Simplified models of quark-flavoured dark matter beyond Minimal Flavour Violation

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Theory seminar

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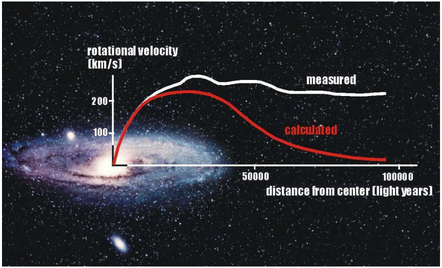
Lots of evidence for dark matter. . .



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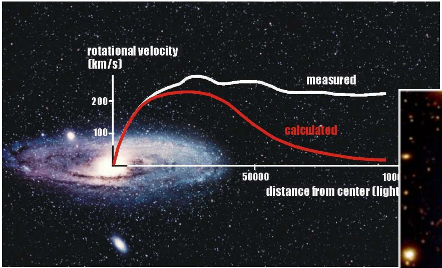

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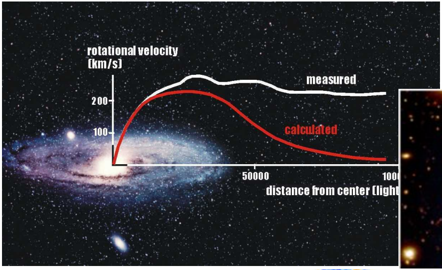

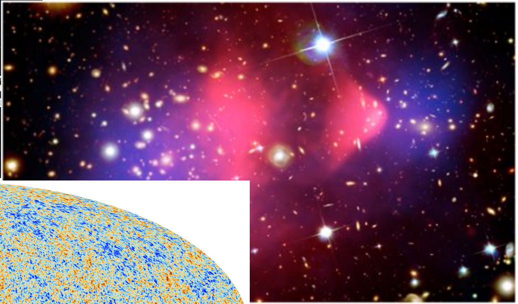

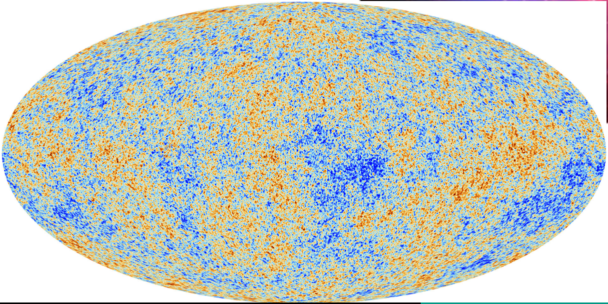

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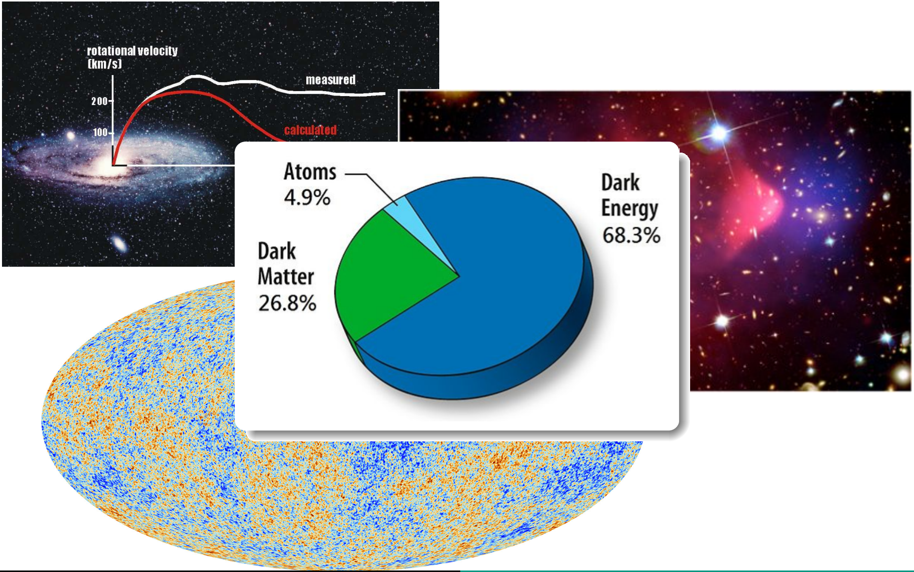


. . . but what is it?

- ☐ 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?

Why should we care about dark flavours?

Flavoured dark matter?

Why should we care about dark flavours?

