zuberi '09
- Bauer, Ligeti, Schmaltz, Thaler, Walker '09
- Arnold, Pospelov, Trott, Wise '09
- Gross, Grossman, Nir, Vitells '10
- Arnold, Fornal, Trott '10

- Buras, Carlucci, Gori, Isidori '10
- Trott, Wise '10

→ B-meson anomalies

- Grinstein, Kagan, Trott, Zupan '11 & '11
- Ligeti, Schmaltz, Tavares '11

→ Top quark forward-backward asymmetry

Stability:

$$\mathcal{O}_{\rm decay} = \chi\, \underbrace{Q\ldots}_{A}\underbrace{\bar{Q}\ldots}_{B}\underbrace{u_R\ldots}_{C}\underbrace{\bar{u}_R\ldots}_{D}\underbrace{d_R\ldots}_{E}\underbrace{\bar{d}_R\ldots}_{F}$$
$$\times \underbrace{Y_u\ldots}_{G}\underbrace{Y_u^\dagger\ldots}_{H}\underbrace{Y_d\ldots}_{I}\underbrace{Y_d^\dagger\ldots}_{J}\,\mathcal{O}_{\rm weak},$$

For each $SU(3)_i$, with $i = c, Q, u_R, d_R$,

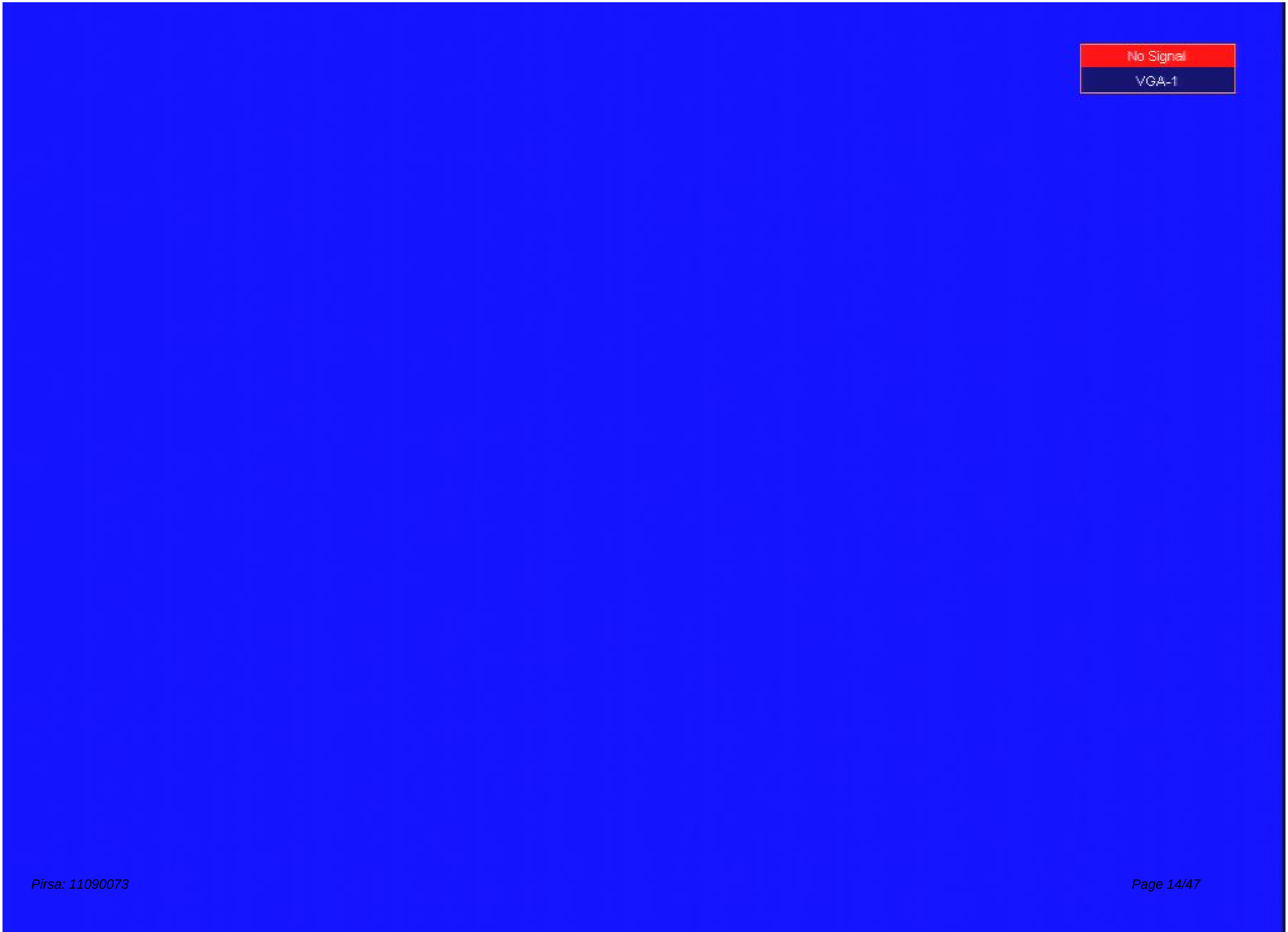
$\mathcal{O}_{\rm decay}$ regarded as tensor product $(p,q)_i$

