Flavored Dark Matter

Jernej F. Kamenik

based on collaboration with
F. Bishara, A. Greljo, E. Stamou & J. Zupan,
1409.xxxx

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Outline

- Relating the SM & NP puzzles of Flavor & DM
- The case for MFV DM
- Flavored DM beyond MFV - general discussion
- Maximally non-MFV DM: a gauged flavor symmetric model

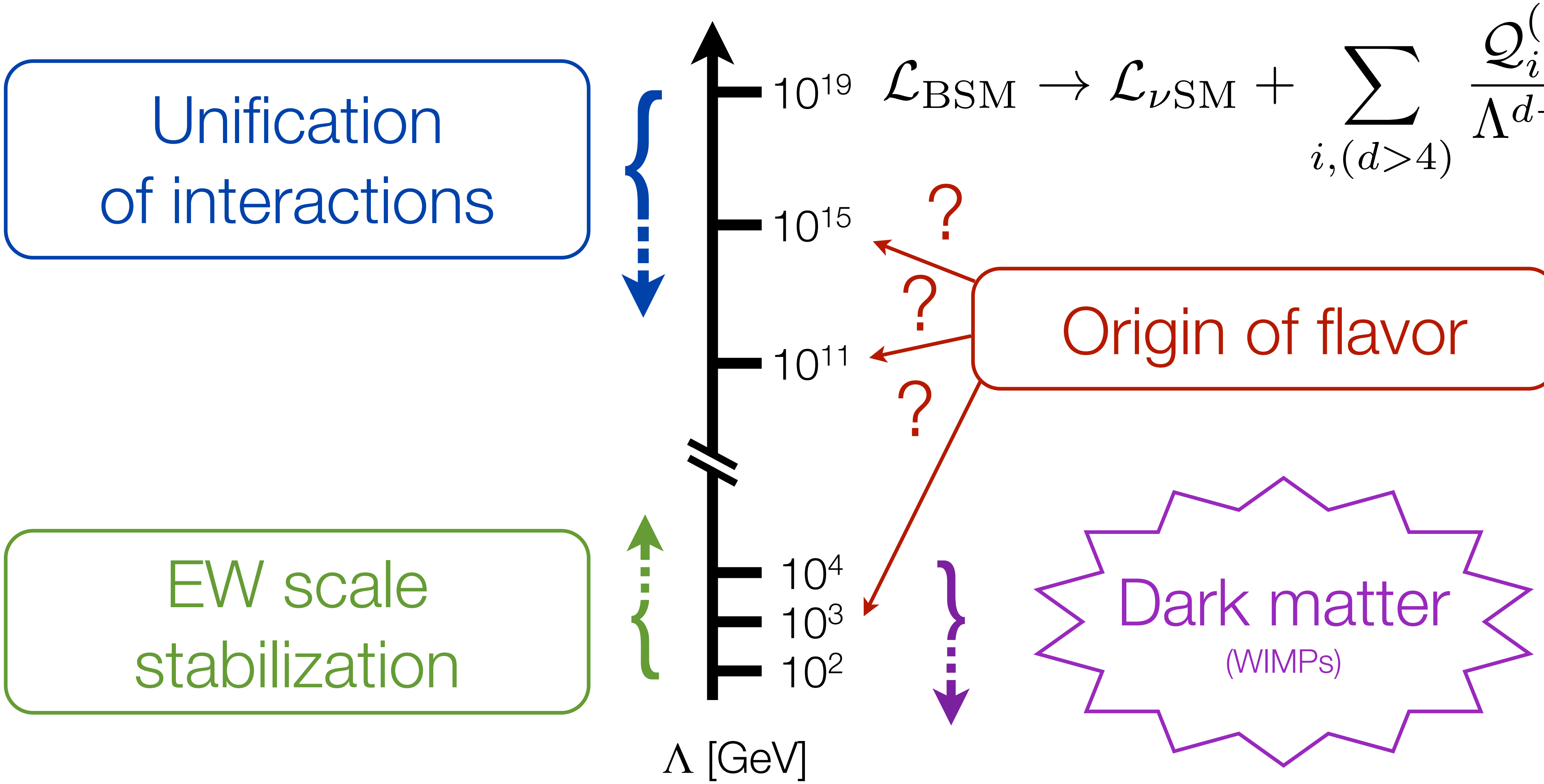
Introduction

SM phenomenologically extremely successful

most likely just (experimentally accessible) effective theory

DM one of strongest experimental indications of NP

$$\mathcal{L}_{\mathrm{BSM}} \to \mathcal{L}_{\nu\mathrm{SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$



DM as a thermal relic (WIMP)

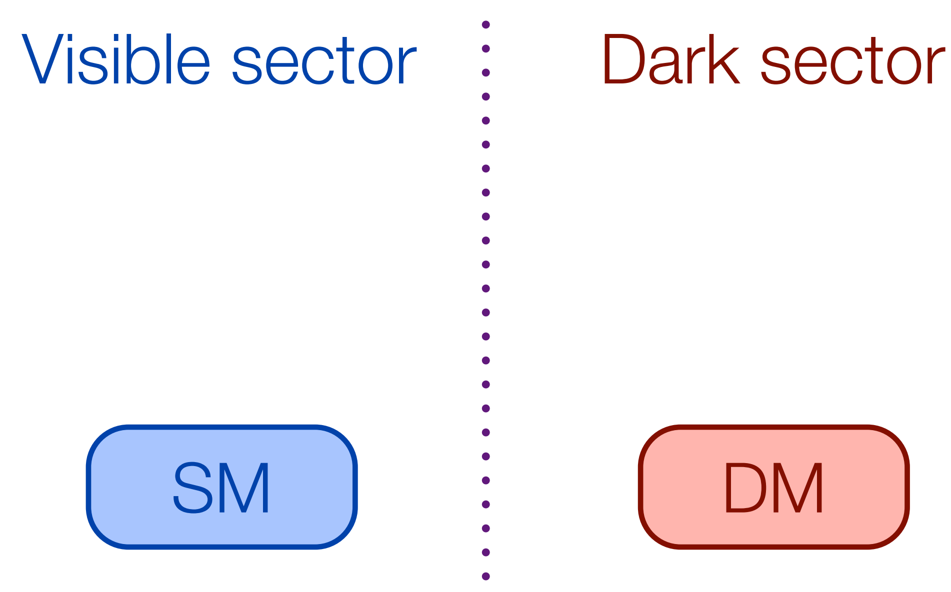
Stable on cosmological scales

- new continuos or discrete symmetries $(U(1), Z_N)$
- accidental symmetries of SM

Cirelli, Fornengo & Strumia, hep-ph/0512090
...