Flavoured dark matter?

unknown DM properties

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

➢ **flavoured?**

Assumption:

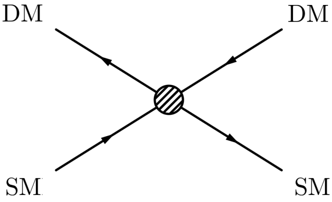
Dark matter carries flavour
and comes in multiple copies

➢ **New coupling to quarks:**

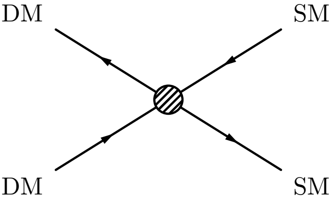
e. g. $\lambda^{ij}\bar{q}_i\chi_j\phi$

q_i quark
χ_j DM particle, flavoured
ϕ new scalar, coloured

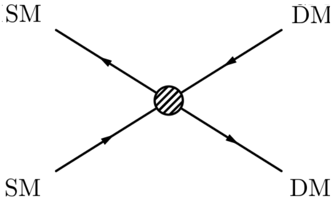
Signatures of flavoured dark matter



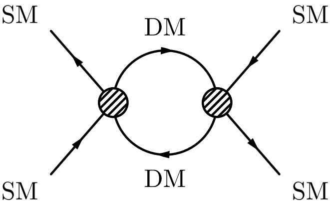
direct detection



indirect detection



collider searches



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 most studies: Minimal Flavour Violation**

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!

Taking one step beyond MFV

Minimal flavour violation (MFV)

- quark flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d$ only broken by SM Yukawa couplings Y_u, Y_d
- FCNC processes governed by the same CKM factors as in the SM

Dark Minimal Flavour Violation (DMFV)

- 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 λ [1]
- new source of flavour violation λ ➢ potentially interesting non-MFV effects in the flavour sector

➢ **various possibilities for model building**

[1] also coupling to leptons can be assumed

Chen, Huang, Takhistov (2015)

DMFV model building

- DM introduced as Dirac fermion χ that carries no gauge quantum numbers, but transforms as $U(3)_\chi$ flavour triplet
- coupling to SM quarks via scalar mediator ϕ, carrying the gauge quantum numbers of the respective quark
- phenomenologically: lightest χ flavour (stable, DM) couples dominantly to third generation

***b*-DMFV**: $\lambda_{ij}\,\phi\,\bar{d}^i_R\,\chi^j$	Agrawal, MB, Gemmler, JHEP 10 (2014) 72
***t*-DMFV**: $\lambda_{ij}\,\phi\,\bar{u}^i_R\,\chi^j$	MB, Kast, JHEP 05 (2017) 162
***q*-DMFV**: $\lambda_{ij}\,\phi\,\bar{q}^i_L\,\chi^j$	MB, Das, Kast, work in progress

➢ **each (simplified) model has distinct phenomenology**

General features of 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)

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

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

b-DMFV

Bottom-flavoured DM beyond MFV

Agrawal, MB, Gemmler (2014)

***b*-DMFV:** simplified model of flavoured Dirac-fermionic DM χ_j coupling to down-type quarks via a coloured scalar mediator

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

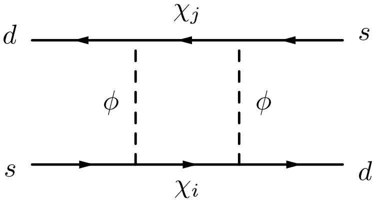
Assumptions:

- **Dark Minimal Flavour Violation (DMFV)**
  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 λ
- DM is bottom-flavoured: $m_{\chi_b} < m_{\chi_d}, m_{\chi_s}$

➢ **rich and interesting phenomenology**

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

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

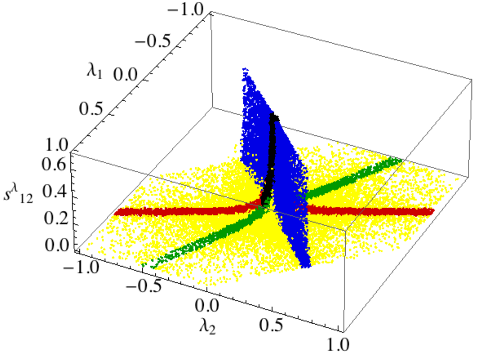
- analogous contributions to $B_{d,s} - \bar{B}_{d,s}$ mixing

Lessons from K and $B_{d,s}$ meson mixing

Large contributions to $K^0 - \bar{K}^0$ and $B_{d,s} - \bar{B}_{d,s}$ mixing

➢ **λ 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_λ



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

fixed: $m_\phi = 850\,\text{GeV}, m_\chi = 200\,\text{GeV}, \lambda_0 = 1$

Agrawal, MB, Gemmler (2014)

What about rare B and K decays?

