DARK MATTER AND CONTINUOUS FLAVOR SYMMETRIES

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based on Kamenik, JZ, 1107.0623
Bishara, JZ, 1408.3852
Bishara, Greljo,Kamenik, Stamou, JZ, 1505.03862

Invisibles 15 Workshop: "Invisibles Meets Visibles", Jun 24 2015

THE AIM/MOTIVATION

- SM has a very nontrivial flavor structure
  - hierarchical fermion masses
  - small flavor violation in quark sector, large in lepton sector
- can this have implications for dark matter searches?

OUTLINE

- three examples
- all based on continuous flavor symmetries in the quark sector
    - dark matter stability
        - gauged flavor model+DM
        - metastable asymmetric DM
    - flavor breaking and DM searches
        - mono-tops at the LHC

DM STABILITY & CONTINUOUS SYMMETRIES

SM flavor group

- the breaking of flavor group may leave an exact discrete group exact
  - this is true in the SM
- if zero Yukawas large flavor group: $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
- we consider quark subgroup, *SU(3)* factors $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$

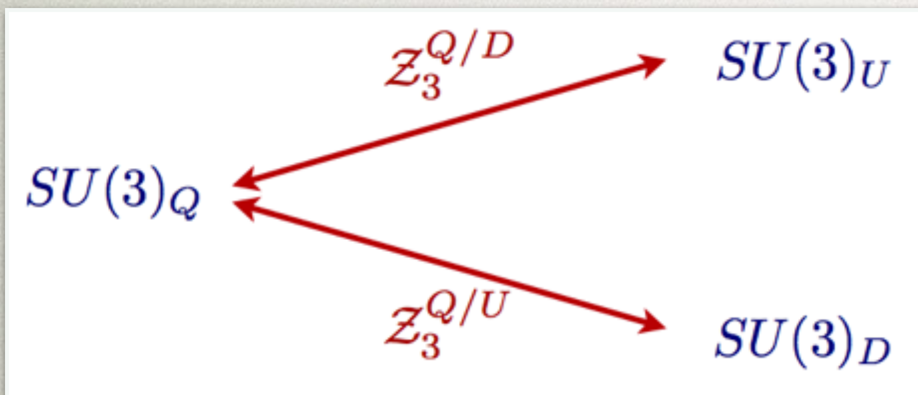
$Q_L \sim (3, 1, 1)$ $\quad U^c_R \sim (1, \bar{3}, 1)$ $\quad D^c_R \sim (1, 1, \bar{3})$

Batell, Pradler, Spannowsky, 1105.1781
Batell, Lin, Wang,1309.4462
Bishara, Greljo,Kamenik, Stamou, JZ, 1505.03862

SM FLAVOR BREAKING

- the SM Yukawas break $G_F \to Z_3^{QUD}$

$$\mathcal{L}_Y = \bar{Q}_L \tilde{H} y_u U_R + \bar{Q}_L H y_d D_R + \text{h.c.}\,.$$



$$Z_3^{QUD}$$

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

- Z_3^{QUD} is an accidental symmetry of the SM
  - preserved in presence of any MFV NP
  - in the SM is a subgroup of $U(1)_B$ (not in general NP)

DARK MATTER STABILITY

- all SM fields: neutral under diag. subgroup $Z_3^{\chi} \subset Z_3^{QUD} \times Z_3^{c}$
- color neutral dark matter charged under Z_3^{χ} is automatically stable
  - suitable G_F representations have nonzero **flavor triality**

