Flavored dark matter beyond Minimal Flavor Violation

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Fermilab

arxiv:1405.6709
P. Agrawal, M. Blanke, KG

Outline

1. Dark Minimal Flavor Violation
2. Analysis of flavor observables
3. Dark Matter Constraints
4. Combined analysis
5. Collider phenomenology

Current status of elementary particle physics

Higgs discovery at the LHC on July 4th, 2012

- Observation of a new boson with the ATLAS and the CMS detector

ATLAS:	$m_H = 126.0 \pm 0.4\,(\text{stat.}) \pm 0.4\,(\text{syst.})$ GeV
CMS:	$m_H = 125.3 \pm 0.4\,(\text{stat.}) \pm 0.5\,(\text{syst.})$ GeV

- Currently all measured properties are compatible with the Standard Model (SM) Higgs boson

The Standard Model is complete!

$\rightarrow$ BUT

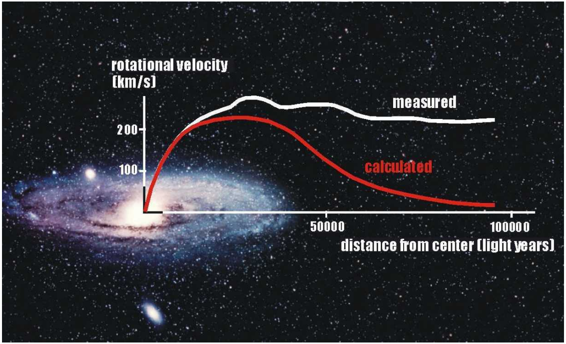
No sign of New Physics yet!

$\rightarrow$ RIGHT?

Current status of particle astrophysics

Evidence for Dark Matter

- galactic rotation curves
- gravitationally lensing
- understanding of clusters
- precision CMB data



How?

$\Rightarrow$ flat rotation curves observed far from the central region while $v \sim r^{-\frac{1}{2}}$ expected

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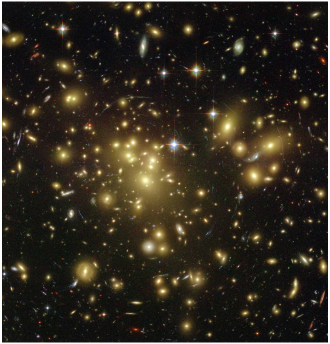

How?

$\Rightarrow$ tangential shear around galaxy falls off much slower than expected

Current status of particle astrophysics

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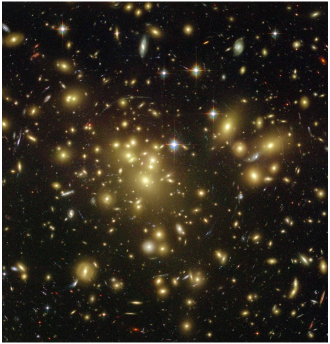

How?

⇒ e.g. lensing & velocities of galaxies in clusters, observations of X-rays emitted by hot gas in clusters allow to relate temperature to total mass

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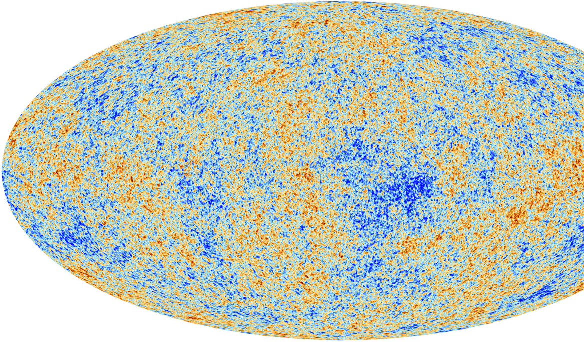

How?

$\Rightarrow$ angular fluctuations in Cosmic Microwave Background spectrum measure very robustly that the matter density is 6 times larger than the baryon density

Dark matter properties

- ☐ non-baryonic
- ☐ interacts gravitational through its mass
- ☐ relic density $\Omega_{DM} h^2 = 0.119$
- ☐ stable
- ☐ neutral, no charge and no color
- ☐ cold, non-relativistic

Impact of theory:

weak scale cross section for annihilation gives automatically correct abundance

$\rightarrow$ WIMP miracle

Flavored dark matter

Particle properties of Dark Matter?

- Coupling to SM particles?
- Single particle or entire sector?

→ Considering the role of flavor in the SM

Assumption

→ Dark matter carries flavor and comes in multiple copies

✔ non-baryonic

✔ neutral, no charge and no color

New coupling to quarks:

$$\lambda^{ij}\bar{d}_{Ri}\chi_j\phi$$

d_{Ri}	-	Right-handed down quark
χ_j	-	Dark matter particle, flavored
ϕ	-	New scalar, colored

Flavored dark matter is not new!

