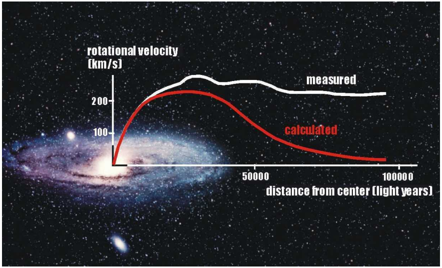
# Flavoured Dark Matter Beyond Minimal Flavour Violation

**Monika Blanke**

Flavorful Ways to New Physics
Freundenstadt – October 29, 2014

# Lots of Evidence for Dark Matter. . .



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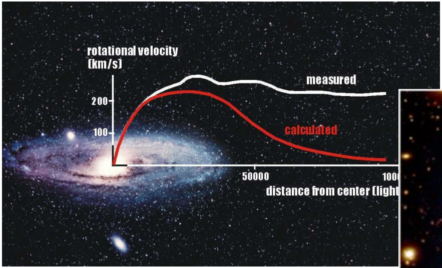


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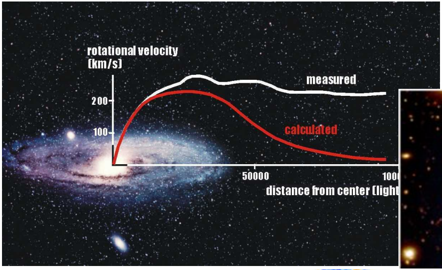


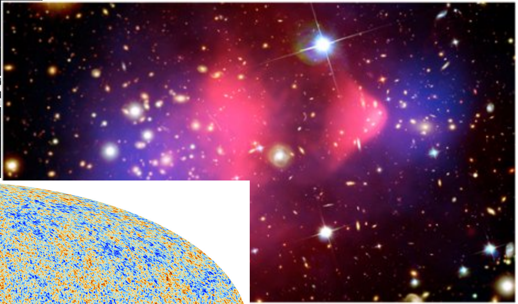

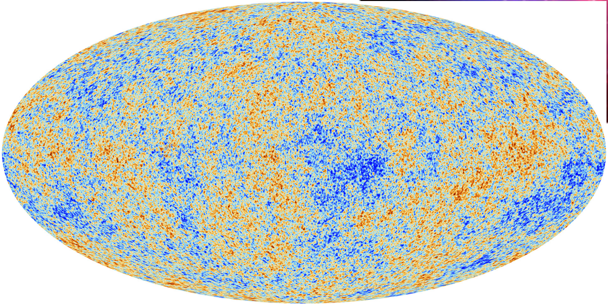

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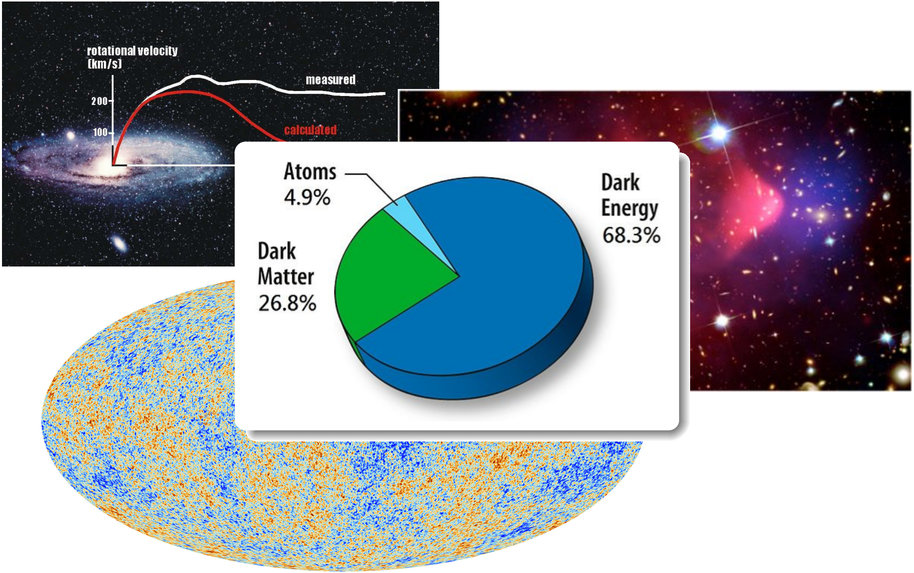