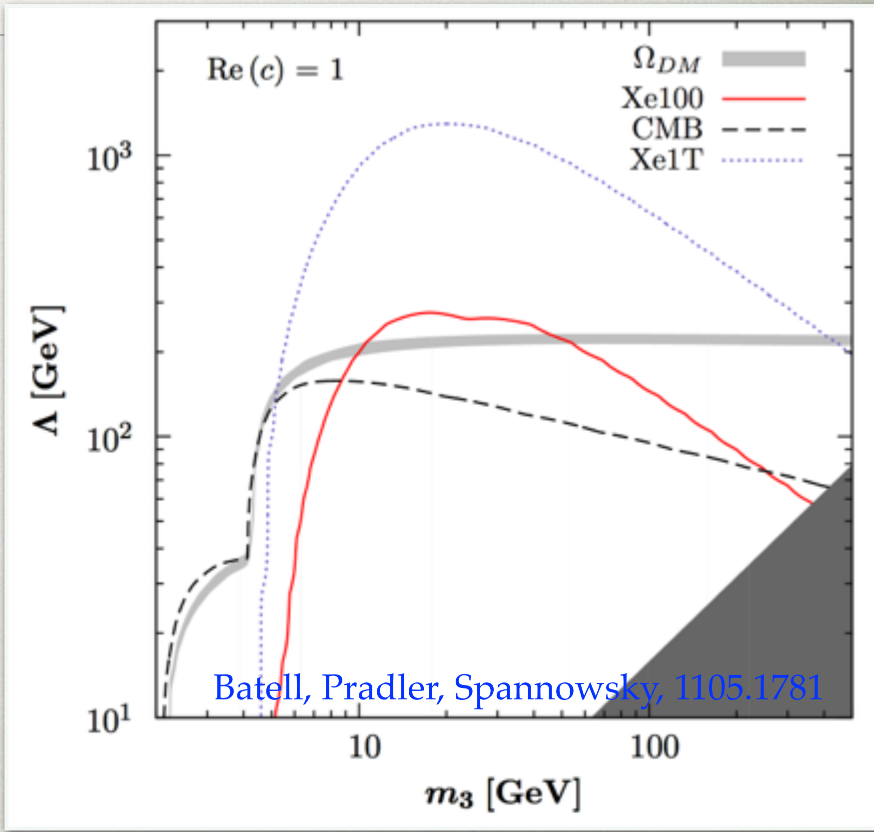
$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$$

$$(n - m) \bmod 3 \neq 0. \qquad m \equiv m_Q + m_u + m_d. \quad n \equiv n_Q + n_u + n_d$$

- in contrast the flavor breaking vevs should have zero flavor triality: $(n_{vev} - m_{vev}) mod\ 3 = 0$ so that Z_3^{χ} unbroken
  - an example: SM Yukawas which are in bi-fundamental

MFV DM

- an example is DM with MFV interactions
  - EFT analysis
  - structure of DM-SM interactions in MFV DM dictated by MFV power counting
  - example: SM singlet $S \sim (3, 1, 1)_{GF}$
  - for inverted spectrum annihilation dominated by $\chi_3\chi_3 \to b\bar{b}$
- does it have to be MFV?
- dynamical origin of interactions?
- will show a non-MFV example
  - not being in EFT limit will be numerically beneficial