$\mathcal{O}_{\rm decay}$ is a singlet under color and flavor only if triality vanishes:

$$t_i \equiv (p-q)_i \bmod 3 = 0, \quad i = c,\, Q,\, u_R,\, d_R.$$

No Signal

VGA-1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$t_Q + t_{u_R} + t_{d_R} - t_c = 0$ ➡ $\mathcal{O}_{\text{decay}}$ is allowed only if

$$(n-m) \bmod 3 = 0$$

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Lowest Dimensional Reps:

(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$	Yes
(2,0)	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$	Yes
(0,2)	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$ $(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$	Yes
(1,1)	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$ $(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$	

Many possible models of flavored dark matter!

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Many possible models of flavored dark matter!

Example: $SU(3)_Q$ triplet, gauge singlet, scalar

$$S \sim (\mathbf{1}, \mathbf{1}, 0)_{\mathrm{SM}} \times (\mathbf{3}, \mathbf{1}, \mathbf{1})_{G_q}$$

Spectrum &
Mixing with SM Higgs

$$\mathcal{L} = \partial^\mu S_i^* \partial_\mu S_i - V(S_i, H) + \mathcal{L}_{\mathrm{eff}},$$

Effective operators
coupling DM to SM quarks

Scalar potential:

$$V \supset m_S^2 S_i^* (a\,\mathbf{1}_{ij} + b\,(Y_u Y_u^\dagger)_{ij} + \ldots) S_j$$
$$+ 2\lambda\, S_i^* (a' \mathbf{1}_{ij} + b' (Y_u Y_u^\dagger)_{ij} + \ldots) S_j\, H^\dagger H,$$

MFV allows insertions of Yukawa Spurions

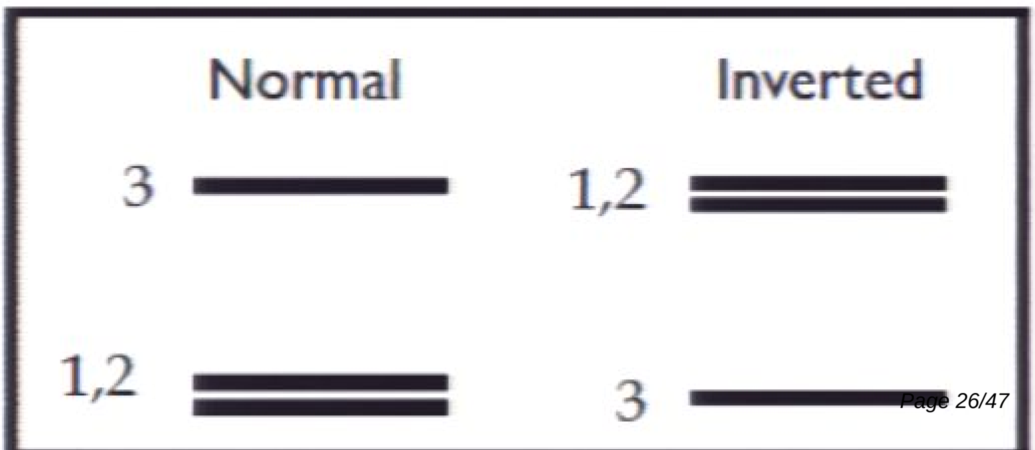
Rotate to background values: $Y_d = \lambda_d, \quad Y_u = V^\dagger \lambda_u$

Diagonalize: $S \to V^\dagger S$

Spectrum:

$$m_1^2 \simeq m_2^2 \simeq m_A^2,$$

$$m_3^2 \simeq m_A^2 + m_B^2 y_t^2$$



Work in EFT:

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}\sum_{I=1}^{5} c^I_{ijk\ell}\mathcal{O}^I_{ijk\ell}$$

$$\begin{aligned}
\mathcal{O}^1_{ijk\ell} &= (\bar{Q}_i\gamma^\mu Q_j)(S^*_k \overleftrightarrow{\partial_\mu} S_\ell),\\
\mathcal{O}^2_{ijk\ell} &= (\bar{u}_{Ri}\gamma^\mu u_{Rj})(S^*_k \overleftrightarrow{\partial_\mu} S_\ell),\\
\mathcal{O}^3_{ijk\ell} &= (\bar{d}_{Ri}\gamma^\mu d_{Rj})(S^*_k \overleftrightarrow{\partial_\mu} S_\ell),\\
\mathcal{O}^4_{ijk\ell} &= (\bar{Q}_i u_{Rj})(S^*_k S_\ell)H^\dagger + \text{h.c.},\\
\mathcal{O}^5_{ijk\ell} &= (\bar{Q}_i d_{Rj})(S^*_k S_\ell)H + \text{h.c.},
\end{aligned}$$

$c^I_{ijk\ell}$ include all possible MFV flavor structures

e.g.

$$\begin{aligned}
c^1_{ijk\ell} &= c^1_1 \mathbf{1}_{ij}\mathbf{1}_{k\ell} + c^1_2 \mathbf{1}_{i\ell}\mathbf{1}_{kj} + c^1_3 (Y_u Y_u^\dagger)_{ij}\mathbf{1}_{k\ell}\\
&+ c^1_4 \mathbf{1}_{ij}(Y_u Y_u^\dagger)_{k\ell} + c^1_5 (Y_u Y_u^\dagger)_{i\ell}\mathbf{1}_{kj}\\
&+ c^{1*}_5 \mathbf{1}_{i\ell}(Y_u Y_u^\dagger)_{kj} + \ldots,
\end{aligned}$$

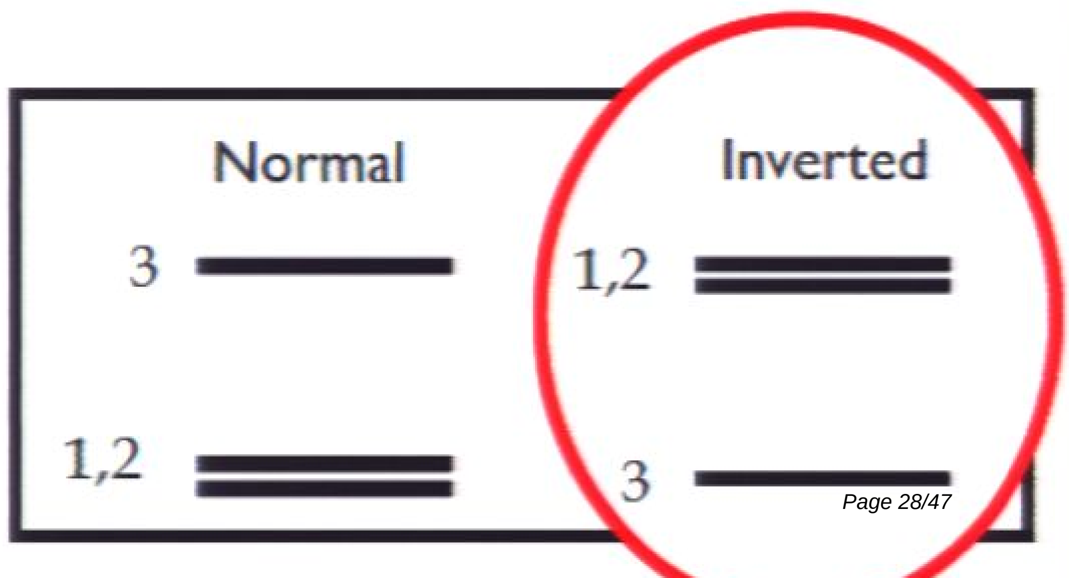
Focus on one operator, one flavor structure:

$$\mathcal{L}_{\rm eff} = \frac{c}{\Lambda^2}[\bar{Q}_i S_i][S_j^*(Y_d)_{jk} d_{Rk}]H + \text{h.c}$$

After EWSB and diagonalization:

$$\mathcal{L}_{\rm eff} \to \frac{c}{\Lambda^2}\frac{v}{\sqrt{2}}[\bar{d}_{Li} V_{ij}^\dagger S_j][S_k^*(V\lambda_d)_{k\ell} d_{R\ell}] + \text{h.c.}\ .$$

Focus on inverted spectrum → S_3 is the DM candidate



Relic Abundance:

$$\mathcal{L}_{\rm eff} \supset \frac{c}{\Lambda^2} m_b |V_{tb}|^2 S_3^* S_3 \bar{b}_L b_R + \text{h.c.} + \ldots$$