$b \to s\gamma$ transition described by

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

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

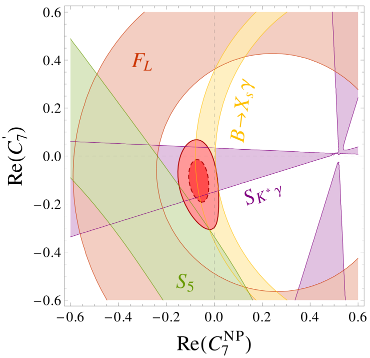
$$Q_7' \sim \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}$$

➢ new contribution

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

➢ **negligible effects in $b \to s\gamma$**

Figure from Altmannshofer, Straub (2013)



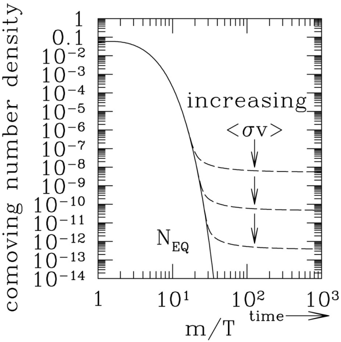
No new one-loop contribution to Z penguin and boxes:

➢ negligible effects also in $B_{s,d} \to \mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$, $K \to \pi\nu\bar{\nu}\ldots$

Agrawal, MB, Gemmler (2014)

Dark matter as thermal relic

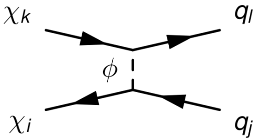
- WIMP production and annihilation in equilibrium in the early universe
- dark matter "freezes out" when annihilation rate $\langle\sigma v\rangle$ drops below Hobble expansion rate
- relic abundance determined by solving Boltzmann equation for DM number density n at late times



$$\frac{dn}{dt} + 3Hn = -\underbrace{\langle\sigma v\rangle_{eff}}_{2.2\times10^{-26}\mathrm{cm}^3/\mathrm{s}}\left(n^2 - n_{eq}^2\right)$$

n	dark matter number density
H	Hubble constant
n_{eq}	equilibrium number density of χ

Flavored dark matter freeze-out

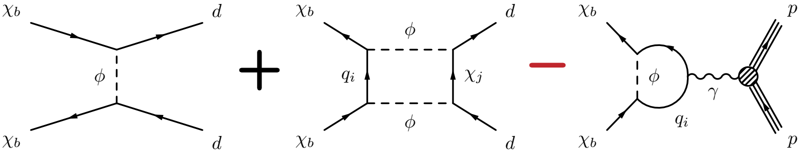


Agrawal, MB, Gemmler (2014)
MB, Kast (2017)

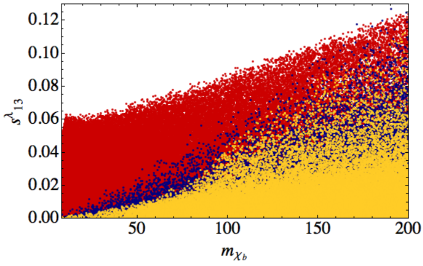
- freeze-out condition depends on life time of heavier dark flavours and on DM mass
- for significant mass splitting $\gtrsim 10\%$ heavy flavours decay fast
  ➢ only χ_b contributes to relic abundance
- for small mass splittings $\lesssim 1\%$ multiple flavours $\chi_{i,k}$ present at freeze-out temperature
  ➢ sum over all DM flavours that are still present
- only sum over final states $q_{j,l}$ that are kinematically accessible (relevant mainly for t-DMFV)

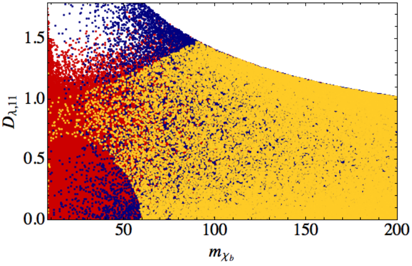
Constraints from LUX & co.