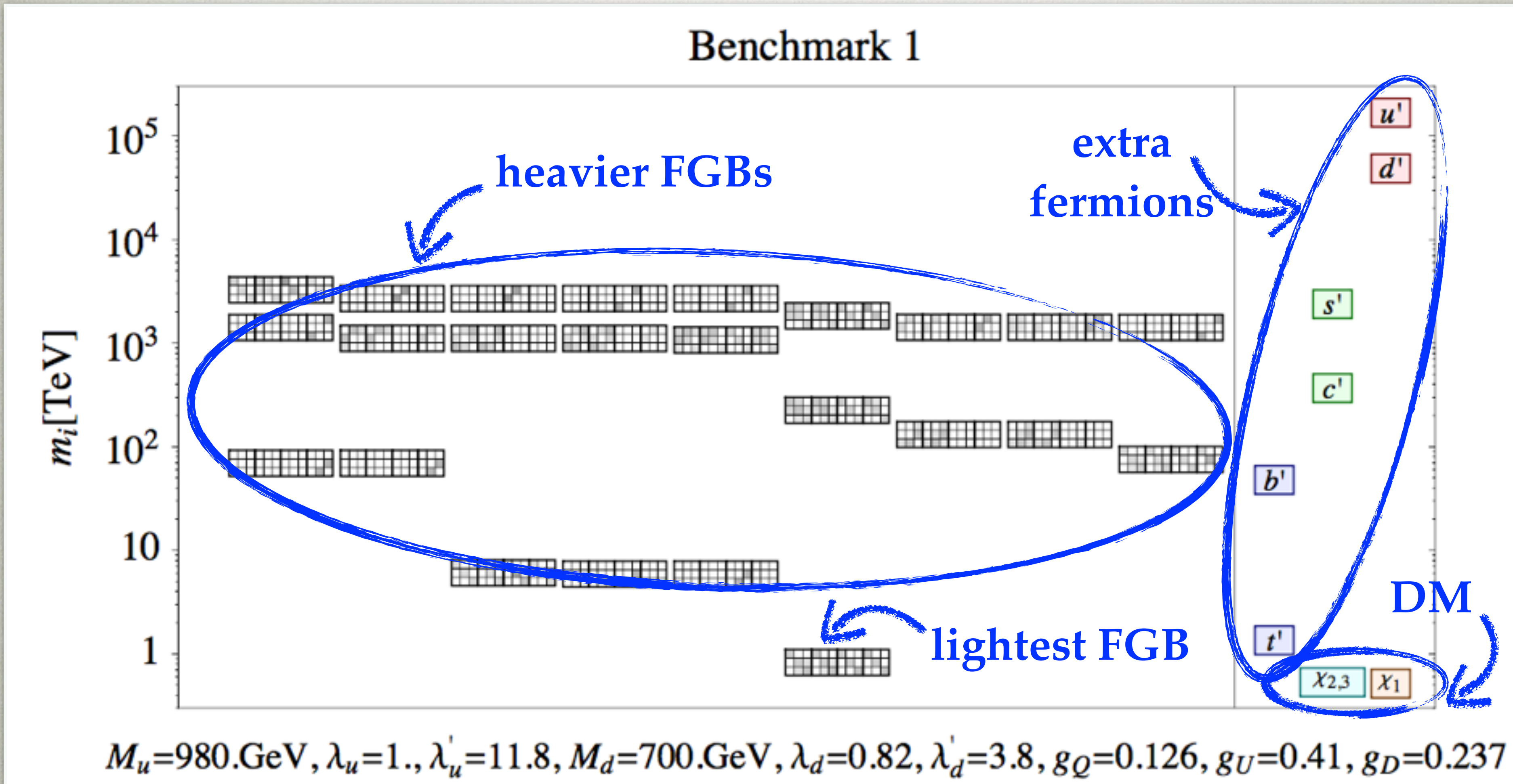
Batell, Pradler, Spannowsky, 1105.1781

see also
Lopez Honorez, Merlo, 1303.1087
Batell, Lin, Wang,1309.4462
Agrawal, Blanke & Gemmler, 1405.6709
Bishara, Greljo,Kamenik, Stamou, JZ, to appear

GENERAL FLAVORED DM

Grinstein, Redi, Villadoro, 1009.2049
Bishara, Greljo,Kamenik, Stamou, JZ, 1505.03862

- an important requirement is that G_F is a good symmetry in the UV
- easiest to achieve by gauging $G_F=SU(3)_Q \times SU(3)_U \times SU(3)_D$
  - for thermal relic DM want flavored gauge bosons ~TeV
  - FCNC constraints are nontrivial in this case
- possible to avoid FCNCs with inverted hierarchy
  - extra fermions to cancel anomaly
  - flavor violating flavored gauge bosons (FGBs) heavier if coupling to lighter quarks