Selection only!

- Flavoured Dark Matter in Direct Detection Experiments and at LHC
  J. Kile, A. Soni (April 2011)
- Dark Matter from Minimal Flavor Violation
  B. Batell, J. Pradler, M. Spannowsky (May 2011)
- Discovering Dark Matter Through Flavor Violation at the LHC
  J. F. Kamenik, J. Zupan (July 2011)
- Flavored Dark Matter, and Its Implications for Direct Detection and Colliders
  P. Agrawal, S. Blanchet, Z. Chacko, C. Kilic (Sep. 2011)
- Top-flavored dark matter and the forward-backward asymmetry
  A. Kumar, S. Tulin (Mar. 2013)
- Flavored Dark Matter and R-Parity Violation
  B. Batell, T. Lin, L.-T. Wang (Sep. 2013)

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$\rightarrow$ BUT common to all these studies

Minimal Flavor Violation

Minimal flavor violation

- SM: GIM mechanism controls pattern of FCNC processes formula
- NP: large new sources of flavor symmetry breaking are excluded at TeV scale ISIDORI, NIR, PEREZ (2010)

Example: bounds from B_d-mixing with generic flavor structure

$$M(B_d - \bar{B}_d) \sim \frac{(y_t V_{ti}^* V_{tj})^2}{16\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2} \quad \text{for} \quad c_{NP} \sim \mathcal{O}(1) \quad \Rightarrow \quad \Lambda \geq 10^3\text{TeV}$$

$\rightarrow$ new flavor couplings to quarks cannot be arbitary but are strongly constrained by flavor observables

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main features of MFV:

- flavor symmetry is only broken by the SM Yukawa couplings
- CKM matrix is the only source of flavor violation
- FCNCs are naturally suppressed

So, what should we do?

→ Minimal Flavor Violation???

non-MFV

→ DANGEROUS

But interesting if you know how to handle it!

MFV

→ HARMLESS

But not very exciting.

The new model

- dirac fermionic DM χ carries flavor and couples to quarks via a scalar colored mediator

$$\begin{aligned}\mathcal{L}_{\rm NP} = \quad & i\bar{\chi}\not{\partial}\chi - m_\chi\bar{\chi}\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{d}_{Ri}\chi_j\phi + \text{h.c.} \\ & + \lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi\end{aligned}$$

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$$+\lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi$$

Assumption

- Flavor symmetry: $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\chi$

$\rightarrow$ only broken by the SM Yukawa couplings and the DM-quark coupling λ

"Dark Minimal Flavor Violation"

(DMFV)

Dark Minimal Flavor Violation - special features

Parametrization of DM-quark coupling

- $U(3)_\chi$ symmetry helps to remove 9 parameters

$$\lambda = U_\lambda D_\lambda$$

U_λ - unitary matrix, 3 mixing angles s^λ_{12}, s^λ_{13}, s^λ_{23} and 3 phases
D_λ - real diagonal matrix, e.g. $D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))$

Dark matter mass

- $U(3)_\chi$ symmetry ensures equal mass for all flavors at tree level
- special form of mass splitting at higher order (loop level)

$$m_{ij} = m_\chi(\delta_{ij} + \eta\, \lambda^\dagger_{ik}\lambda_{kj}) = (m_\chi + m_\chi \eta\, D^2_{\lambda,ii})\delta_{ij}$$

Dark matter stability

- DM stability is guaranteed if Dark Minimal Flavor Violation is exact

Dark matter stability

Consider the operator

SIMILAR PROOF IN MFV: ARXIV:1105.1781
B. BATELL, J. PRADLER, M. SPANNOWSKY

$$\mathcal{O} \sim \chi \dots \bar{\chi} \dots \phi \dots \phi^\dagger \dots q_L \dots \bar{q}_L \dots u_R \dots \bar{u}_R \dots d_R \dots \bar{d}_R \dots G \dots \mathcal{S}$$

invariant under ...

- QCD if the number of $SU(3)_c$ triplet minus the number of $SU(3)_c$ antitriplets is a multiple of three
- flavor symmetry if $Y_u \dots Y_u^\dagger \dots Y_d \dots Y_d^\dagger \dots \lambda \dots \lambda^\dagger \dots$