# . . . but What is It?


- ☐ non-baryonic
- ☐ gravitational interactions
- ☐ relic density $\Omega_{DM} h^2 = 0.119$
- ☐ stable
- ☐ neutral – no em. charge and no colour
- ☐ cold (or warm. . . ), non-relativistic

**Theory prejudice:** expect new particles at the weak scale

➢ **“WIMP miracle”:** weak scale annihilation cross section automatically gives correct relic density

# Flavoured Dark Matter

**unknown DM properties**

- coupling to SM particles?
- single particle or entire sector?
- analogy to ordinary SM matter
  ➢ **flavoured?**

**Assumption:**

dark matter carries flavour and comes in multiple copies



✓ non-baryonic

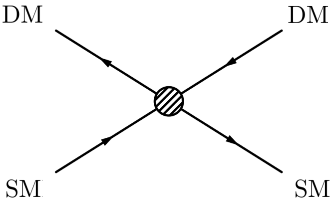
✓ gauge singlet

**New coupling to quarks:**

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

| | |
|---|---|
| $d_{Ri}$ | right-handed down quarks |
| $\chi_j$ | DM particle, flavoured |
| $\phi$ | new scalar, coloured |

# How to Detect Flavoured Dark Matter




**direct detection**

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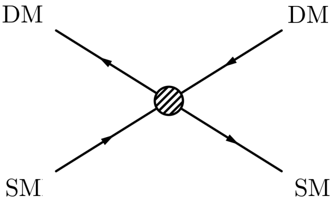


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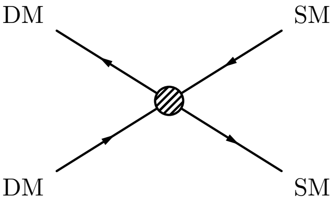


**indirect detection**

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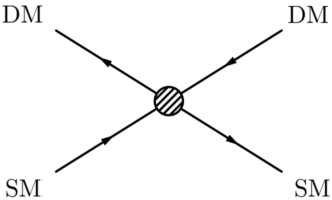


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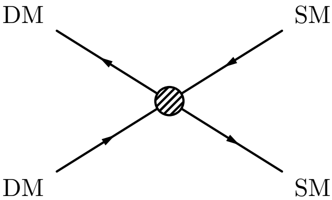


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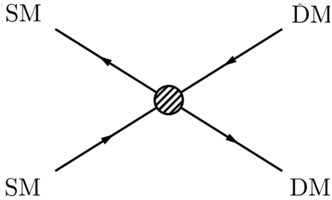


**collider searches**

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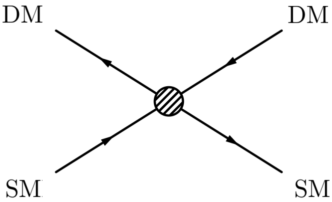


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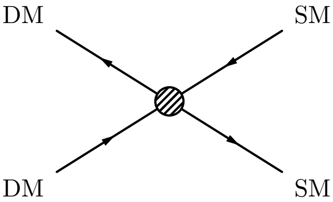


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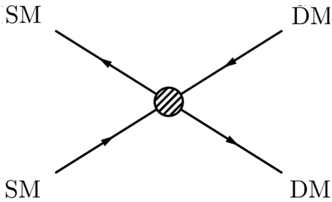


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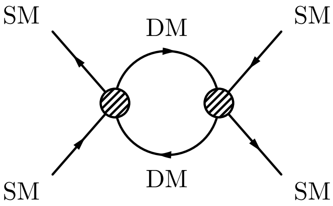


**precision flavour data**

# The Idea is not New...

**Flavoured DM received a lot of attention in recent years**, see e. g.

- 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)

➢ **common to all these studies:**

Minimal Flavour Violation

# Why Minimal Flavour Violation (MFV)?

- flavour violating observables in impressive agreement with SM
- new flavour violating interactions must be very suppressed
- naturally achieved if no new sources of flavour violation are introduced

**Minimal Flavour Violation:**
flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d$
only broken by Yukawa couplings $Y_u$, $Y_d$

**Consequences:**

- smallness of flavour violating effects carries over to BSM sector
- all flavour violating effects parametrised in an expansion in $Y_{u,d}$

# Going beyond MFV

**MFV**

➢ HARMLESS

But not very exciting.

# Going beyond MFV

**MFV**


➢ HARMLESS

But not very exciting.