Weak scale interactions to ensure late time-decoupling

- SM weak interactions
- Higgs portal
- new mediators



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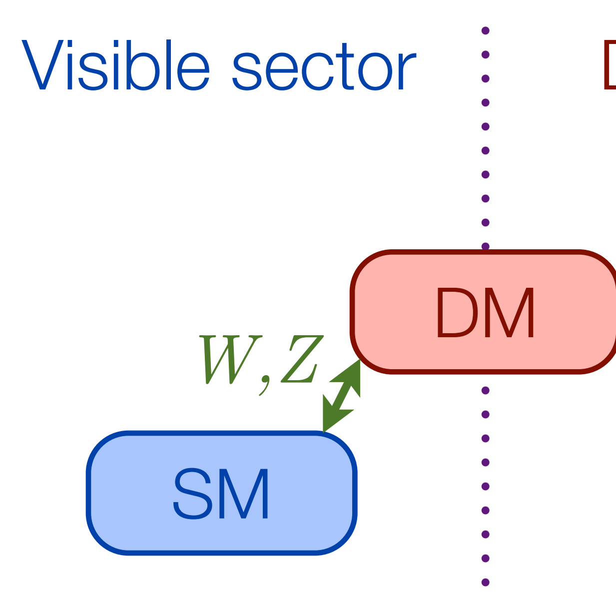

$Y_{DM} \neq 0$ excluded

$Y_{DM} = 0$ probed

c.f.
Cirelli & Strumia, 0903.3381

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Weak scale interactions to ensure late time-decoupling

- SM weak interactions
- Higgs portal
  Barger et al., 0706.4311
  ...
- new mediators

Visible sector | Dark sector

$m_{DM} < m_h/2$ mostly excluded

$m_{DM} \gtrsim m_h/2$ within exp. reach

SM $\xleftrightarrow{H}$ DM

c.f.
A. Greljo, Julio, J.F.K. & Zupan, 1309.3561

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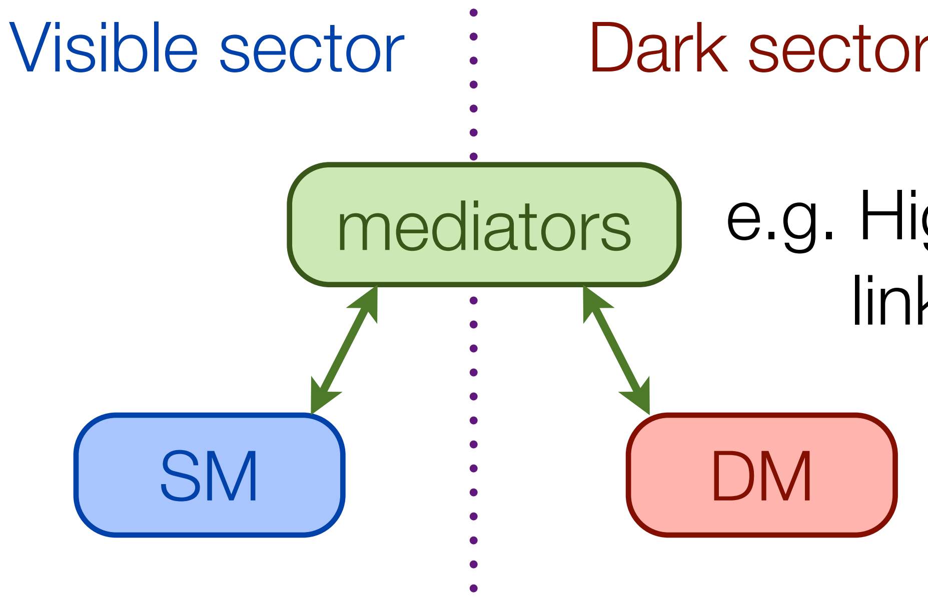