	Invariance	Condition
I	$SU(3)$	$(N_\phi - N_{\phi^\dagger} + N_q + N_u + N_d - N_{\bar{q}} - N_{\bar{u}} - N_{\bar{d}}) \mod 3 = 0$
II	$U(3)_q$	$(N_q - N_{\bar{q}} + N_{Y_u} - N_{Y_u^\dagger} + N_{Y_d} - N_{Y_d^\dagger}) \mod 3 = 0$
III	$U(3)_u$	$(N_u - N_{\bar{u}} - N_{Y_u} + N_{Y_u^\dagger}) \mod 3 = 0$
IV	$U(3)_d$	$(N_d - N_{\bar{d}} - N_{Y_d} + N_{Y_d^\dagger} + N_\lambda - N_{\lambda^\dagger}) \mod 3 = 0$
V	$U(3)_\chi$	$(N_\chi - N_{\bar{\chi}} - N_\lambda + N_{\lambda^\dagger}) \mod 3 = 0$
$\sum$ II+III+IV+V−I		$(N_\chi - N_{\bar{\chi}} - N_\phi + N_{\phi^\dagger}) \mod 3 = 0$

$\rightarrow \chi$ and ϕ decays into SM fields forbidden

Violation of Dark Minimal Flavor Violation

$\hookrightarrow$ assuming DMFV to be exact is unnatural

$\hookrightarrow$ expect all operators allowed by gauge symmetries to be generated

renormalizable operators

- renormalizable operators consistent with gauge symmetry are

$$\mathcal{O}_L = \bar{l}_L \chi H + \text{h.c.}$$
$$\mathcal{O}_B = \bar{q}_L (i\sigma^2) q_L^\dagger \phi^\dagger + \text{h.c.}$$
$$\mathcal{O}_m = \delta m_{ij} \bar{\chi}_i \chi_j$$

higher dimensional operators

- dark matter has to be stable on cosmological time scales

✔ stable

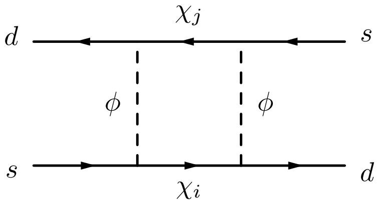
additional discrete symmetries need to be imposed

Main goals of our analysis

1. Which are the allowed structures of the coupling matrix λ beyond MFV?
2. What are viable mass hierarchies for the flavored dark matter spectrum?
3. What happens when combining flavor and dark matter constraints?
4. How strong are the mass bounds on the new particles from LHC searches?

New contributions to meson anti-meson mixing

- new box diagram:



- dominant NP mixing amplitude for the K meson system

$$M_{12}^{K,\text{new}} \sim (\xi_K^*)^2 F(x) \quad \text{where} \quad \xi_K = (\lambda\lambda^\dagger)_{sd} = \sum_{i=1}^{3} \lambda_{si}\lambda_{di}^*$$

ξ_K - involves elements of matrix λ, dependent on the meson system
$F(x)$ - box loop function

- analogous contributions to $B_{d,s} - \bar{B}_{d,s}$ mixing

The $B \to X_s\gamma$ decay

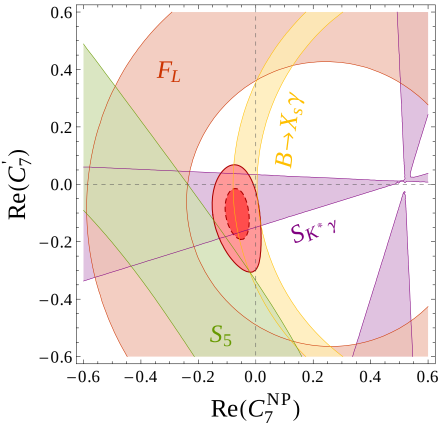
FIGURE FROM: ARXIV:1308.1501
W. ALTMANNSHOFER, D. STRAUB

- effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} \sim (C_7 Q_7 + C_7' Q_7' + \cdots)$$

with

$$Q_7 \sim \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}$$
$$Q_7' \sim \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}$$



- SM: C_7' is strongly suppressed due to the chiral structure of weak interactions

$$C'_{7,\text{SM}} = \frac{m_s}{m_b} C_{7,\text{SM}}$$

- new contribution

$$|\delta C_7'| \sim 0.04 \left[\frac{500\,\text{GeV}}{m_\phi}\right]^2 \left|\sum_{i=1}^{3} \lambda_{si}\lambda_{bi}^*\right|$$

→ NEGLIGIBLE

Negligible effects in ...