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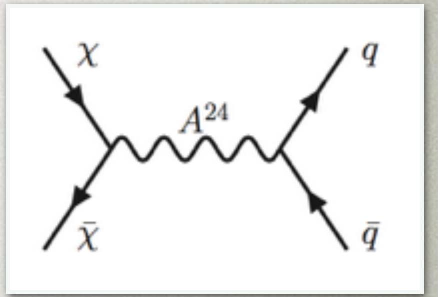
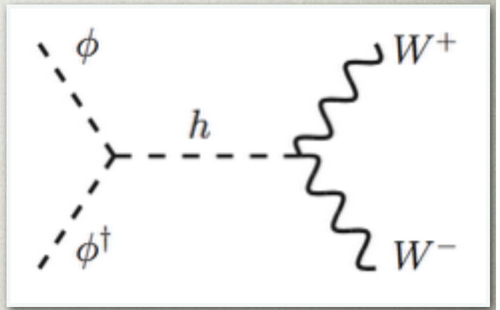
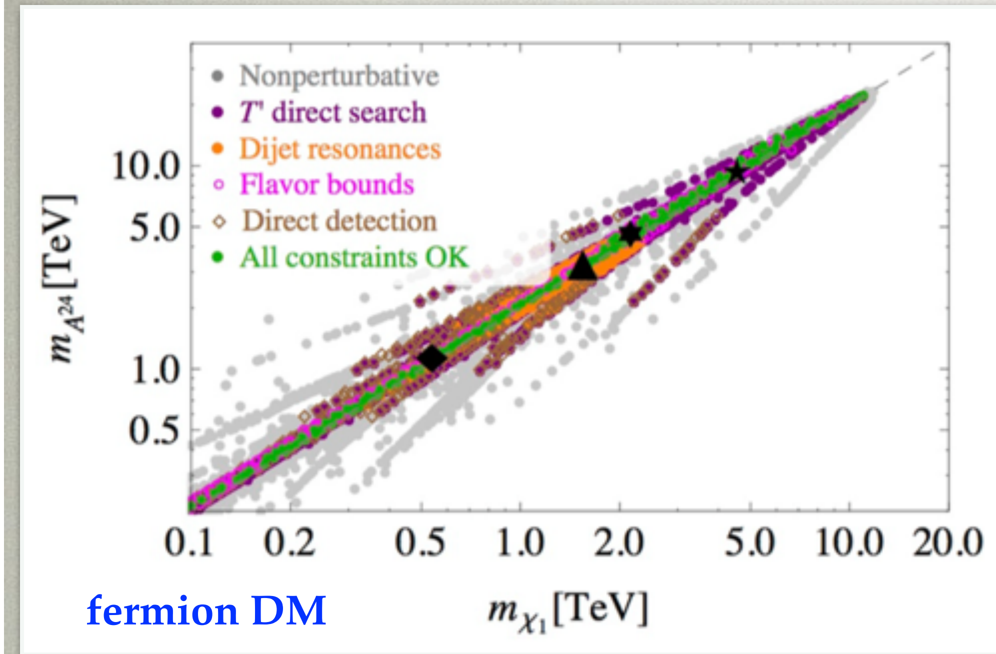
the inclusion of DM

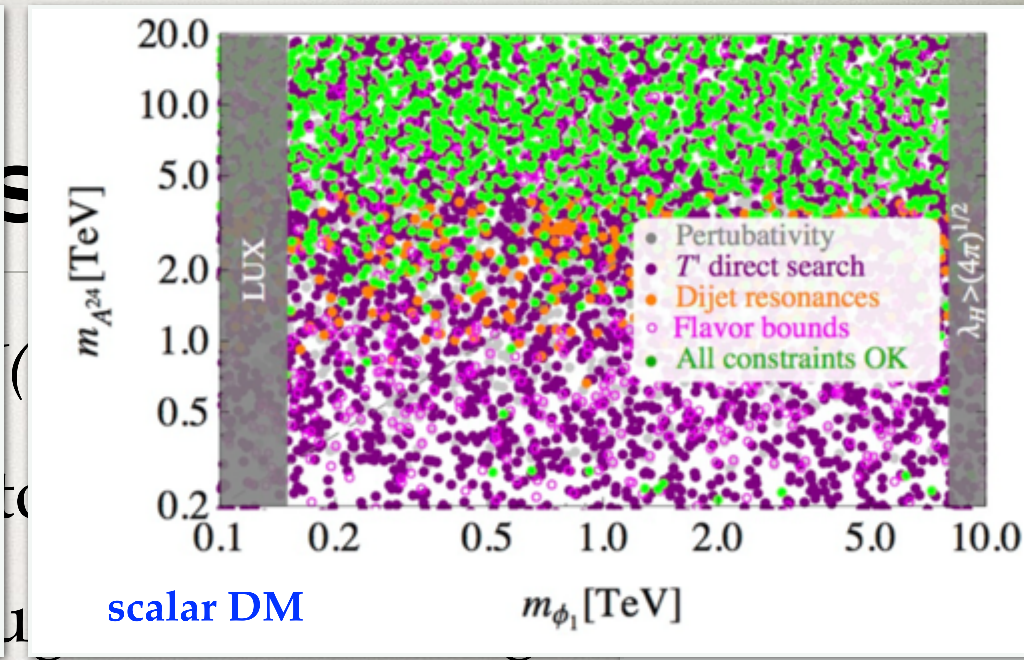
- take DM triplet of $SU(3)_U$, so Z_3^χ odd
  - fermionic DM (vectorlike fermions)
    - thermalizes through FGB exchanges
  - scalar DM
    - thermalizes through Higgs portal
- note: flavons are taken to be heavy
  - in principle also possible that they are the dominant mediators, e.g. in U(1) horizontal models

