# Dark Matter from Minimal Flavor Violation

Brian Batell
Perimeter Institute & U of Chicago

with Josef Pradler & Michael Spannowsky

JHEP 1108:038,2011 [arXiv:1105.1781]

SUSY2011
August 30, 2011

# 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 $\chi$ :

- 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 $\chi$ stable, if MFV is imposed?

# 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:

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

# Triality conditions:

$$t_c = (A - B + C - D + E - F) \bmod 3 = 0,$$
$$t_Q = (n_Q - m_Q + A - B + G - H + I - J) \bmod 3 = 0,$$
$$t_{u_R} = (n_u - m_u + C - D - G + H) \bmod 3 = 0,$$
$$t_{d_R} = (n_d - m_d + E - F - I + J) \bmod 3 = 0.$$

$t_Q + t_{u_R} + t_{d_R} - t_c = 0$ ⇒ $\mathcal{O}_{\rm decay}$ is allowed only if

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

$$n \equiv n_Q + n_{u_R} + n_{d_R}$$
$$m \equiv m_Q + m_{u_R} + m_{d_R}$$

$\chi$ is stable if

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

# 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) | $(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$<br>$(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$ | Yes |
| (0,2) | $(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$<br>$(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$ | Yes |
| (1,1) | $(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$<br>$(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$<br>$(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$ | |

Many possible models of flavored dark matter!

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

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

Spectrum &
Mixing with SM Higgs

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

Effective operators
coupling DM to SM quarks

# Scalar potential:

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

MFV allows insertions of Yukawa Spurions

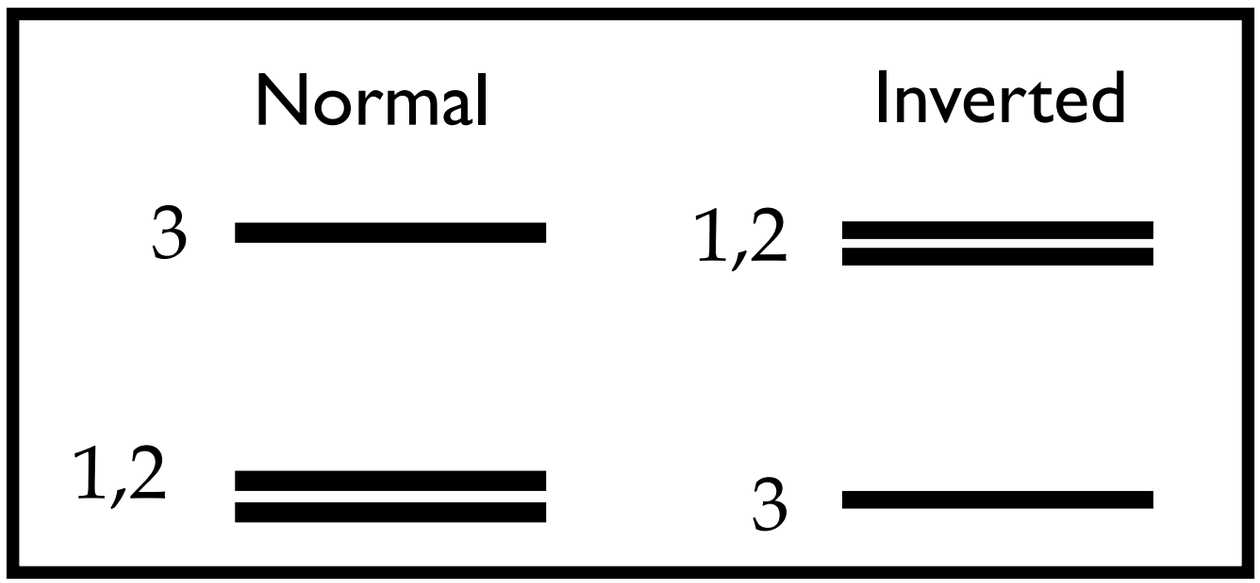
Rotate to background values: $Y_d = \lambda_d, \quad Y_u = V^\dagger \lambda_u$

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:

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

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

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

e.g.