Rare decays $K \to \pi\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$

- no box contribution
  since no coupling to leptons in final states
- Z penguin contribution is zero
  due to chiral structure/new couplings to right-handed quarks only
- γ penguin is negliglible
  estimate from supersymmetric models

Electric dipole elements

- no relevant contribution since chirality flips are required

Electroweak precision tests

- γ and Z self-energies (scalar ϕ in the loop) are highly suppressed

Strategy for phenomenology

Step 1: **Preanalysis of flavor constraints**

- parametrize full mixing amplitude, e.g. B_q mixing

$$M_{12}^{B_q} = C_{B_q} e^{2i\varphi_{B_q}} M_{12}^{B_q,\text{SM}} \qquad (q = d, s)$$

SM corresponds to $C_{B_q} = 1$ and $\varphi_{B_q} = 0$

- use results of the model-independent NP fit by the UTfit collaboration
- fix flavor conserving parameters m_ϕ, m_χ and λ_0 to the values

$$m_\phi = 850\,\mathrm{GeV} \qquad m_\chi = 200\,\mathrm{GeV} \qquad \lambda_0 = 1$$

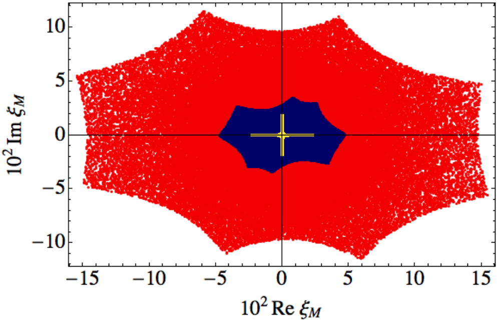
Step 2: **Combined analysis of flavor and DM constraints**

Lessons from flavor physics

$K^0 - \bar{K}^0$ mixing

$B_d^0 - \bar{B}_d^0$ mixing

$B_s^0 - \bar{B}_s^0$ mixing



- strongest constraint comes from $K^0 - \bar{K}^0$ mixing, the CP-violating parameter ε_K
- flavor constraints are under control if

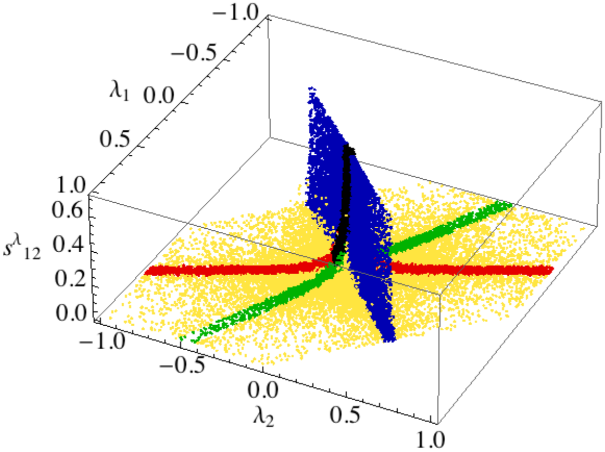
$$\begin{aligned} \xi_M \sim\ & \lambda\lambda^\dagger \\ =\ & U_\lambda D_\lambda D_\lambda^\dagger U_\lambda^\dagger = U_\lambda D_\lambda^2 U_\lambda^\dagger \\ \sim\ & \mathrm{diag}(\star_1, \star_2, \star_3) \end{aligned}$$

$\rightarrow$ "Universality"

"Flavor safe" dark matter scenarios

Universality is automatically fullfilled for ...

1. **universal scenario** (black): $\lambda_1 = \lambda_2 = 0$
2. **12-degeneracy** (blue): $\lambda_1 = \lambda_2$
3. **13-degeneracy** (red): $\lambda_2 = -2\lambda_1$
4. **23-degeneracy** (green): $\lambda_2 = -1/2\lambda_1$
5. **small mixing** (yellow): arbitrary D_λ



RECALL:

$$D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))$$

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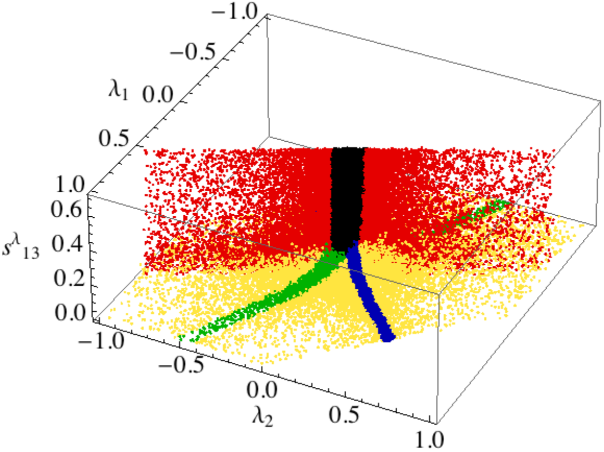