Dark matter scattering off nuclei. . . AGRAWAL, MB, GEMMLER (2014)



. . . constrains the DM coupling matrix λ





constraints imposed: LUX only, flavour only , LUX & flavour

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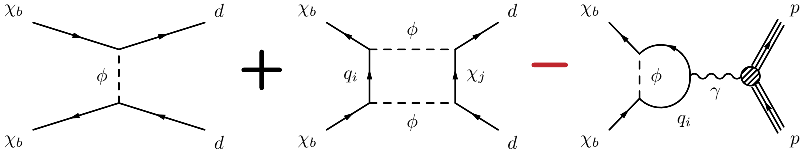

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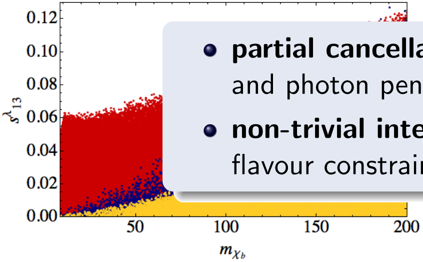
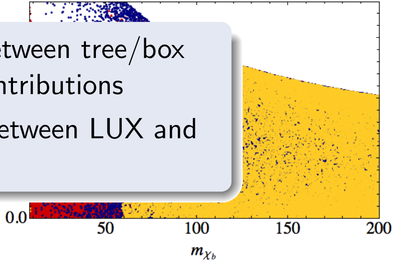




- **partial cancellation** between tree/box and photon penguin contributions
- **non-trivial interplay** between LUX and flavour constraints

constraints imposed: LUX only, flavour only , LUX & flavour

b-DMFV at the LHC

Agrawal, MB, Gemmler (2014)

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

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

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

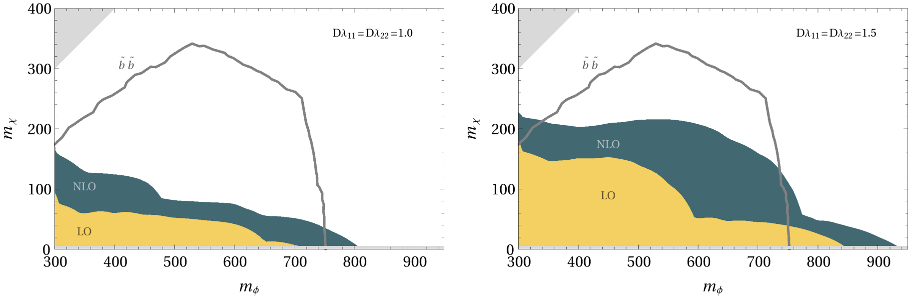
coloured scalar mediator ϕ

- pair-produced through QCD and through t-channel χ_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 $bb + \not{E}_T$

Agrawal, MB, Gemmler (2014)

- 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 χ_d exchange
  - $bb + \not{E}_T$ signal suppressed by $\phi \to b\chi_b$ branching ratio



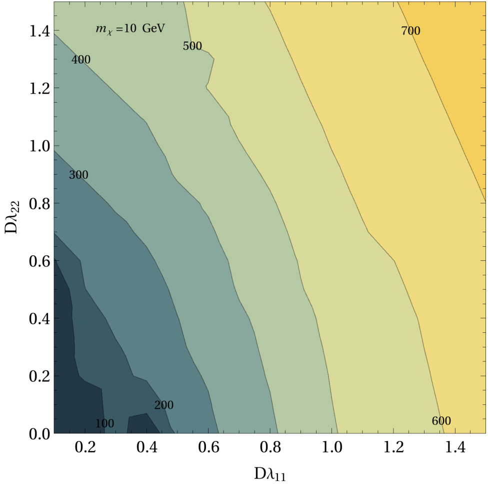
Constraints from monojet searches I

- monojet searches sensitive to χ pair-production with ISR hard jet
- recasting exp. bounds

  ATLAS-CONF-2012-147
  CMS-PAS-EXO-12-048

  ➢ limit on m_ϕ depending on couplings $D_{\lambda,ii}$
- rather independent of m_χ

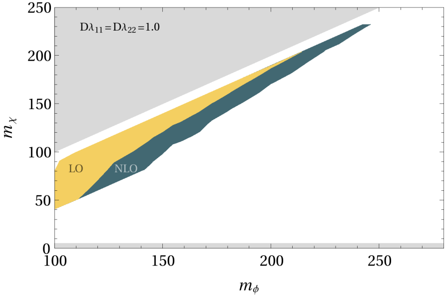
AGRAWAL, MB, GEMMLER (2014)