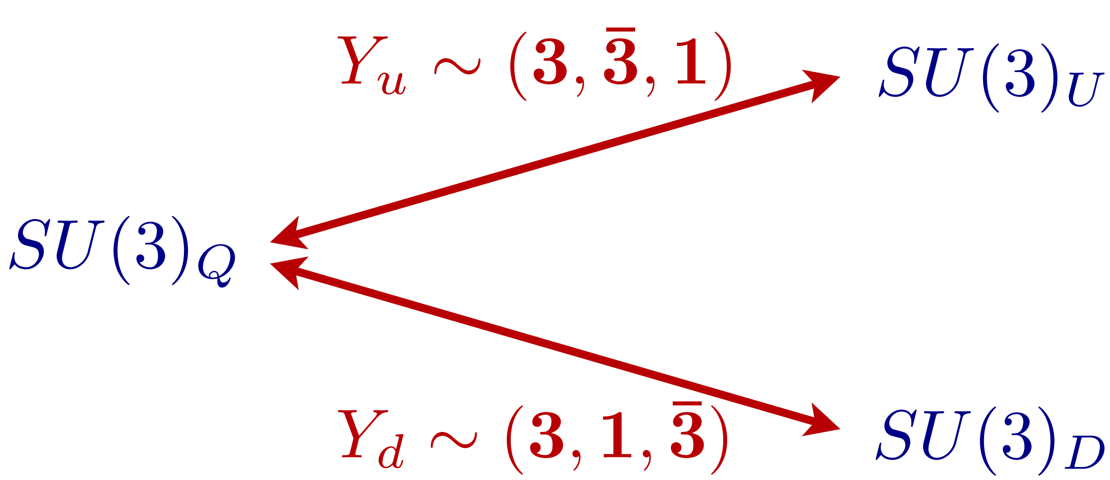
e.g. Higgsinos in MSSM
linked to EWHP

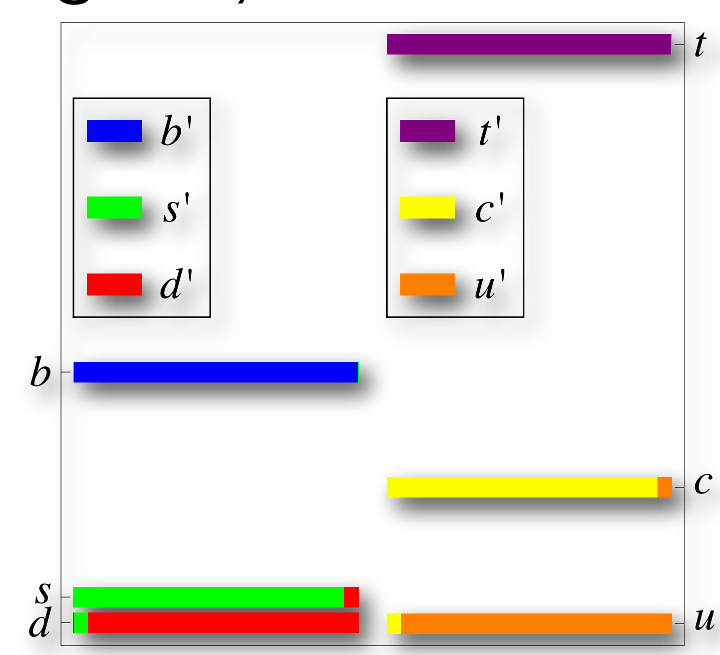
SM & NP Flavor problems

- Flavor is approximately conserved in SM

$$\mathcal{G}_q^{\mathrm{SM}} = U(3)_Q \times U(3)_U \times U(3)_D$$
$$= \underbrace{SU(3)_Q \times SU(3)_U \times SU(3)_D}_{\mathcal{G}_F^{\mathrm{SM}}} \times U(1)_Y \times U(1)_{PQ} \times U(1)_B$$

- The breaking is very specific (hierarchical, aligned)





SM Flavor Puzzle

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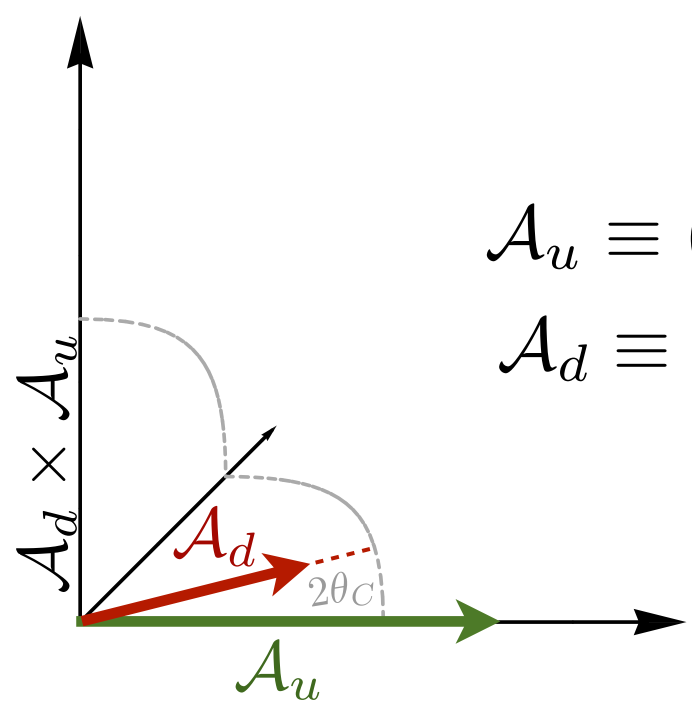
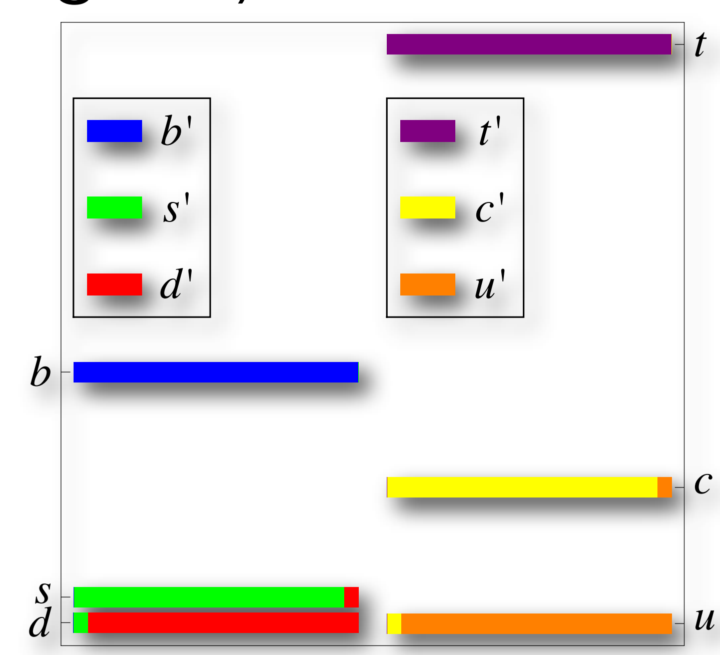


$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\cancel{\text{tr}}}\,,$$
$$\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\cancel{\text{tr}}}$$



SM Flavor Puzzle

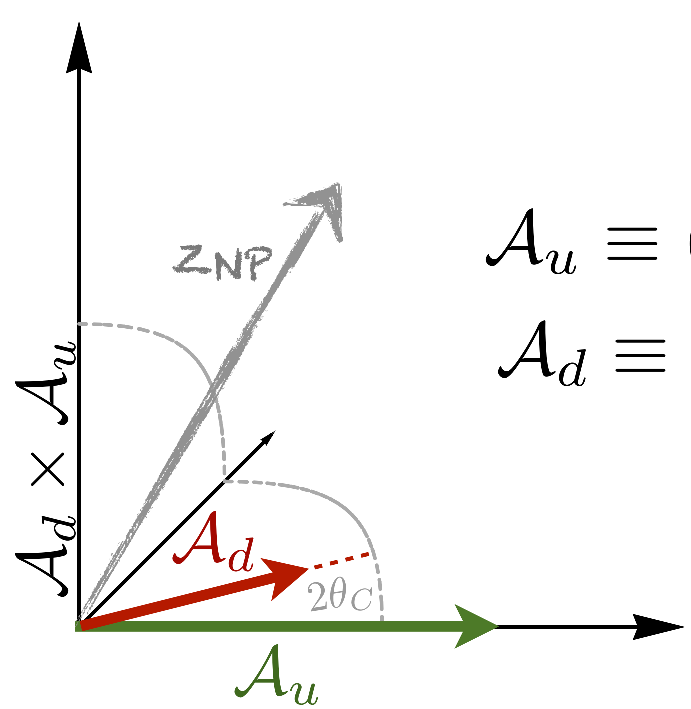
SM & NP Flavor problems

- BSM generically involves new sources of flavor breaking

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

- severely constrained:



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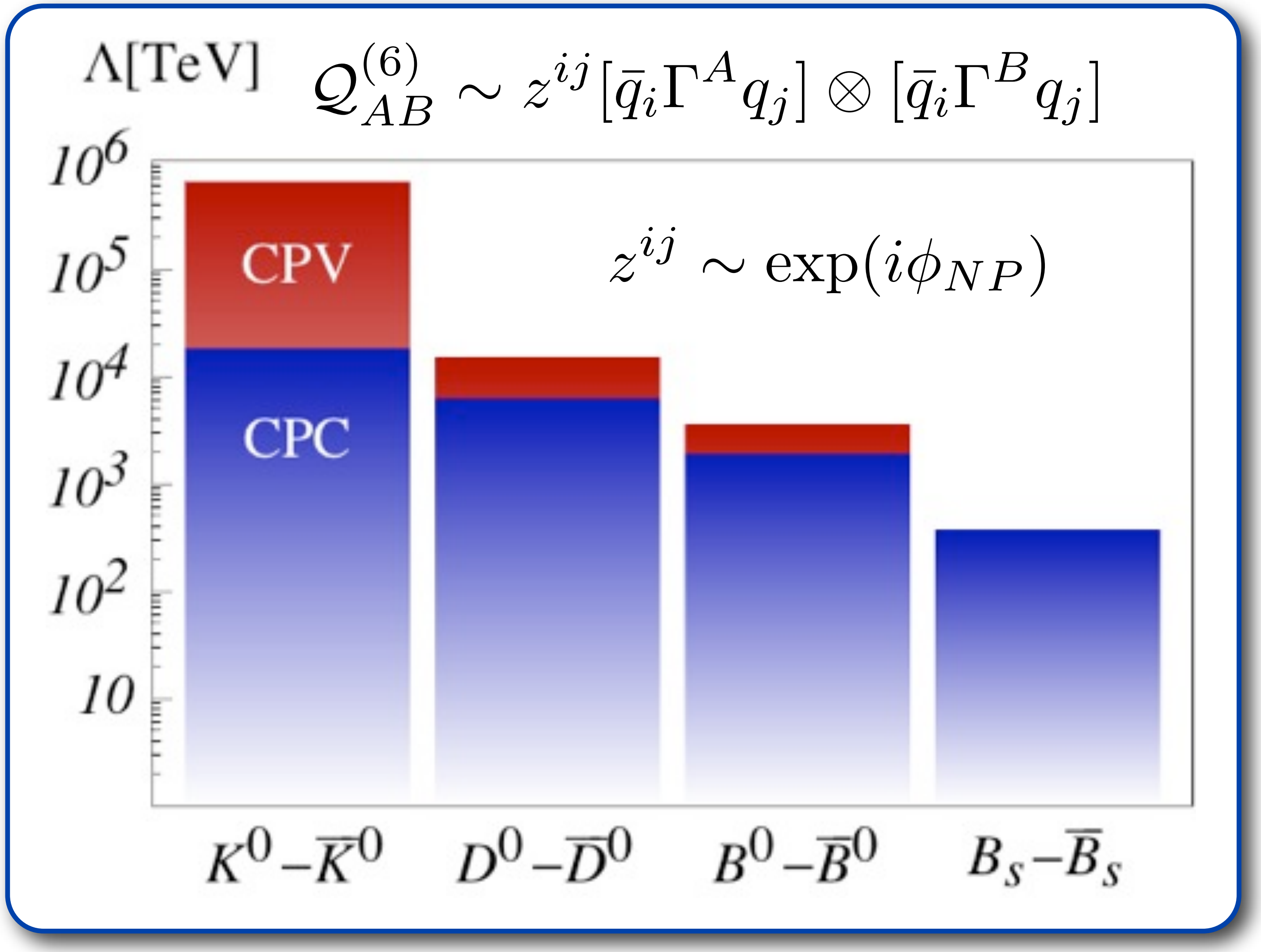
NP Flavor Puzzle



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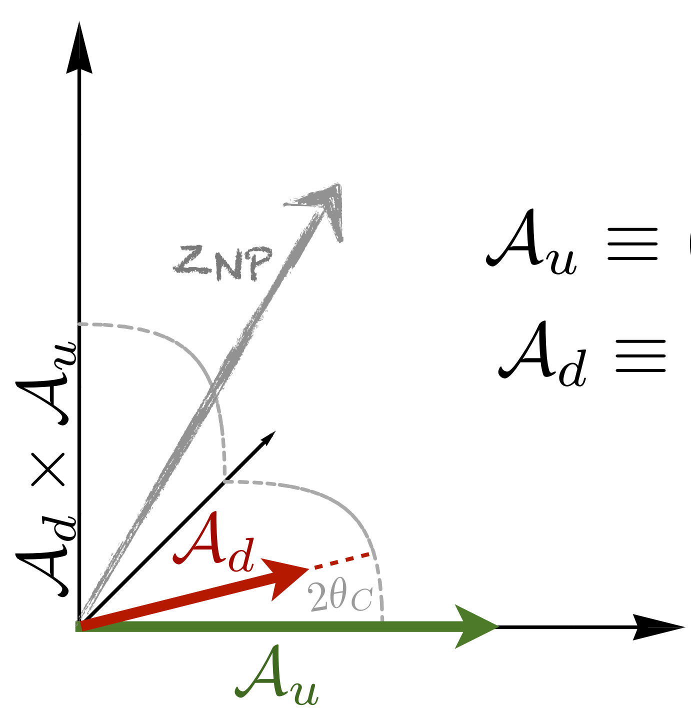