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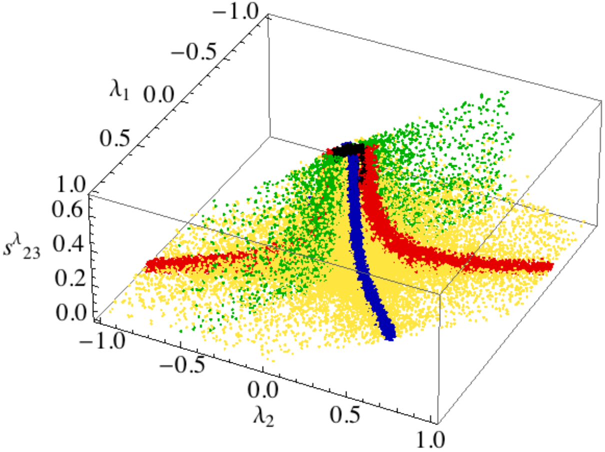

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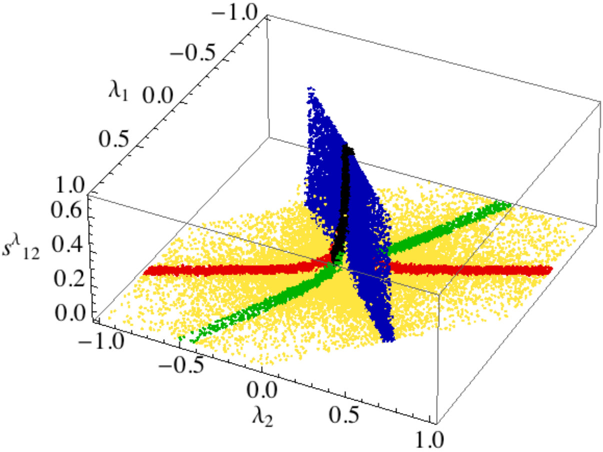

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Recovering the Minimal Flavor Violation limit

- Minimal Flavor Violation:
  quark-dark matter coupling has a very specific structure

$$\lambda = \alpha \mathbb{1} + \beta Y_d^\dagger Y_d$$

where

$$Y_d = \frac{\sqrt{2}}{v} \mathrm{diag}(m_d, m_s, m_b)$$

- mass pattern is fixed through

$$m_{ij} = m_\chi(\delta_{ij} + \eta\, \lambda_{ik}^\dagger \lambda_{kj})$$

- only a small subset of specific points fullfills condition
  $\rightarrow$ near the 12-degeneracy line, where ALL mixing angles are small

$\rightarrow$ DMFV is clearly BEYOND MFV
only the concept is similar

Mass hierarchies in the dark sector

Flavor observables do not fix the mass spectrum m_{χ_i}!

☹ *d*-flavored dark matter ☹

→ severely constrained by direct detection experiments and LHC searches

s- and *b*-flavored dark matter

→ similar for flavor physics and direct detection

☺ *b*-flavored dark matter ☺

→ *b*-jet signatures at colliders

→ possible explanation of γ ray signal from galactic center

P. AGRAWAL, B. BATELL, D. HOOPER, T. LIN (2014)

WE ASSUME ALWAYS:

→ *b*-flavored dark matter

$$\begin{aligned} m_{\chi_b} &< m_{\chi_d}, m_{\chi_s} \\ D_{\lambda,33} &> D_{\lambda,11}, D_{\lambda,22} \end{aligned}$$

Recall:

$$m_{\chi_i} = m_\chi(1 - |\eta|\, D^2_{\lambda,ii})$$

Dark matter phenomenology

Step 1: **Preanalysis of flavor constraints**

- so far: flavor conserving parameters have been fixed

Step 2: **Combined analysis of flavor and DM constraints**

- parameters are varied as follows

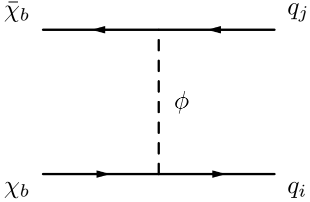
$$m_\phi = 850\,\mathrm{GeV} \qquad m_\chi : \text{ free} \qquad \lambda : \text{ free}$$

1. "single-flavor" freeze-out:
   for large mass splittings $\gtrsim 10\%$ between DM flavors only lightest flavor remains in the termal bath
2. "two-flavor" freeze-out:
   if small mass splittings $\lesssim 1\%$ between DM flavors multiple flavors can be present at freeze-out
3. ("three-flavor" freeze-out)

Relic abundance for single-flavor freeze-out

- relic abundance of the dark matter is set by annihilation

$$\langle \sigma v \rangle_{bb} = \frac{D^4_{\lambda,33}\, m^2_{\chi_b}}{32\pi (m^2_{\chi_b} + m^2_{\phi})^2}$$