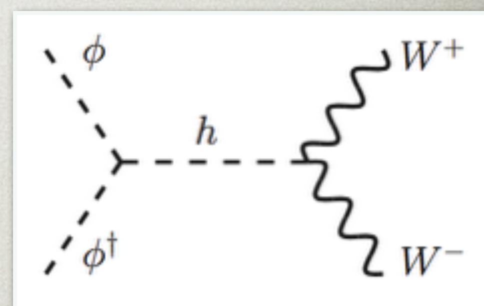




Calibbi, Crivellin, Zaldivar, 1501.07268







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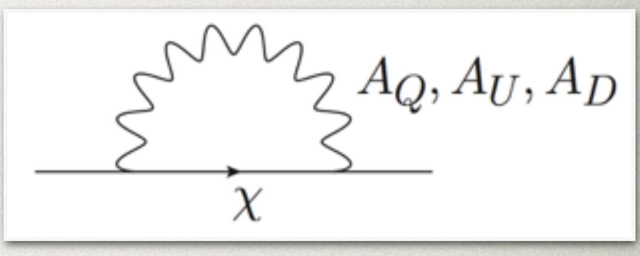
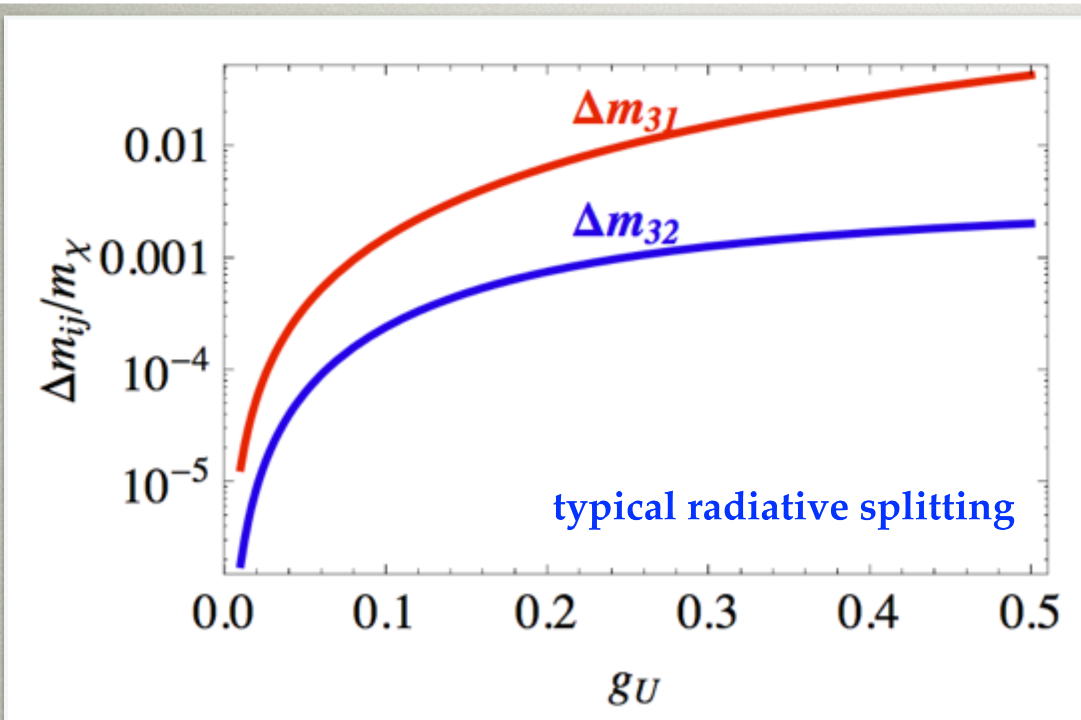
Calibbi, Crivellin, Zaldivar, 1501.07268