$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{tr}}\,,$$
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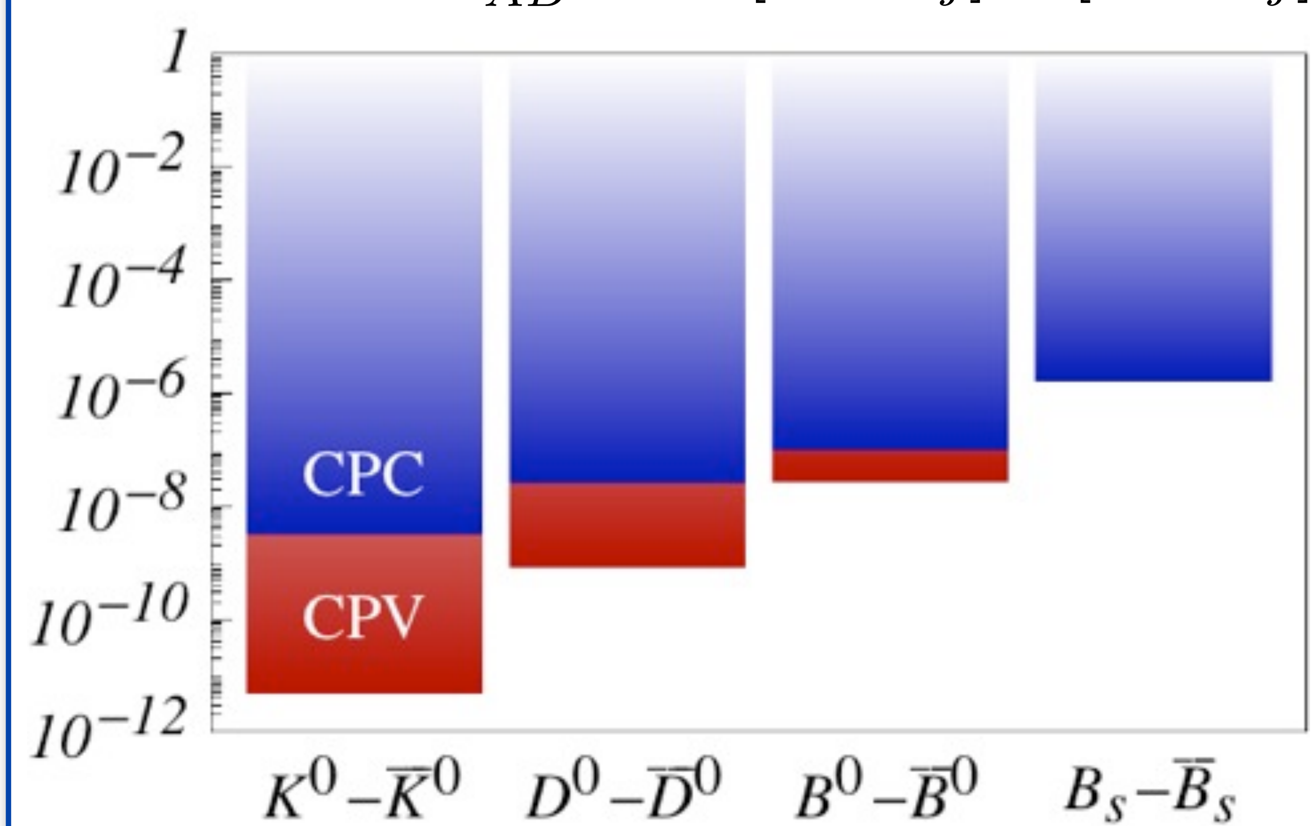
NP Flavor Puzzle

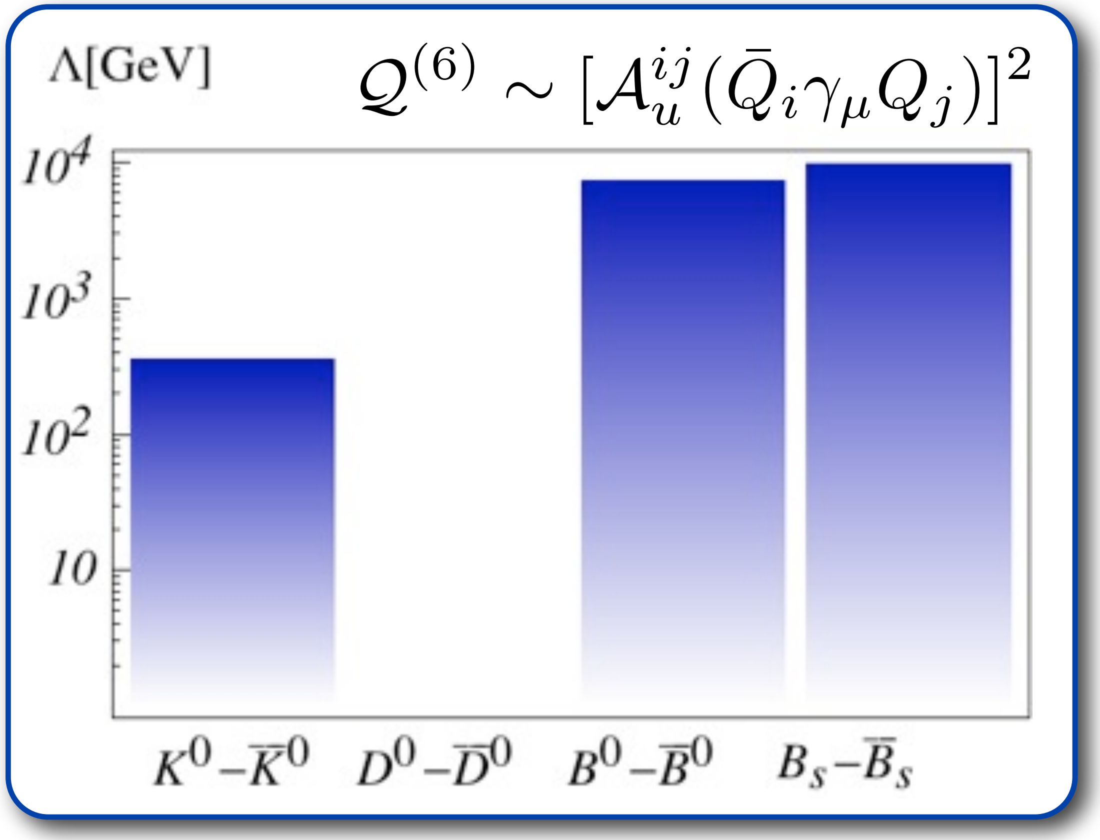
z^{ij} $(\Lambda{=}1\text{TeV})$ $\mathcal{Q}_{AB}^{(6)} \sim z^{ij} [\bar{q}_i \Gamma^A q_j] \otimes [\bar{q}_i \Gamma^B q_j]$



SM & NP Flavor problems

- Idea of MFV: NP formally invariant under $\mathcal{G}_F^{\rm SM}$, all breaking can be (Taylor) expanded in terms of only $Y_{U,D}$
  - Example: $z_{ij}\bar{Q}^i\gamma_\mu Q^j \quad \Rightarrow \quad \mathbf{z} = \mathbf{1} + a_1\mathcal{A}_u + a_2\mathcal{A}_d + \ldots$

$a_{i>2} \lesssim a_{1,2}$ "Minimal Flavor Violation"



d'Ambrosio et al., hep-ph/0207036
Colangelo et al., 0807.0801

Relevance for DM?