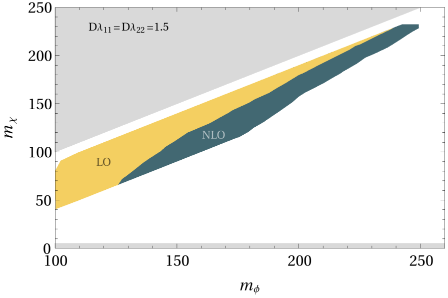


Constraints from monojet searches II

Agrawal, MB, Gemmler (2014)

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





t-DMFV

Top-flavoured dark matter beyond MFV

Flavoured Dirac-fermionic DM χ_j and couples to up-type quarks via a coloured scalar mediator ϕ MB, Kast (2017)

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

Assumptions:

- DMFV: λ constitutes the *only* new source of flavour violation
- DM is top-flavoured: $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

Parametrisation of DM-quark coupling: $\lambda = U_\lambda D_\lambda$

U_λ unitary matrix, 3 mixing angles θ_{12}, θ_{13}, θ_{23} and 3 phases
D_λ real diagonal matrix, e.g. $D_\lambda = \mathrm{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})$

LHC constraints

- most stringent constraints from mediator pair production
- signatures similar to SUSY squarks
  - ➢ $t\bar{t} + \not{E}_T$, $jj + \not{E}_T$
  - ➢ also $tj + \not{E}_T$

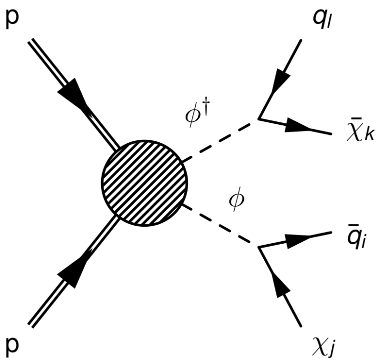
recall Flavoured Naturalness:
MB, Giudice, Paradisi, Perez, Zupan (2014)

- imposing ATLAS run 1 cross-section limits on our model, we find

$$m_\phi \gtrsim 850\,\text{GeV}$$

for DM couplings $D_{\lambda,ii} \leq 2$

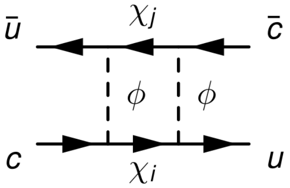
MB, Kast (2017)

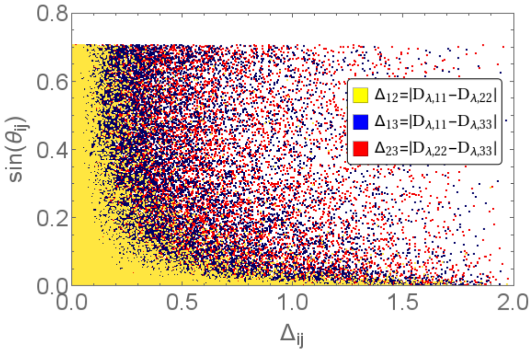


Flavour constraints

MB, Kast (2017)

- no impact on K and B meson decays
- contribution to $D^0 - \bar{D}^0$ mixing





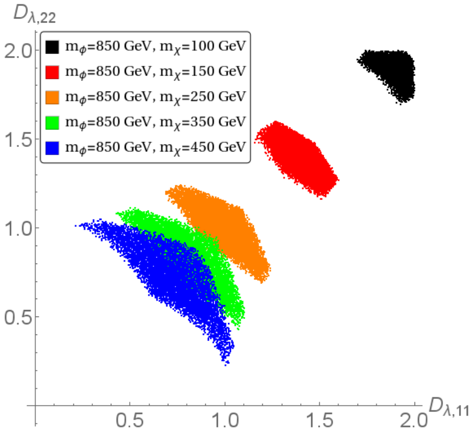
large 12-mixing only for quasi-degenerate $\chi_{u,c}$:

$\Delta_{12} \ll 1$ or $\theta_{12} \sim 0$

Constraint from observed relic abundance

MB, Kast (2017)

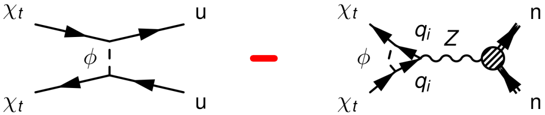
- annihilation cross-section relates mediator mass m_ϕ, DM mass m_χ, and DM couplings $D_{\lambda,ii}$
- for fixed mediator mass, smaller DM mass implies larger couplings
- $D_{\lambda,ii} > 2$ causes problems with LHC constraints