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

## Focus on one operator, one flavor structure:

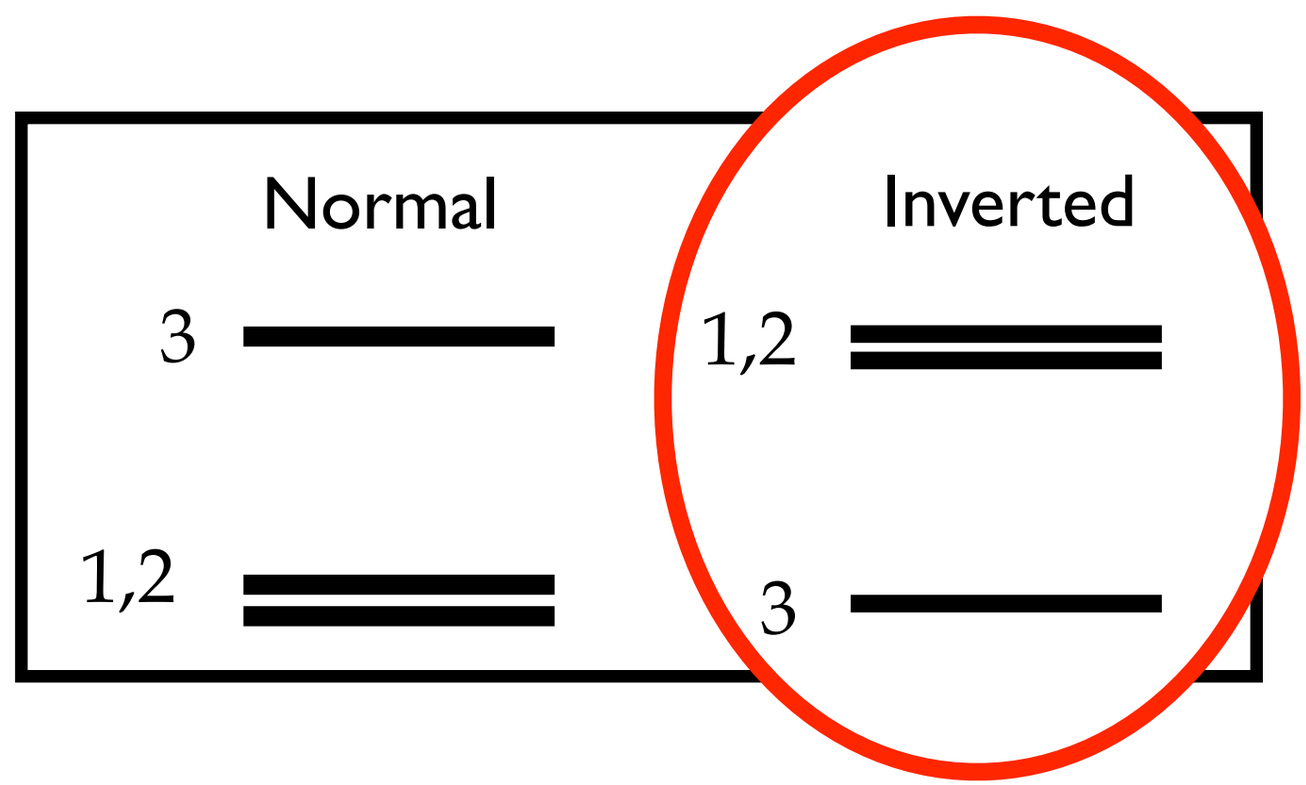
$$\mathcal{L}_{\rm eff} = \frac{c}{\Lambda^2}[\bar{Q}_i S_i][S_j^*(Y_d)_{jk} d_{Rk}]H + \text{h.c}$$