{

BNV in presence of MFV

$\mathcal{G}_F^{\rm SM}$ can ensure proton stability in absence of *B*

C. Smith, 1105.1723

- Exact $\mathcal{G}_F^{\rm SM}$: $\mathcal{H}_{eff}^{gauge,SM3} = \frac{1}{\Lambda^{14}}((LQ^3)^3 + (EU^2D)^3 + (EUQ^{\dagger 2})^3 + (LQD^\dagger U^\dagger)^3 + h.c.)$,
  - all contractions antisymmetric in color, weak and flavor indices
- MFV: $\mathcal{H}_{eff}^{Yukawa,SM3} = \frac{1}{\Lambda^5}(EL^{\dagger 2}U^3 + L^{\dagger 3}Q^\dagger U^2 + D^4U^2 + D^3UQ^{\dagger 2} + D^2Q^{\dagger 4} + h.c.)$,
  - most constraining operator involves two up-Yukawa insertions

$$L^{\dagger 3}Q^\dagger U^2 = \varepsilon^{IJK}L^{\dagger I}L^{\dagger J}L^{\dagger K} \otimes \varepsilon^{LMN}Q^{\dagger L}(U\mathbf{Y}_u)^M(U\mathbf{Y}_u)^N + ... ,$$

$$\propto \left(\frac{m_u}{v_u}\right)^2 V_{ub} \sim 10^{-13} \quad \Rightarrow \quad \tau_p^{\Delta B=3} \sim 10^{30}\,\mathrm{yrs}\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^{10}$$

see also
Nikolidakis & Smith, 0710.3129
Csaki, Grossman & Heidenreich, 1111.1239

}

Flavor - DM connections

- $\langle Y_u \rangle, \langle Y_d \rangle$ also leave a discrete $\mathcal{G}_F^{\rm SM}$ subgroup exactly preserved

$$
\begin{tikzcd}
 & SU(3)_U \\
SU(3)_Q \arrow[ur, leftrightarrow, "\mathcal{Z}_3^{Q/D}"] \arrow[dr, leftrightarrow, "\mathcal{Z}_3^{Q/U}"'] & \\
 & SU(3)_D
\end{tikzcd}
$$

$$\mathcal{Z}_3^{QUD}$$

$$\{U_R, D_R, Q_L\} \to e^{i2\pi/3}\{U_R, D_R, Q_L\}$$

- $\mathcal{Z}_3^{QUD}$ accidental symmetry of SM, exactly preserved in presence of any MFV NP

Batell, Pradler & Spannowsky, 1105.1781

- Color neutral matter charged under $\mathcal{Z}_3^{\chi} \subset \mathcal{Z}_3^{UDQ} \times \mathcal{Z}_3^{c}$ automatically stable

- Suitable $\mathcal{G}_F^{\rm SM}$ representations $\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$,

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

$$m \equiv m_Q + m_u + m_d.$$

$$n \equiv n_Q + n_u + n_d$$

MFV DM

Structure of DM-SM interactions in MFV DM dictated by MFV power counting

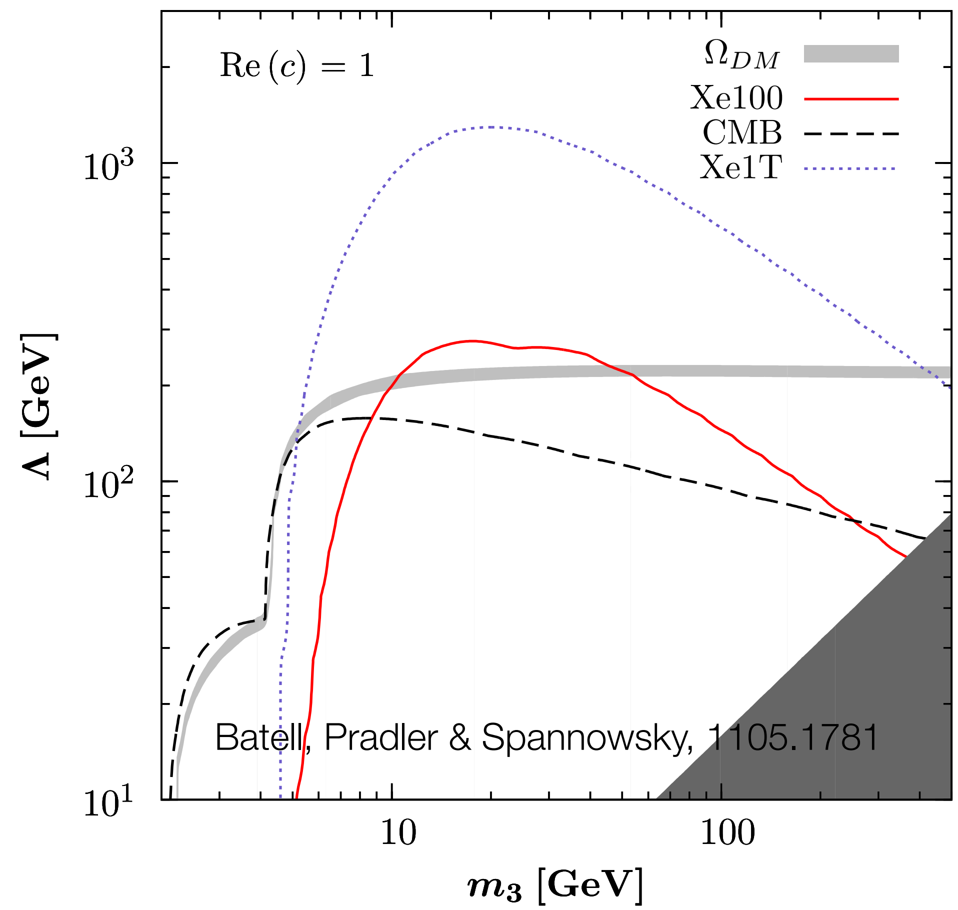
- Example: $S \sim (\mathbf{1},\mathbf{1},0)_{\rm SM} \times (\mathbf{3},\mathbf{1},\mathbf{1})_{G_q}.$

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

- for inverted S_i spectrum, dominant interactions with $b\underline{b}$, $b\underline{s}$,...

$$\sigma(S_3^* S_3 \to d_i d_j) \propto |V_{ti}|^2 |V_{tj}|^2 \frac{m_i m_j}{\Lambda^4}$$

Dynamical origin of Λ & MFV?



see also
Lopez-Honorez & Merlo, 1303.1087
Batell, Lin & Wang, 1309.4462

Deconstructing MFV DM

$\mathcal{Z}_3^{QUD}$ in SM coincides with subgroup of $U(1)_B$

- automatically respected by any B preserving (flavor) NP - even beyond MFV
- in absence of B, $\mathcal{Z}_3^{QUD}$ preserved by any BSM flavor breaking commuting with the center product of $\mathcal{G}_F^{\mathrm{SM}}$
  - <u>*any*</u> such flavor structure can still be decomposed in a <u>*finite*</u> sum involving only $Y_{U,D}$ and their traces