Dominant annihilation mode: $S_3 S_3^\dagger \to \bar{b}b$

$$\langle \sigma v \rangle_{33\to\bar{b}b} = \frac{3}{4\pi\Lambda^4} m_b^2 |V_{tb}|^4 \left(1 - \frac{m_b^2}{m_3^2}\right)^{1/2} \times \left\{ [\text{Re}(c)]^2 \left(1 - \frac{m_b^2}{m_3^2}\right) + [\text{Im}(c)]^2 \right\}.$$

$$\langle \sigma v \rangle_{33\to\bar{b}b} \simeq 1\,\text{pb} \left(\frac{200\,\text{GeV}}{\Lambda}\right)^4,$$

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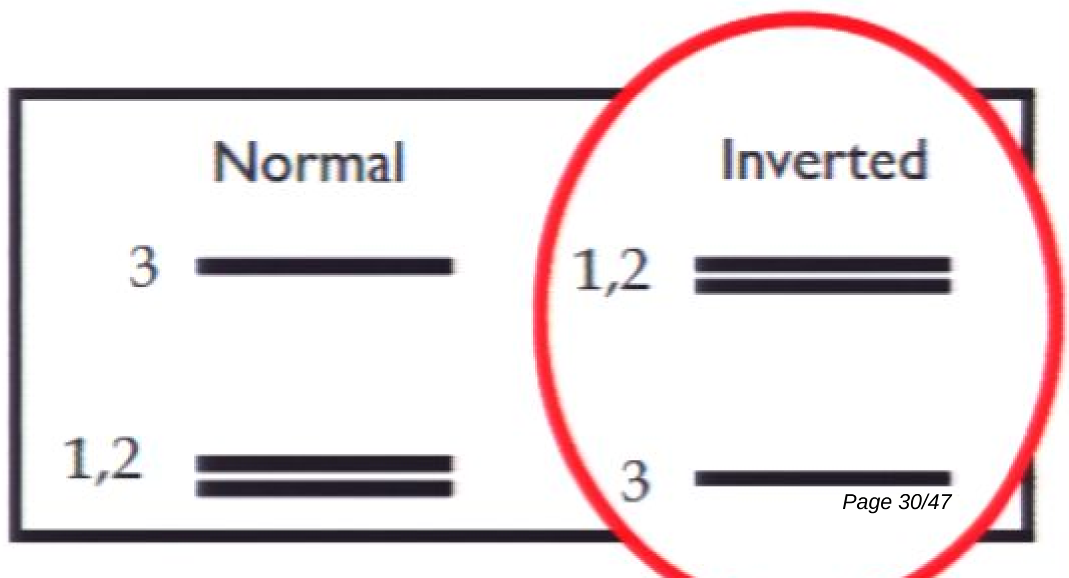

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Direct Detection:

$$\mathcal{L}_{\text{eff}} \supset \frac{\text{Re}(c)}{\Lambda^2} \sum_{i=1}^{3} m_{d_i} |V_{3i}|^2 S_3^* S_3 \bar{d}_i d_i .$$