**non-MFV**

➢ DANGEROUS

But interesting if you know how to handle it!

# Outline

1. Dark Minimal Flavour Violation – a Minimal Model
2. Phenomenology
   - Flavour Constraints
   - Dark Matter Phenomenology
   - Collider Signatures
3. Conclusions

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based on: P. Agrawal, MB, K. Gemmler, JHEP 10 (2014) 072

# A Simple Model of Flavoured Dark Matter

Flavoured Dirac-fermionic DM $\chi_j$ and couples to down quarks via a coloured scalar mediator

$$\begin{aligned}\mathcal{L}_{\rm NP} \quad = \quad & i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{d}_{Ri}\chi_j\phi \\ & + \lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi\end{aligned}$$

**Assumption:** Flavour symmetry

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\chi$$

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

➢ "Dark Minimal Flavour Violation" (DMFV)

# A Closer Look at DMFV

## Dark matter mass

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

$$m_{\chi_i} = m_\chi(\mathbb{1} + \eta\,\lambda^\dagger\lambda + \ldots)_{ii}$$

## Dark matter stability

- DM stability is guaranteed if DMFV is exact (unbroken $\mathbb{Z}_3$ symmetry)

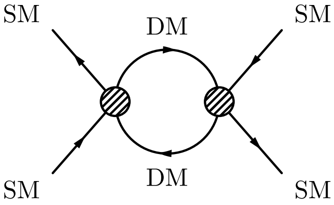
## Parametrisation of DM-quark coupling

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

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

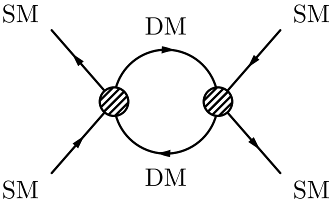
| | |
|---|---|
| $U_\lambda$ | unitary matrix, 3 mixing angles $s^\lambda_{12}$, $s^\lambda_{13}$, $s^\lambda_{23}$ and 3 phases |
| $D_\lambda$ | real diagonal matrix, e.g. $D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1+\lambda_2))$ |

# How to Detect Flavoured Dark Matter in. . .




**precision flavour data**

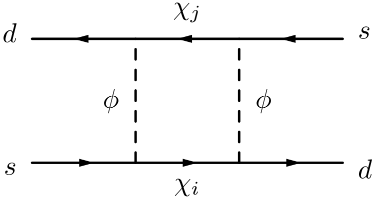
# How to Constrain Flavoured Dark Matter by...




**precision flavour data**

# New Contributions to Meson-Antimeson Mixing

- new box diagram for $K^0 - \bar{K}^0$ mixing




- dominant NP mixing amplitude for the $K$ meson system

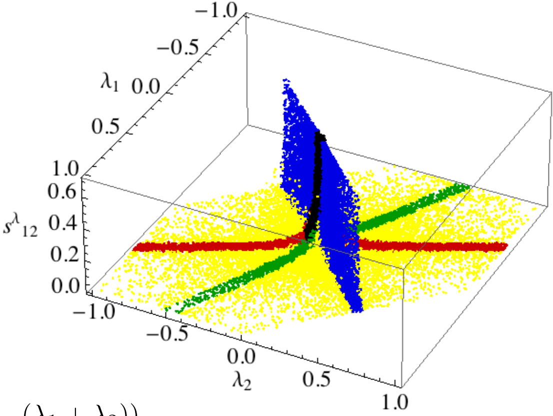
$$M_{12}^{K,\text{new}} \sim (\xi_K^*)^2 F(x) \quad \text{where} \quad \xi_K = (\lambda\lambda^\dagger)_{sd} = \sum_{i=1}^{3} \lambda_{si}\lambda_{di}^*$$

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

# "Flavour Safe" Dark Matter Scenarios

Strong constraints from $K^0 - \bar{K}^0$ and $B_{d,s} - \bar{B}_{d,s}$ mixing ➢ **$\lambda$ has to be non-generic**

- **3-flavour universality**
  (black): $\lambda_1 = \lambda_2 = 0$
- **2-flavour universalities**
  (blue): $\lambda_1 = \lambda_2$
  (red): $\lambda_2 = -2\lambda_1$
  (green): $\lambda_2 = -1/2\lambda_1$
- **small mixing**
  (yellow): arbitrary $D_\lambda$




Recall: $D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))$
fixed: $m_\phi = 850\,\text{GeV}, m_\chi = 200\,\text{GeV}, \lambda_0 = 1$