Colangelo, Nikolidakis & Smith, 0807.0801

Deconstructing MFV DM

Example: $z_{ij}\bar{Q}^i\gamma_\mu Q^j$

$$
\begin{aligned}
z_{ij} &= z_1\mathbf{1} + z_2\mathbf{Y}_u^\dagger\mathbf{Y}_u + z_3\mathbf{Y}_d^\dagger\mathbf{Y}_d + z_4(\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2 + z_5(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2 \\
&+ z_6\left(\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u + \text{h.c.}\right) + z_7\mathbf{Y}_u^\dagger\mathbf{Y}_u\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u \\
&+ z_8\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u\mathbf{Y}_d^\dagger\mathbf{Y}_d + z_9\left((\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2 + \text{h.c.}\right) \\
&+ iz_{10}(\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u - \text{h.c.}) + iz_{11}\left((\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2\mathbf{Y}_d^\dagger\mathbf{Y}_d - \text{h.c.}\right) \\
&+ iz_{12}\left((\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2\mathbf{Y}_u^\dagger\mathbf{Y}_u - \text{h.c.}\right) + iz_{13}\left((\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2 - \text{h.c.}\right) \\
&+ iz_{14}\left(\mathbf{Y}_u^\dagger\mathbf{Y}_u\mathbf{Y}_d^\dagger\mathbf{Y}_d(\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2 - \text{h.c.}\right) + iz_{15}\left(\mathbf{Y}_d^\dagger\mathbf{Y}_d\mathbf{Y}_u^\dagger\mathbf{Y}_u(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2 - \text{h.c.}\right) \\
&+ iz_{16}\left(\mathbf{Y}_u^\dagger\mathbf{Y}_u(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2(\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2 - \text{h.c.}\right) + iz_{17}\left(\mathbf{Y}_d^\dagger\mathbf{Y}_d(\mathbf{Y}_u^\dagger\mathbf{Y}_u)^2(\mathbf{Y}_d^\dagger\mathbf{Y}_d)^2 - \text{h.c.}\right)
\end{aligned}
$$

- MFV corresponds to a limit with $|z_i|<1$

Is this limit necessary for successful flavored DM?

General Flavored DM

Basic requirements for DM stability due to $\mathcal{Z}_3^{QUD}$

- $\mathcal{G}_F^{\mathrm{SM}}$ good symmetry of the UV theory

- broken by spurions $X_{ij} \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$,

$$(n-m) \bmod 3 = 0 \qquad \begin{aligned} m &\equiv m_Q + m_u + m_d. \\ n &\equiv n_Q + n_u + n_d \end{aligned}$$

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

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

Explicit non-MFV model example?

Maximally non-MFV DM

Grinstein, Redi & Villadoro, 1009.2049

- A model of fully gauged $\mathcal{G}_F^{\mathrm{SM}}$:
  - spontaneously broken by $\Phi_u \sim (\bar{3}, 3, 1)\,, \quad \Phi_d \sim (\bar{3}, 1, 3)$
  - anomaly cancelation via additional chiral fermions (vector-like under SM gauge)

$$\Psi^c_{uR} \sim (\bar{3}, 1, 1)\,, \qquad \Psi^c_{dR} \sim (\bar{3}, 1, 1)\,, \qquad \Psi_{uL} \sim (1, 3, 1)\,, \qquad \Psi_{dL} \sim (1, 1, 3)\,,$$

  - fermion masses (after flavor & EWSB)

$$\mathcal{L}_{\mathrm{mass}} \supset \lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \bar{\Psi}_{uL} \Phi_u \Psi_{uR} + M_u \bar{\Psi}_{uL} U_R$$
$$+ \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda'_d \bar{\Psi}_{dL} \Phi_d \Psi_{dR} + M_d \bar{\Psi}_{dL} D_R + \mathrm{h.c.},$$

$\mathcal{G}_F^{\mathrm{SM}}$ symmetric Higgs Yukawas

flavon Yukawas to q-parners

kinetic mixing

Maximally non-MFV DM

Grinstein, Redi & Villadoro, 1009.2049

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$$\Psi_{uR}^c \sim (\bar{3}, 1, 1)\,, \qquad \Psi_{dR}^c \sim (\bar{3}, 1, 1)\,, \qquad \Psi_{uL} \sim (1, 3, 1)\,, \qquad \Psi_{dL} \sim (1, 1, 3)\,,$$

  - fermion masses (after flavor & EWSB) $$\mathcal{L}_{\rm mass} \supset \lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda_u' \bar{\Psi}_{uL} \Phi_u \Psi_{uR} + M_u \bar{\Psi}_{uL} U_R + \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda_d' \bar{\Psi}_{dL} \Phi_d \Psi_{dR} + M_d \bar{\Psi}_{dL} D_R + \mathrm{h.c.},$$
  - SM effective Yukawas non-analytic in fundamental flavor spurions!

$$Y_u = \frac{\lambda_u M_u}{\lambda_u' \langle \Phi_u \rangle}\,, \qquad Y_d = \frac{\lambda_d M_d}{\lambda_d' \langle \Phi_d \rangle}\,.$$