note CKM suppression for 1st, 2nd generation

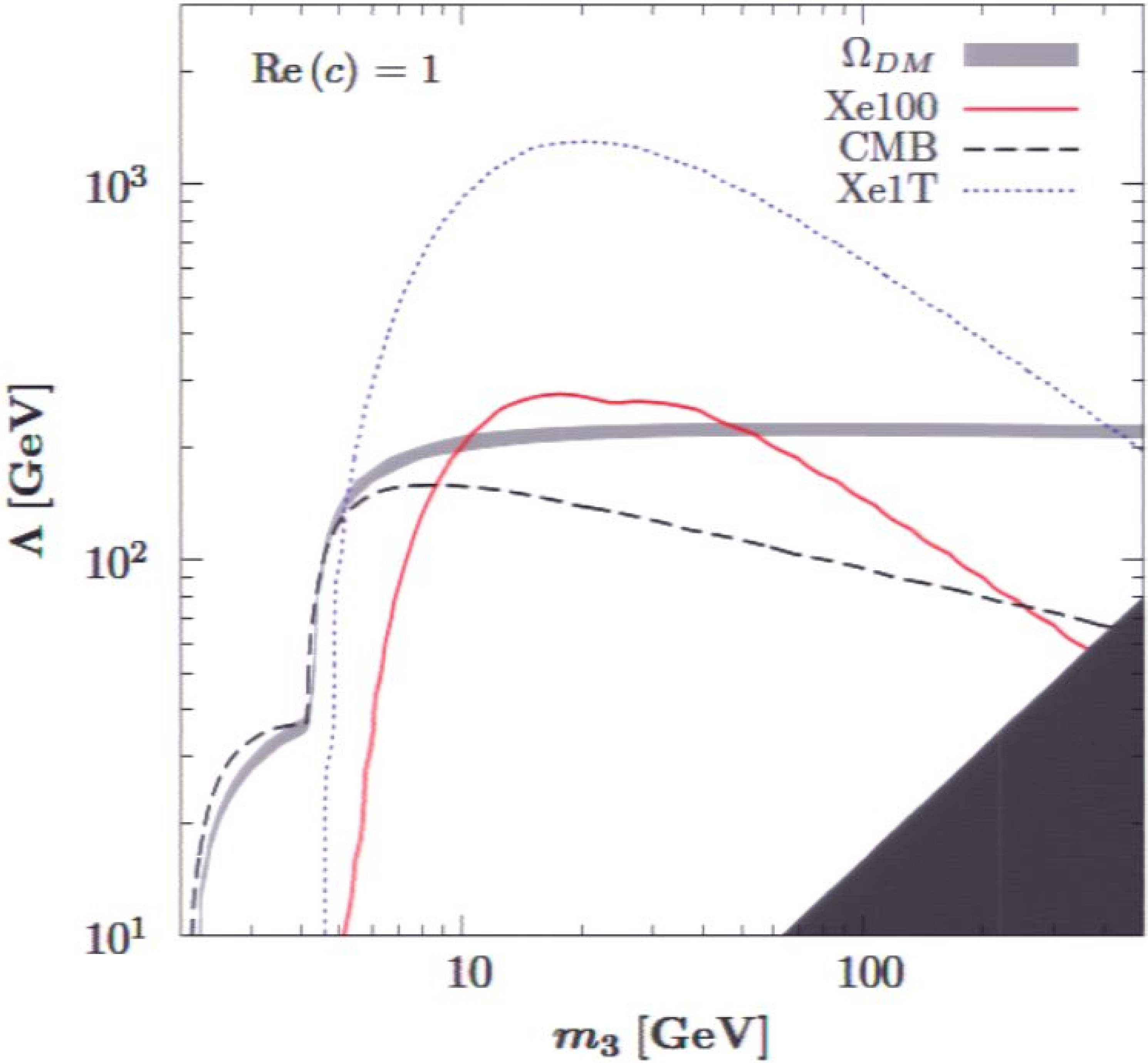
only b - quark content in nucleon relevant for scattering

$$f_{n,b} \equiv \langle n | m_b \bar{b} b | n \rangle = m_n \frac{2}{27} f_{TG}^{(n)} \simeq 0.04,$$

SI DM-nucleon scattering cross section

$$\sigma_n = \frac{[\text{Re}(c)]^2 |V_{tb}|^2 f_{n,b}^2 \mu_n^2}{4\pi m_3^2 \Lambda^4}$$

$$\simeq 3 \times 10^{-43}\,\text{cm}^2\,[\text{Re}(c)]^2 \left(\frac{10\,\text{GeV}}{m_3}\right)^2 \left(\frac{200\,\text{GeV}}{\Lambda}\right)^4 .$$



Re (c) = 1
Ω_{DM}
Xe100
CMB
Xe1T
10^3
10^2
10^1
Λ [GeV]
10
100
m_3 [GeV]