- and is determined by solving the Boltzmann equation for the dark matter number density n at late times

$$\frac{dn}{dt} + 3Hn = -\underbrace{\langle \sigma v \rangle_{eff}}_{2.2\times 10^{-26}\mathrm{cm}^3/\mathrm{s}} (n^2 - n^2_{eq})$$

n - dark matter number density
H - Hubble constant
n_{eq} - equilibrium number density of χ
$\langle \sigma v \rangle_{eff}$ - $\langle \sigma v \rangle_{eff} = \frac{1}{2}\langle \sigma v \rangle$

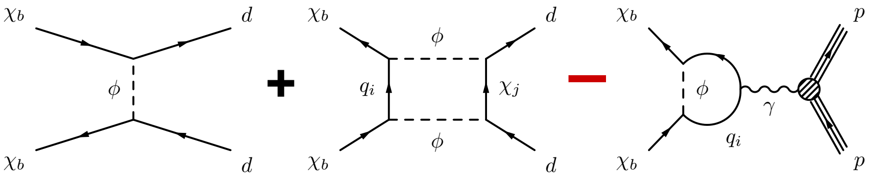
✔ relic density

Constraints from direct detection

- spin-independent contribution to the WIMP-nucleus scattering

$$\sigma_n^{SI} = \frac{\mu_n^2}{\pi}(Zf_p + (A - Z)f_n)^2$$

relevant processes:



$\rightarrow$ cancelation between the direct detection box diagram and the one-loop photon contribution

$\rightarrow$ we apply the bounds from the LUX experiment

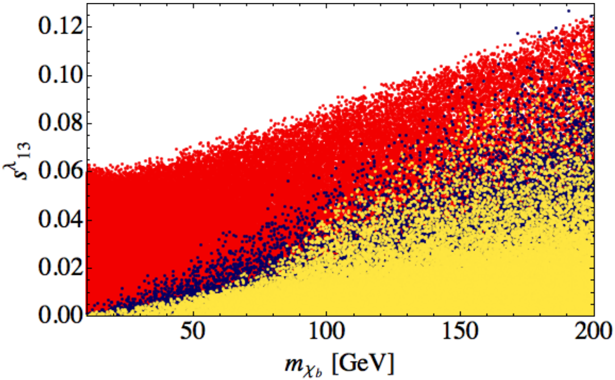
Results of combined analysis

constraints imposed:

Relic abundance fixes $D_{\lambda,33}$

- LUX only
- flavor only
- LUX & flavor

single-flavor freeze-out



→ non-trivial interplay of dark matter and flavor constraints

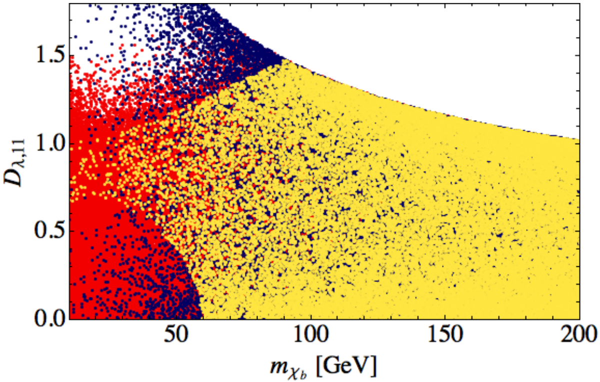
Results of combined analysis

constraints imposed:

Relic abundance
fixes $D_{\lambda,33}$

- LUX only
- flavor only
- LUX & flavor

single-flavor freeze-out



→ upper and a lower bound on the size of $D_{\lambda,11}$

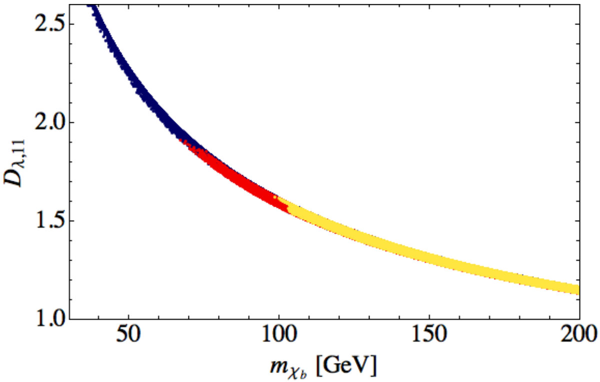
Results of combined analysis

constraints imposed:

Relic abundance fixes combination of $D_{\lambda,11}$ & $D_{\lambda,33}$

- LUX only
- flavor only
- LUX & flavor

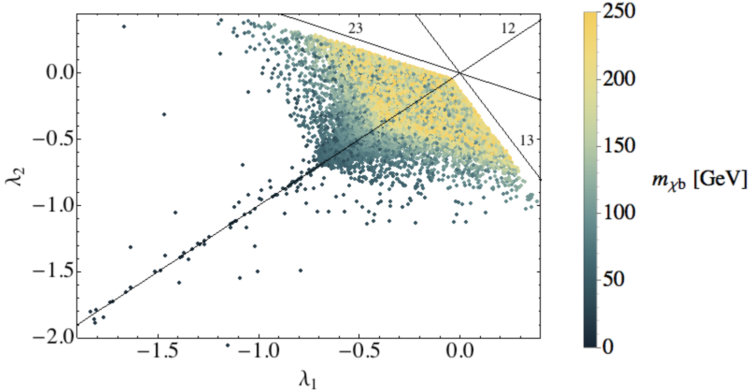
two-flavor freeze-out e.g. 13-degeneracy



→ 13-degeneracy scenario ruled out below $m_{\chi_b} \simeq 100\,\mathrm{GeV}$

Recovering flavor scenarios

Example: single-flavor freeze-out

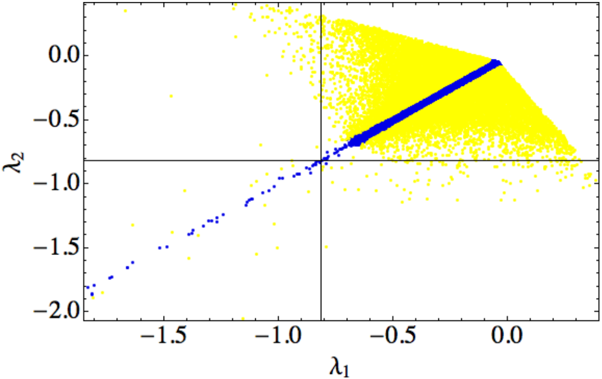


Recall: $D_\lambda = \lambda_0 \cdot \mathbb{1} + \text{diag}(\lambda_1, \lambda_2, -\lambda_1 - \lambda_2)$

$\rightarrow$ small m_{χ_b} implies sizeable non-universality $\lambda_{1,2} \neq 0$

Recovering flavor scenarios

Example: single-flavor freeze-out



Recall: $D_\lambda = \lambda_0 \cdot \mathbb{1} + \text{diag}(\lambda_1, \lambda_2, -\lambda_1 - \lambda_2)$

$\rightarrow$ only 12-degeneracy and small mixing scenario survive

A brief look at collider phenomenology

new particles within the reach of LHC

Dark Minimal Flavor Violation

$\rightarrow$ χ_i are nearly degenerate

$\rightarrow$ new particles have to be pair-produced

$\rightarrow$ particle spectrum is similar to simplified models of squarks and neutralinos in the MSSM

1. dark matter fermion χ_b and the heavier flavors $\chi_{d,s}$

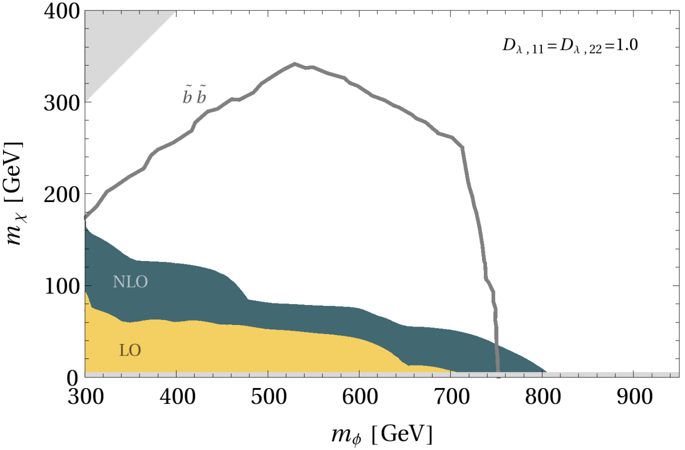
- $\chi_{d,s}$ decay to χ_b produces soft particles (jets, photons) + missing E_T

2. coloured scalar mediator ϕ

- pair-produced through QCD and through t-channel χ_d exchange
- decay $\phi \rightarrow q_i \chi_i$ with branching ratios given by $D^2_{\lambda,ii}$
  $\Rightarrow bb + \not{E}_T$, $bj + \not{E}_T$, $jj + \not{E}_T$ signatures

Mass bounds from dijet constraints

- CMS (& ATLAS) put strong bounds on sbottom and squark pair-production CMS-PAS-SUS-13-018
- bound on cross-section can be applied to DMFV