## 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: $S_3 S_3^\dagger \to \bar{b}b$

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

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

# Direct Detection:

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

note CKM suppression for 1st, 2nd generation

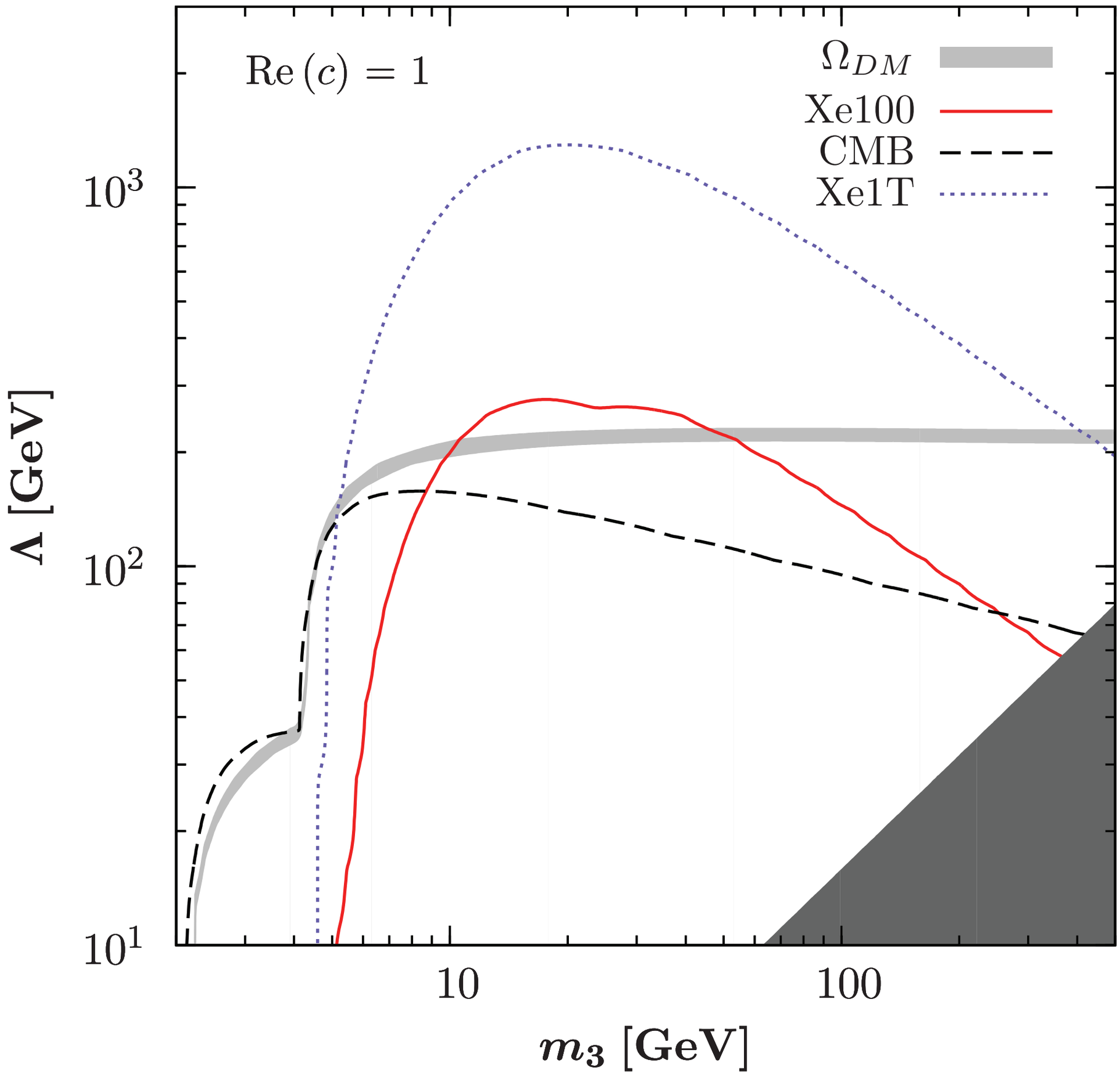
only $b$ - quark content in nucleon relevant for scattering