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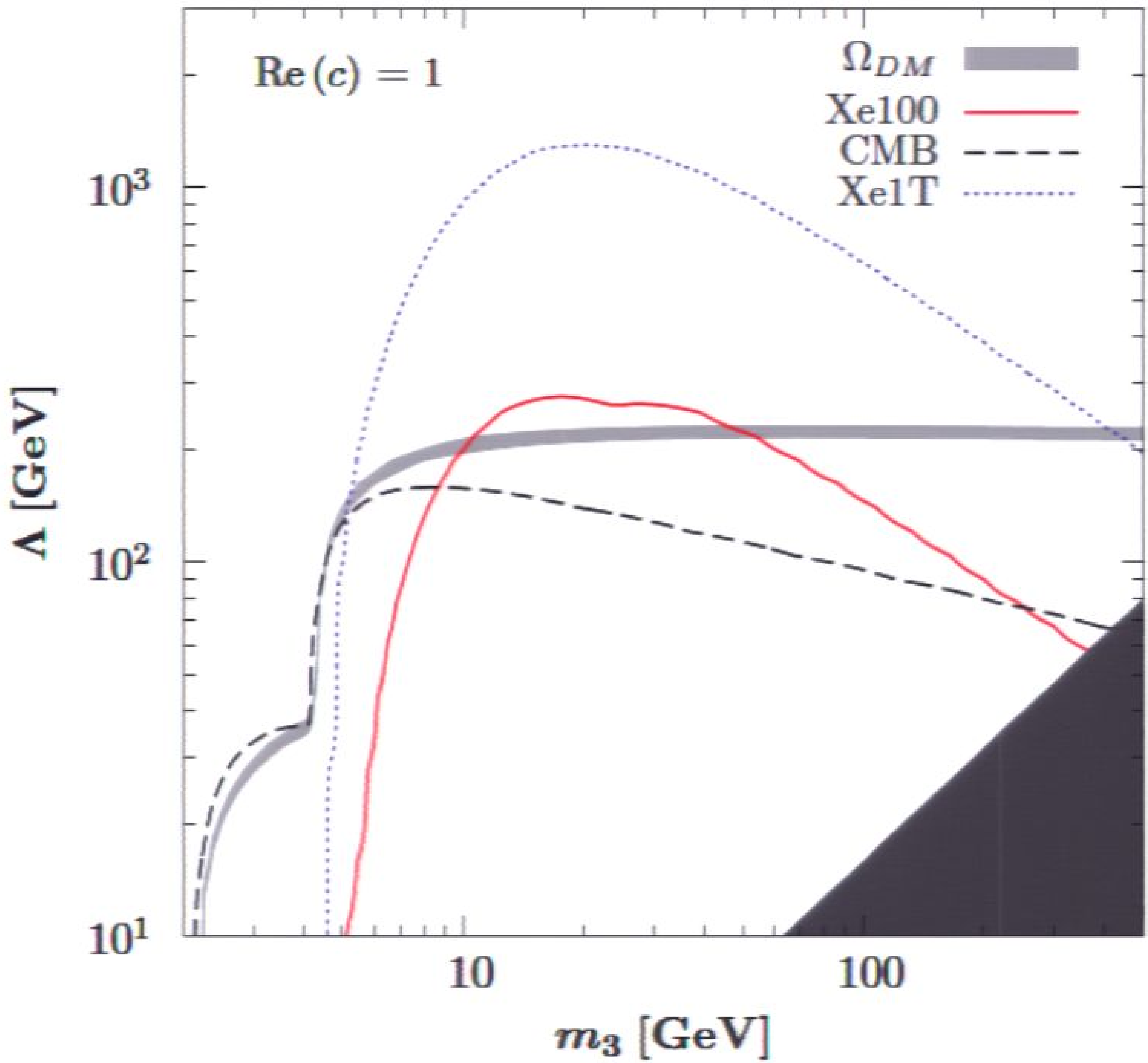
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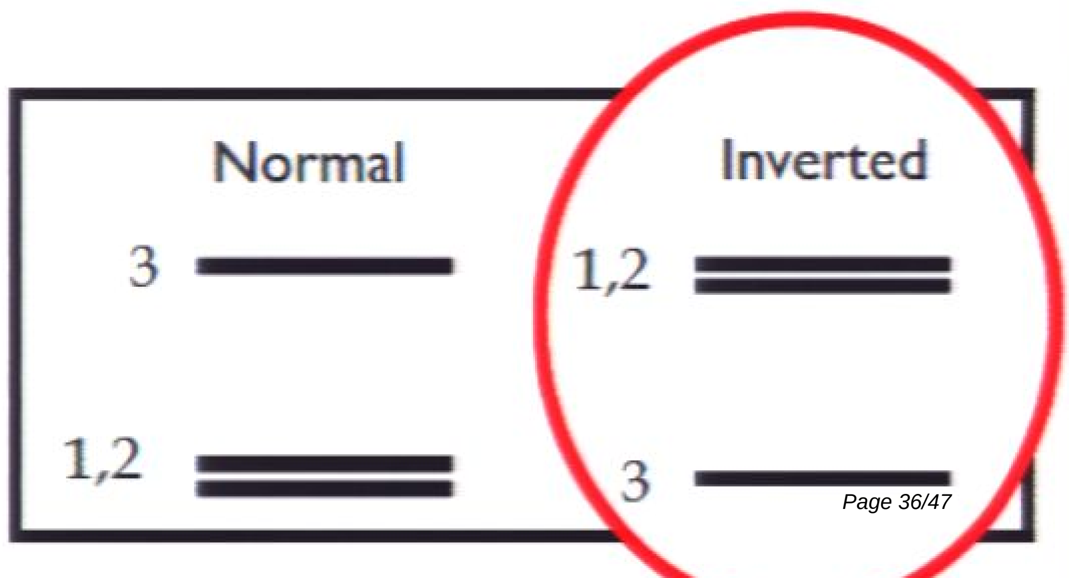