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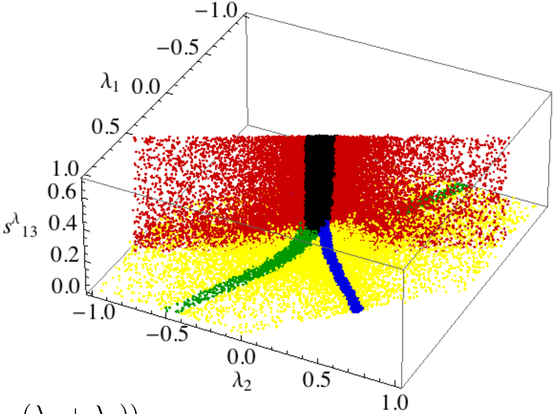


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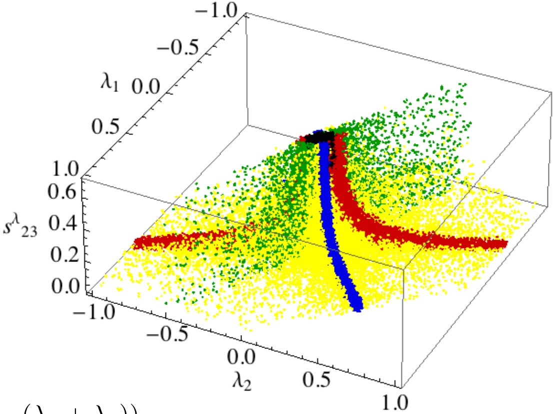


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# A Look at $B \to X_s\gamma$

- effective Hamiltonian:

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

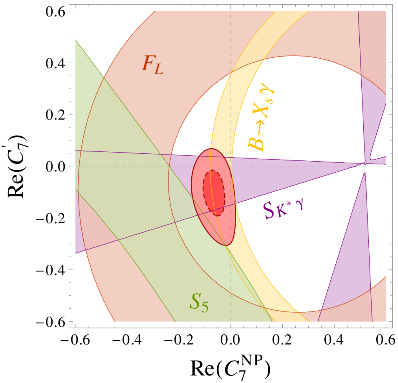
$$Q_7 \sim \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}$$

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

- SM: $C_7'$ strongly suppressed by chiral structure of weak interactions

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

Figure from Altmannshofer, Straub (2013)



# A Look at $B \to X_s\gamma$

- effective Hamiltonian:

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

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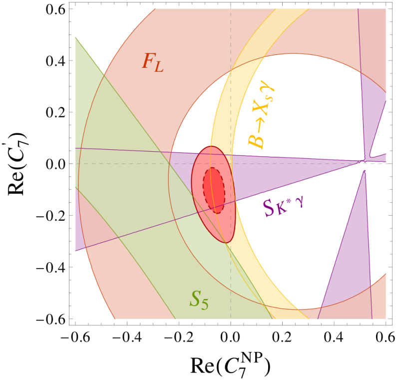
- SM: $C_7'$ strongly suppressed by chiral structure of weak interactions

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

- new contribution

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

Figure from Altmannshofer, Straub (2013)




➢ **negligible!**

# Negligible Effects in...

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

- 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
- $\gamma$ penguin ($\mu^+\mu^-$ final state) is negligible
  obtained from corresponding SUSY results

**Electric dipole elements**

- no one-loop contribution since chirality flips are required
- two-loop Barr-Zee diagram is CP-conserving

**Electroweak precision tests**

- loop contributions with additional suppression by $U(1)_Y$ coupling

# Mass Spectrum in the Dark Sector

Meson mixing observables place strong constraints on the structure of $\lambda$ but do not fix the mass spectrum $m_{\chi_i}$ in the dark matter sector!