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

## SI DM-nucleon scattering cross section

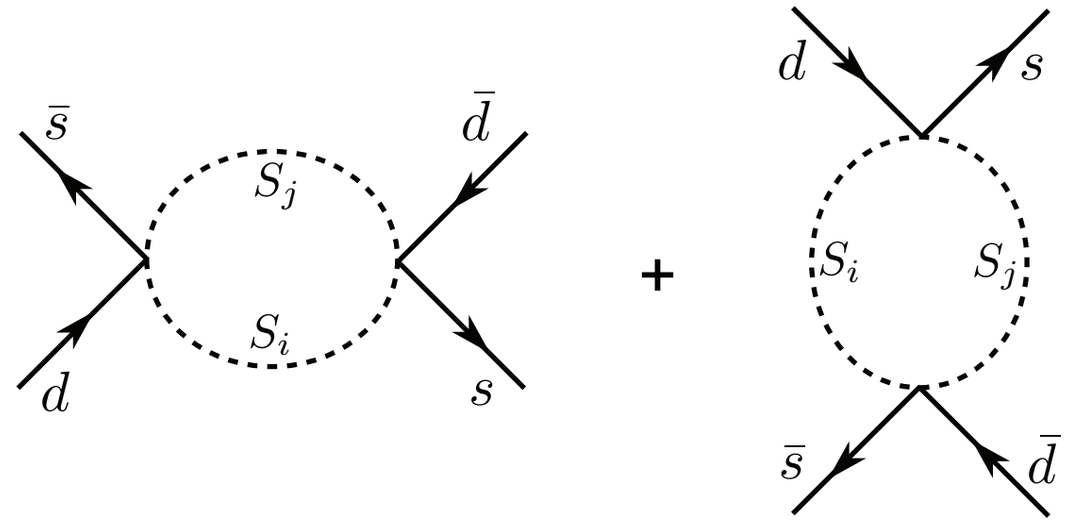
$$\sigma_n = \frac{[{\rm Re}(c)]^2 |V_{tb}|^2 f_{n,b}^2 \, \mu_n^2}{4\pi m_3^2 \Lambda^4}$$

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


Re (c) = 1
$\Omega_{DM}$
Xe100
CMB
Xe1T
$10^3$
$10^2$
$10^1$
$\Lambda$ [GeV]
10
100
$m_3$ [GeV]

# Flavor constraints?

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




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

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

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

# Monojet constraints?

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

Couplings Yukawa, CKM suppressed

$\bar{q}_i q_j \to S_k S_\ell^\dagger$

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

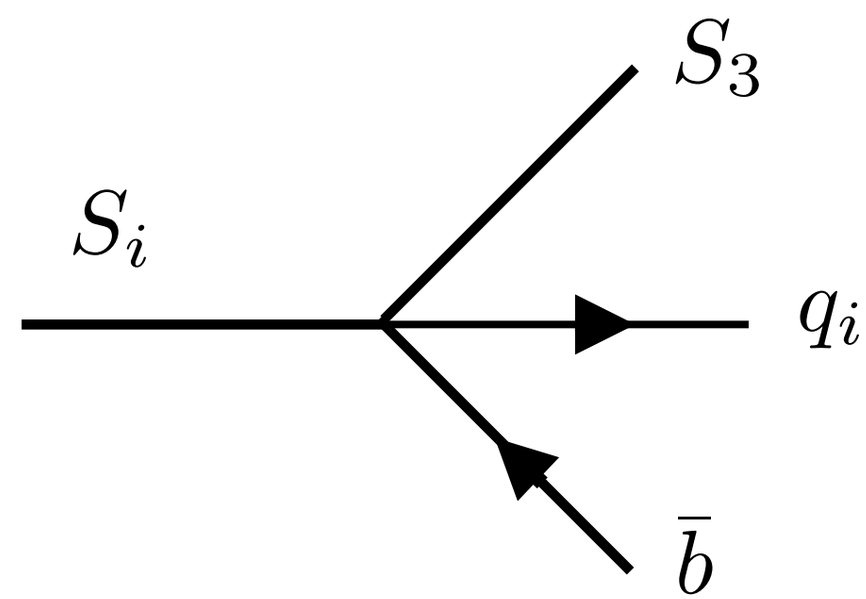
Heavy dark flavors may be stable or unstable

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

# Decays of heavy flavors

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

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




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

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

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 $\Delta R_{j_{50},Z} < 1.5$ | 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** $15\ \mathrm{fb}^{-1}, \sqrt{s} = 14\ \mathrm{TeV}$

# Conclusions

- 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