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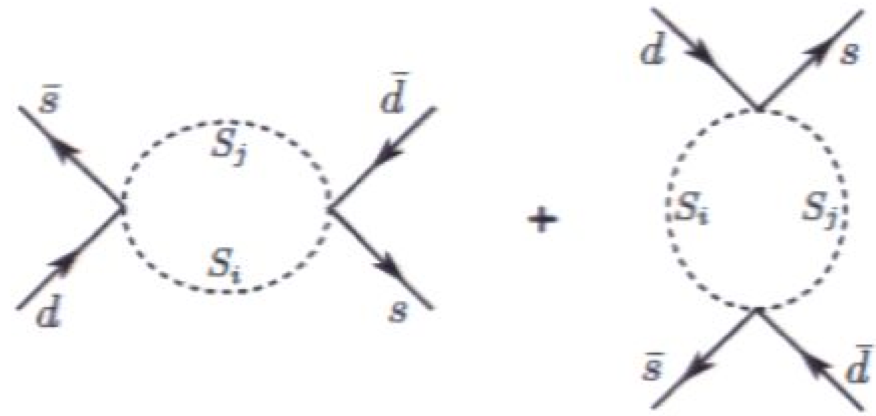
Flavor constraints?

e.g. $\bar{K} - K$ mixing



$$\Rightarrow \mathcal{L}_{sd} = C_S^{sd}(\bar{s}_R d_L)(\bar{s}_R d_L) + \text{h.c.}$$

$$C_S^{sd} \sim \frac{1}{16\pi^2}\frac{m_s^2}{\Lambda^4}(V_{td}V_{ts}^*)^2$$

$\Rightarrow$ suppressed by $m_S^2/m_W^2 \sim 10^{-6}$ compared to SM

Monojet constraints?

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Couplings Yukawa, CKM suppressed $\Rightarrow$ $\bar{q}_i q_j \to S_k S_\ell^\dagger$ negligible

LHC signatures: Heavy Dark Flavors

Many possible production mechanisms in general:

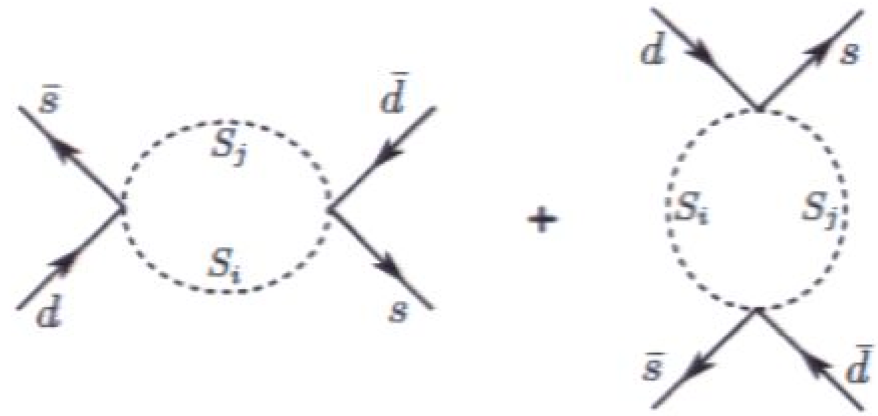
- Direct production
- Produced in decay of flavored connector
- Produced in decay of resonance, e.g. Higgs

Heavy dark flavors may be stable or unstable

- If stable, then multi-component DM (spectroscopy?)
- If unstable, decay modes typically flavor-sensitive

Flavor constraints?

e.g. $\bar{K} - K$ mixing



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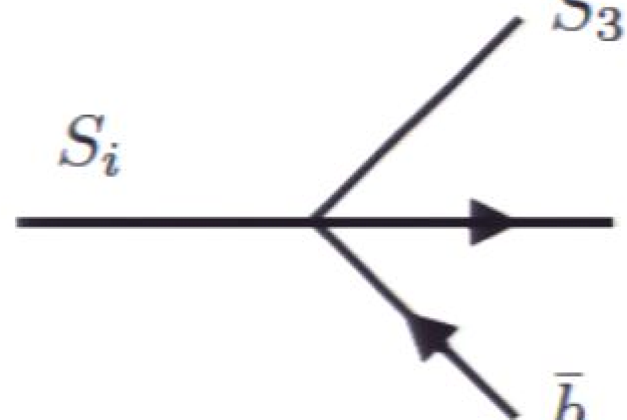
Decays of heavy flavors

$$\mathcal{L}_{\text{eff}} \supset \frac{c}{\Lambda^2} m_b V_{tb} V_{cs}^* S_3^* S_2 \bar{s}_L b_R + \frac{c}{\Lambda^2} m_b V_{tb} V_{ud}^* S_3^* S_1 \bar{d}_L b_R + \text{h.c.} \; .$$

$$S_2 \to S_3 s \bar{b},$$
$$S_1 \to S_3 d \bar{b}.$$



$$\Gamma_{i\to 3qb} \simeq \frac{|cV_{tb}V_{ii}^*|^2 m_b^2 m_i^3}{512\pi^3\Lambda^4}$$

$$c\tau \simeq 10\,\text{nm} \times \left(\frac{25\,\text{GeV}}{m_i}\right)^3 \left(\frac{\Lambda}{200\,\text{GeV}}\right)^4 .$$

prompt decay

Example: production via Higgs decay

$$pp \to hZ$$

$$Z \to \ell^+\ell^-$$

$$h \to S_1^* S_1 \to b\bar{b}d\bar{d}S_3^* S_3,$$

$$h \to S_2^* S_2 \to b\bar{b}s\bar{s}S_3^* S_3.$$

m_h	m_1	m_2	m_3	$\widetilde{\lambda}_1$	$\widetilde{\lambda}_2$	$\widetilde{\lambda}_3$
120	25	25	10	0.15	0.15	0.01