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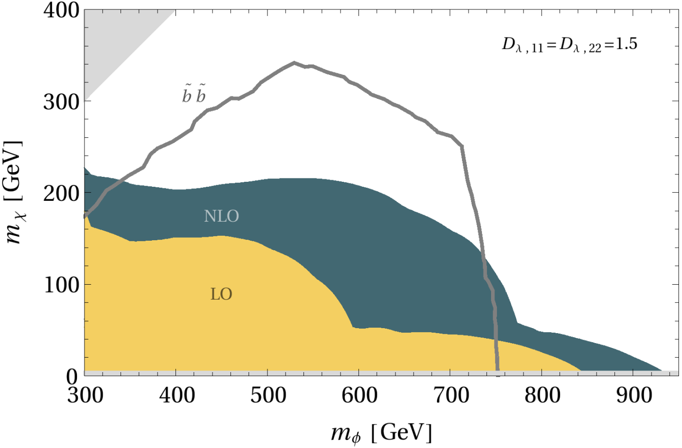
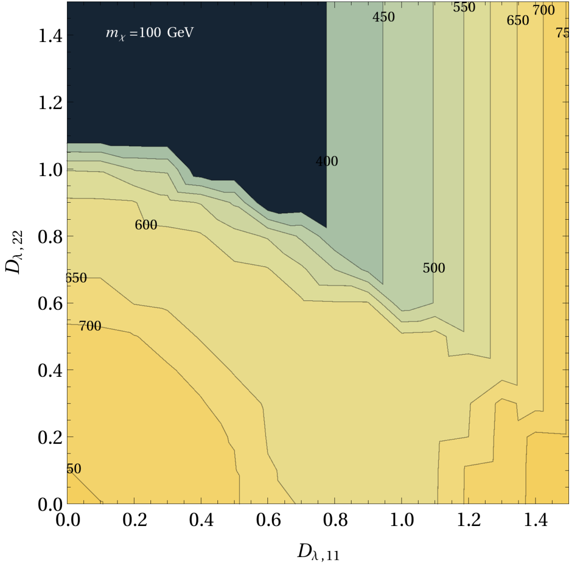


Exclusion contours from dijet constraints

exclusion contours for m_ϕ (in GeV) from the CMS sbottom and squark searches

$D_{\lambda,33}$ fixed by relic abundance

$m_\chi = 100$ GeV



Conclusions

- the mechanism to generate the flavor structure of the SM is unknown, assuming a similar mechanism in the dark sector suggests

"Dark Minimal Flavor Violation"

flavor symmetry, enlargered by an additional $U(3)_\chi$, is only broken by the new coupling λ and SM Yukawas

- the lightest dark matter particle is stable if DMFV is exact

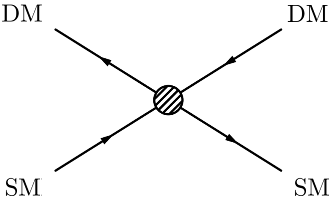
otherwise additional discrete symmetry is needed

- "flavor-safe" scenarios - beyond MFV - can be identified

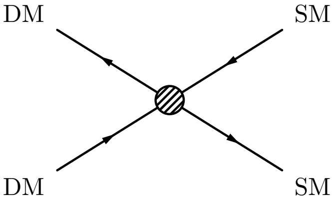
these can be directly used for further study

- non-trivial interplay of DM and flavor phenomenology
- LHC places strong bounds on the mediator mass, however there is still plenty of room for discovery

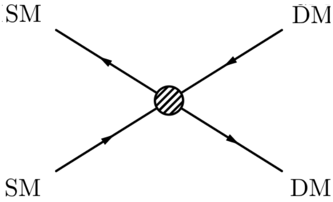
It is ~~worse~~ worth to consider flavored dark matter models beyond MFV!



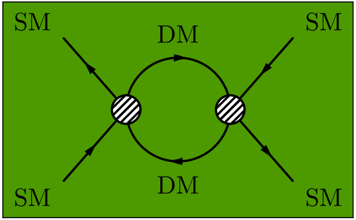
direct detection



indirect detection



collider searches

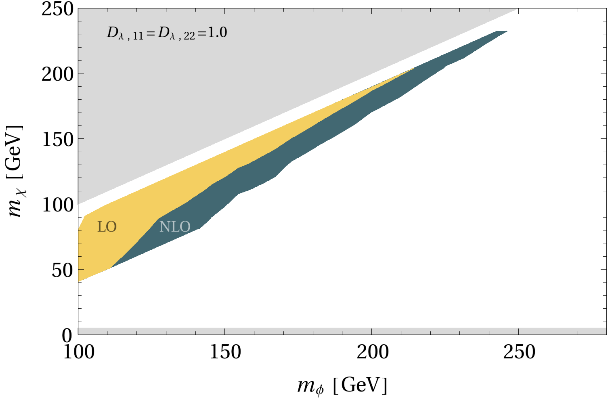


precision flavor data

Constraints from Monojet Searches

- monojet searches sensitive to ϕ pair-production
  if decay products are soft

- constraint on the compressed region $m_\chi \lesssim m_\phi$



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