- $d$-flavored dark matter severely constrained by direct detection experiments and LHC searches ☹
- $s$- and $b$-flavored DM similar for flavor physics and direct detection
- advantages of $b$-flavored DM
  - $b$-jet signatures at colliders ☺
  - possible explanation of $\gamma$ ray signal from galactic center ☺

Hooper et al. (2009)..., Agrawal et al. (2014)

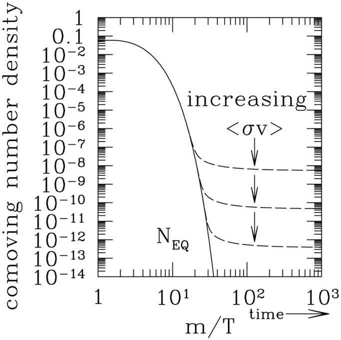
➢ **For the rest of this talk we assume $b$-flavoured dark matter**

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

Recall: $m_{\chi_i} = m_\chi(1 + \eta\, D^2_{\lambda,ii} + \dots)$

# Dark Matter as Thermal Relic

- WIMP production and annihilation in equilibrium in the early universe
- dark matter "freezes out" when annihilation rate $\langle \sigma v \rangle$ drops below Hobble expansion rate
- relic abundance determined by solving Boltzmann equation for DM number density $n$ at late times




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

| | |
|---|---|
| $n$ | dark matter number density |
| $H$ | Hubble constant |
| $n_{eq}$ | equilibrium number density of $\chi$ |

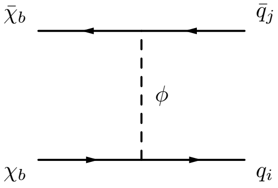

✓ relic density

# Flavored Dark Matter Freeze-out

- freeze-out condition depends on life time of heavier dark flavours

- for significant mass splitting $\gtrsim 10\%$ heavy flavours decay fast
  - ➢ only $\chi_b$ contributes to relic abundance

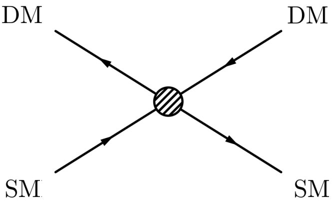
$$\langle \sigma v \rangle_{bb} = \frac{D^4_{\lambda,33} m^2_{\chi_b}}{32\pi (m^2_{\chi_b} + m^2_\phi)^2}$$




- for small mass splittings $\lesssim 1\%$ multiple flavours present at freeze-out temperature
  - ➢ sum over all flavours $i, j$ present at freeze-out

$$\langle \sigma v \rangle = \sum_{i,j} \langle \sigma v \rangle_{ij}$$

# Flavoured Dark Matter in. . .




**direct detection**

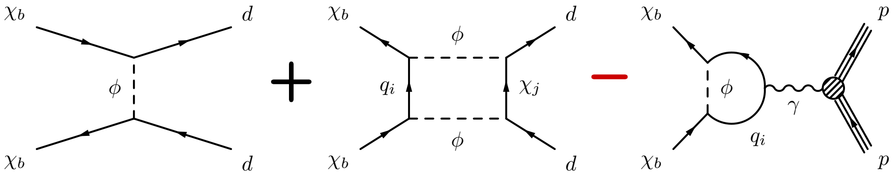
# Direct Detection Experiments

Spin-independent contribution to the WIMP-nucleus scattering

$$\sigma^{SI} = \frac{\mu_N^2}{\pi}|Zf_p + (A-Z)f_n|^2$$

constrained in direct detection experiments, e. g. LUX

**relevant processes:**



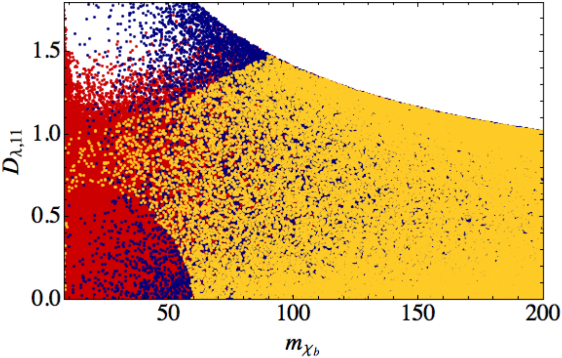

➢ partial cancellation between tree/box and photon penguin contributions

# Single Flavor Freeze-out

$m_\phi = 850\,\text{GeV}$
$m_{\chi_{d,s}} > 1.1 m_{\chi_b}$
relic abundance fixes $D_{\lambda,33}$

constraints imposed:

- LUX only
- flavour only
- LUX & flavour

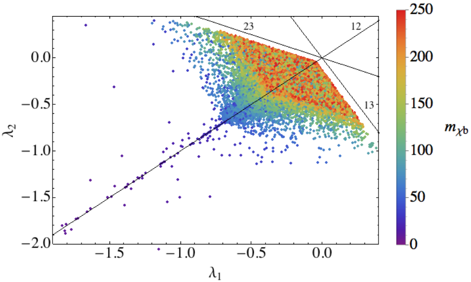



**for low DM mass:**

- combined constraint stronger than individual ones
- *lower* bound on $\chi_i$ coupling to $d$ quark, $D_{\lambda,11}$