MadEvent (signal), Herwig++ (backgrounds & showering)

	FDM	$t\bar{t}$	ZZ	WZ	WW
$n_j \geq 1$, $n_l = 2$ and $p_{T,l_1} > 80$ GeV	12.7	8903.7	202.3	168.5	242.2
$\not{E}_T > 50$ GeV	7.8	5744.1	20.6	20.4	118.8
Z reconst. and $p_{T,Z} > 150$ GeV, no $\Delta R_{j50,Z} < 1.5$	4.3	9.9	5.8	3.8	0.7
$\Delta\phi_{\not{E}_T,Z} > 2.0$	4.2	4.6	5.2	3.3	0.03
b-tag	2.2	2.2	0.2	0.1	0.01

$S/B \sim 1, \quad S/\sqrt{B} \sim 5$ with $15\ \mathrm{fb}^{-1}, \sqrt{s} = 14$ TeV

Summary

- MFV → novel organizing principle for DM
- Flavor intertwined with DM physics
- Predicts new Heavy Dark Flavors

Future directions

- Extend MFV to leptons -- leptonic DM
- Investigate different flavor representations
- Constrain systematically EFTs of MFV DM
- UV completions for EFTs

Flavor constraints?

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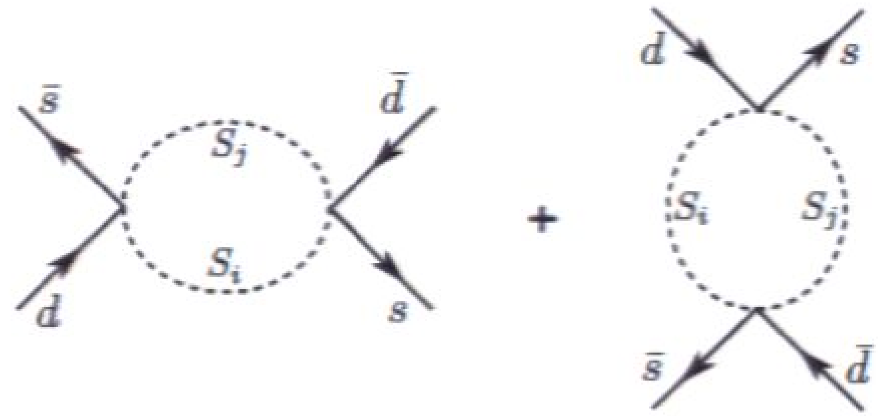

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Relic Abundance:

$$\mathcal{L}_{\rm eff} \supset \frac{c}{\Lambda^2} m_b |V_{tb}|^2 S_3^* S_3 \bar{b}_L b_R + \text{h.c.} + \ldots$$

Dominant annihilation mode: $S_3 S_3^\dagger \to \bar{b}b$

$$\langle \sigma v \rangle_{33\to\bar{b}b} = \frac{3}{4\pi\Lambda^4} m_b^2 |V_{tb}|^4 \left(1 - \frac{m_b^2}{m_3^2}\right)^{1/2} \times \left\{ [\text{Re}(c)]^2 \left(1 - \frac{m_b^2}{m_3^2}\right) + [\text{Im}(c)]^2 \right\}.$$

$$\langle \sigma v \rangle_{33\to\bar{b}b} \simeq 1\,\text{pb} \left(\frac{200\,\text{GeV}}{\Lambda}\right)^4,$$

Focus on one operator, one flavor structure:

$$\mathcal{L}_{\rm eff} = \frac{c}{\Lambda^2}[\bar{Q}_i S_i][S_j^*(Y_d)_{jk} d_{Rk}]H + \text{h.c}$$

After EWSB and diagonalization:

$$\mathcal{L}_{\rm eff} \to \frac{c}{\Lambda^2}\frac{v}{\sqrt{2}}[\bar{d}_{Li} V_{ij}^\dagger S_j][S_k^*(V\lambda_d)_{k\ell} d_{R\ell}] + \text{h.c.} \ .$$

Focus on inverted spectrum → S_3 is the DM candidate