Maximally non-MFV DM

Grinstein, Redi & Villadoro, 1009.2049

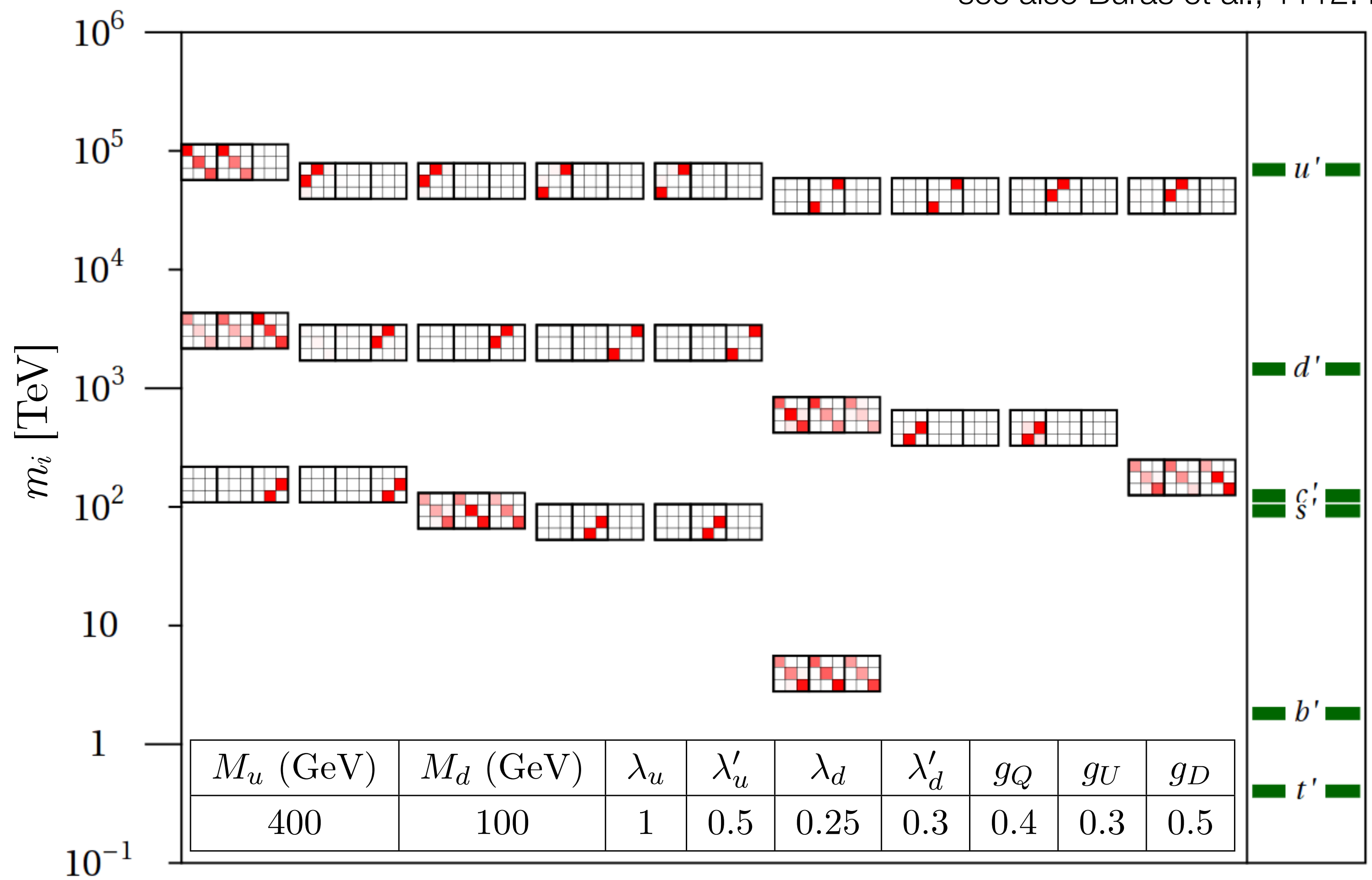
- A model of fully gauged $\mathcal{G}_F^{\rm SM}$:
  - extra fermions exhibit inverted hierarchy - lightest top, bottom partners
  - even for sizable departures from MFV, FCNCs under control via heaviness of corresponding FGBs

see also Buras et al., 1112.4477

  - Benchmark:

$$m_{t'} \sim 520\,\mathrm{GeV}$$
$$m_{FGB}^{\rm min} \sim 3.2\,\mathrm{TeV}$$

(possibly in tension with LHC bounds)



Maximally non-MFV DM

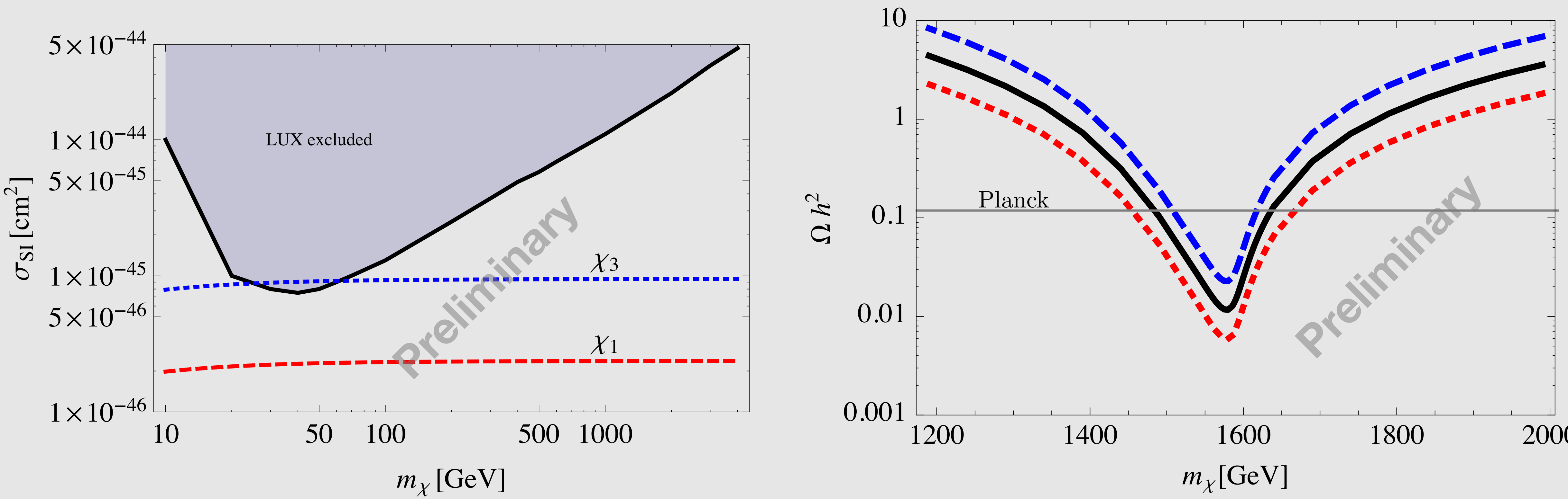
- A model of fully gauged $\mathcal{G}_F^{\rm SM}$ + DM:
  - introduce SM gauge singlet (vector-like fermion)

$$\chi_L \sim (1,3,1), \qquad \chi_R^c \sim (1,\bar{3},1), \qquad \mathcal{L}^{\rm DM} = \bar{\chi}(i\not{D} - m_\chi)\chi$$

  - mass degeneracy broken at 1-loop
  - Benchmark: only the lightest FGB relevant for DM phenomenology
    - approximate *SU*(3) (T_8) relations between χ_{123} interactions
      - annihilation into $t'\underline{t}'$, $t\underline{t}$, jj with comparable fractions
    - DM mass the only relevant new parameter of the model

Maximally non-MFV DM

- A model of fully gauged $\mathcal{G}_F^{\mathrm{SM}}$ + DM:



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Conclusions

- DM charged under SM flavor presents intriguing possibilities of relating two of outstanding SM puzzles

see also Agrawal et al., 1109.3516
Agrawal, Blanke & Gemmler, 1405.6709
Bishara & Zupan, 1408.3852

- DM stability by existing SM flavor symmetry can be ensured in a large class of flavor models well beyond MFV
    - including models of B violation
- A toy model example based on maximally gauged SM flavor symmetry can relate DM signals to LHC searches for top-partners, flavored Z' resonances