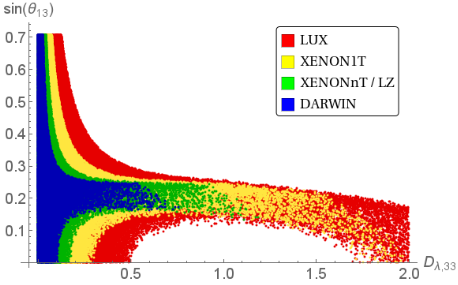
➢ **lower bound on DM mass from combination of thermal relic condition and LHC data**

Constraints from direct detection experiments

- with top-flavoured DM, Z-penguin contribution becomes relevant



➢ realisation of xenophobic DM scenario Feng, Kumar, Sanford (2013)



- cancellation between tree-level and Z-penguin contribution requires non-zero mixing angle θ_{13}
- for future experiments, cancellation not sufficiently effective for all xenon isotopes

  ➢ **upper bound on coupling**

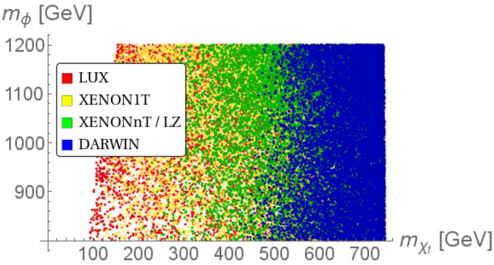
MB, Kast (2017)

Results of combined analysis

MB, Kast (2017)

Putting everything together:

- interesting interplay of different constraints
- non-trivial constraints on parameter space, i. e. masses, couplings, and mixing angles



- increasingly stringent lower bound on DM mass from future liquid xenon experiments

Conclusions

- mechanism generating 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 λ

- DMFV (if exact) ensures stability of lightest dark flavour
- various simplified models possible, depending on coupling to SM quarks
- rich and interesting phenomenology

Backup slides

Dark matter stability (for b-DMFV)

AGRAWAL, MB, GEMMLER (2014)
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 $Y_u \ldots Y_u^\dagger \ldots Y_d \ldots Y_d^\dagger \ldots \lambda \ldots \lambda^\dagger \ldots$

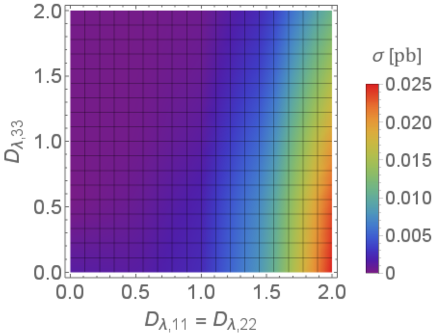
I	$SU(3)_c$	$(N_\phi - N_{\phi^\dagger} + N_q + N_u + N_d - N_{\bar{q}} - N_{\bar{u}} - N_{\bar{d}}) \mod 3 = 0$
II	$U(3)_q$	$(N_q - N_{\bar{q}} + N_{Y_u} - N_{Y_u^\dagger} + N_{Y_d} - N_{Y_d^\dagger}) \mod 3 = 0$
III	$U(3)_u$	$(N_u - N_{\bar{u}} - N_{Y_u} + N_{Y_u^\dagger}) \mod 3 = 0$
IV	$U(3)_d$	$(N_d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

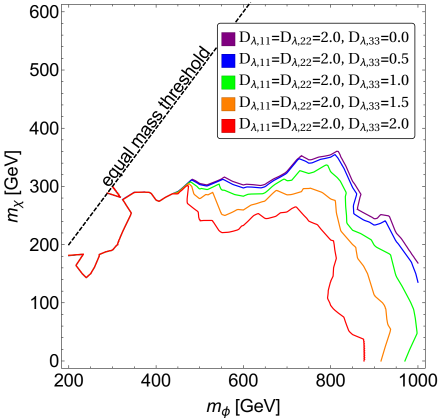
$\sum$ II+III+IV+V−I $(N_\chi - N_{\bar{\chi}} - N_\phi + N_{\phi^\dagger}) \mod 3 = 0$

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

t-DMFV and $jj + \not{E}_T$ at LHC8

MB, Kast (2017)





t-DMFV and $t\bar{t} + \not{E}_T$ at LHC8

MB, Kast (2017)