# Recovering Flavour Scenarios

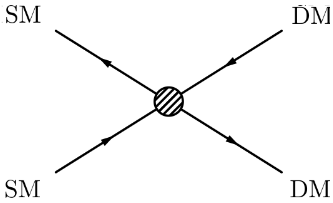
## 1. Single flavour freeze-out




- only 12-degeneracy and small mixing scenario survive
- small DM mass $m_{\chi_b}$ implies sizeable non-universality $\lambda_{1,2} \neq 0$

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

# Flavoured Dark Matter in. . .




**collider searches**

# Flavoured Dark Matter at the LHC

DMFV ➢ unbroken $\mathbb{Z}_3$ ➢ new particles have to be pair-produced

**dark matter fermion $\chi_b$ and the heavier flavours $\chi_{d,s}$**

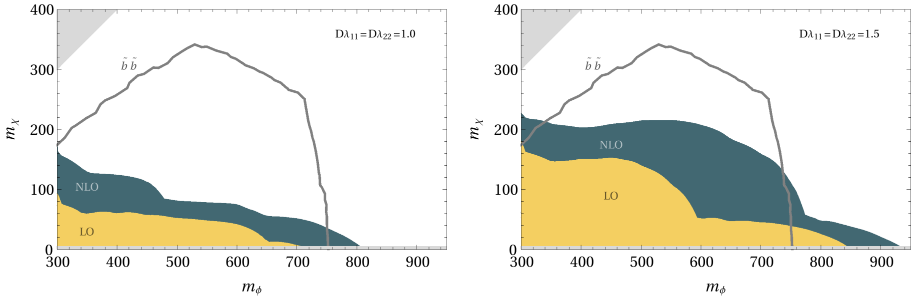
- nearly degenerate due to DMFV
- $\chi_{d,s}$ decay to $\chi_b$ produces soft particles (jets, photons) + missing $E_T$
  ➢ LHC monojet+$\not{E}_T$ searches sensitive to $\chi$ pair production

**coloured scalar mediator $\phi$**

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

# Constraints from $bb + \not{E}_T$

- CMS (& ATLAS) put strong bounds on bottom squark pair-production from $bb + \not{E}_T$ CMS-PAS-SUS-13-018
- bound on cross-section can be applied to DMFV
  - production cross section enhanced by $t$-channel $\chi_d$ exchange
  - $bb + \not{E}_T$ signal suppressed by $\phi \to b\chi_b$ branching ratio



# Conclusions

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

**"Dark Minimal Flavour Violation"**

additional $U(3)_\chi$ flavour symmetry

only broken by the new coupling matrix $\lambda$

- DMFV (if exact) ensures stability of lightest Dark Flavour

(otherwise additional symmetry is needed)

- flavour constraints imply non-generic structure for coupling matrix $\lambda$
  ➢ coupling universalities or small mixing angles

- non-trivial interplay of dark matter, flavour and LHC phenomenology

# Back-up

# Dark Matter Stability

Similar proof in MFV: Batell, Pradler, Spannowsky (2011)

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

**invariant under ...**

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

| | | |
|---|---|---|
| I | $SU(3)_c$ | $(N_\phi - N_{\phi^\dagger} + N_q + N_u + N_d - N_{\bar{q}} - N_{\bar{u}} - N_{\bar{d}}) \mod 3 = 0$ |
| 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 $(N_\chi - N_{\bar{\chi}} - N_\phi + N_{\phi^\dagger}) \mod 3 = 0$

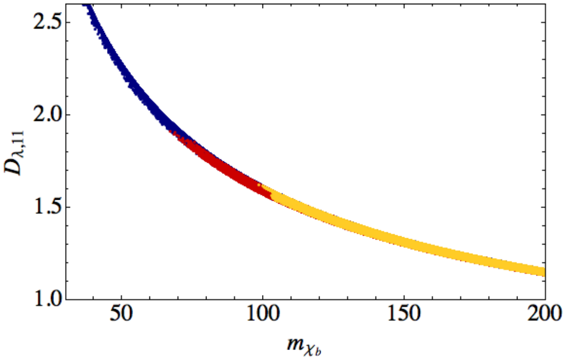
➢ $\mathbb{Z}_3$ **symmetry forbids $\chi$ and $\phi$ decays into SM fields**

# Multi Flavour Freeze-out – 13-Degeneracy

relic abundance fixes $D^2_{\lambda,11} + D^2_{\lambda,33}$

$m_\phi = 850$ GeV

$m_{\chi_d} \simeq m_{\chi_b}, m_{\chi_s} > 1.1 m_{\chi_b}$



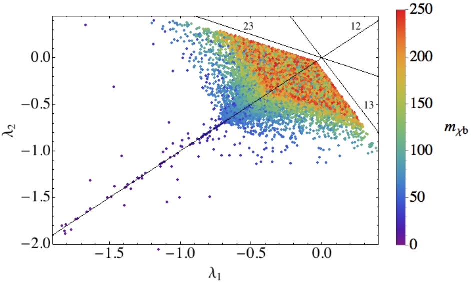

constraints imposed:

- LUX only
- flavour only
- LUX & flavour

➢ **lower bound on DM mass:** $m_{\chi_b} \gtrsim 95$ GeV

# Recovering Flavour Scenarios

## 1. Single flavour freeze-out

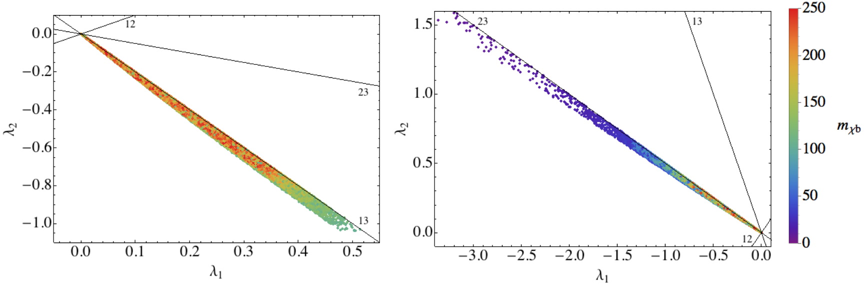



- only 12-degeneracy and small mixing scenario survive
- small DM mass $m_{\chi_b}$ implies sizeable non-universality $\lambda_{1,2} \neq 0$

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

# Recovering Flavour Scenarios

## 2. Two flavour freeze-out

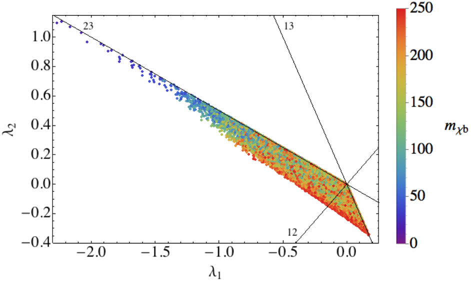



- 13- or 23-degeneracy scenario
- small DM mass $m_{\chi_b}$ implies sizeable non-universality $\lambda_{1,2} \neq 0$

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

# Recovering Flavour Scenarios

## 3. Three flavour freeze-out




- all flavor scenarios present
- small DM mass $m_{\chi_b}$ implies sizeable non-universality $\lambda_{1,2} \neq 0$

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

# Constraints from Monojet Searches I

- monojet searches sensitive to $\chi$ pair-production with ISR hard jet
- recansting exp. bounds

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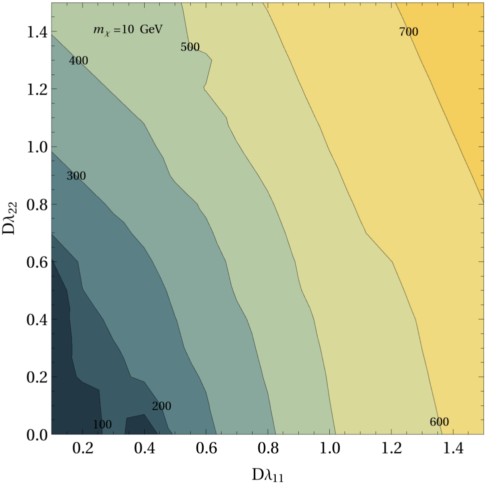
  ➢ limit on $m_\phi$ depending on couplings $D_{\lambda,ii}$

- rather independent of $m_\chi$



# Constraints from Monojet Searches II

- monojet searches also sensitive to $\phi$ pair-production if decay products are soft
- constraint on the compressed region $m_\chi \lesssim m_\phi$