fermionic flavored DM

- phenomenology depends on whether DM mass splitting due to
  - radiative corrections alone
  - additional source of flavor breaking

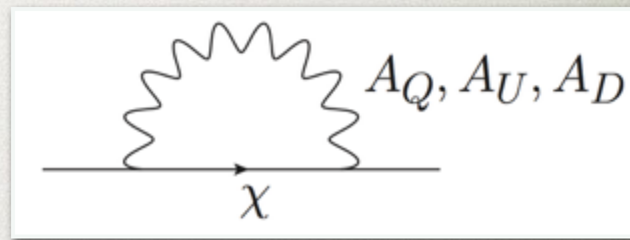


- for radiative splitting: long lived states, BBN constraints apply
- an aside: this model is non-MFV
  - χ_2 and χ_3 degenerate, mass gap with (lighter) χ_1



VORED DM

ds on whether DM



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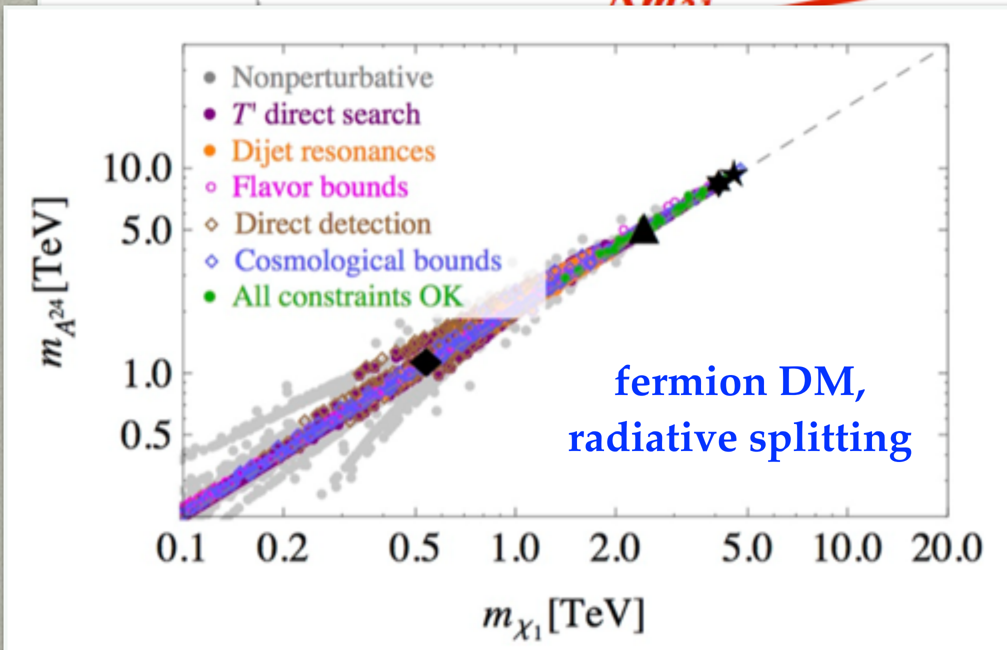

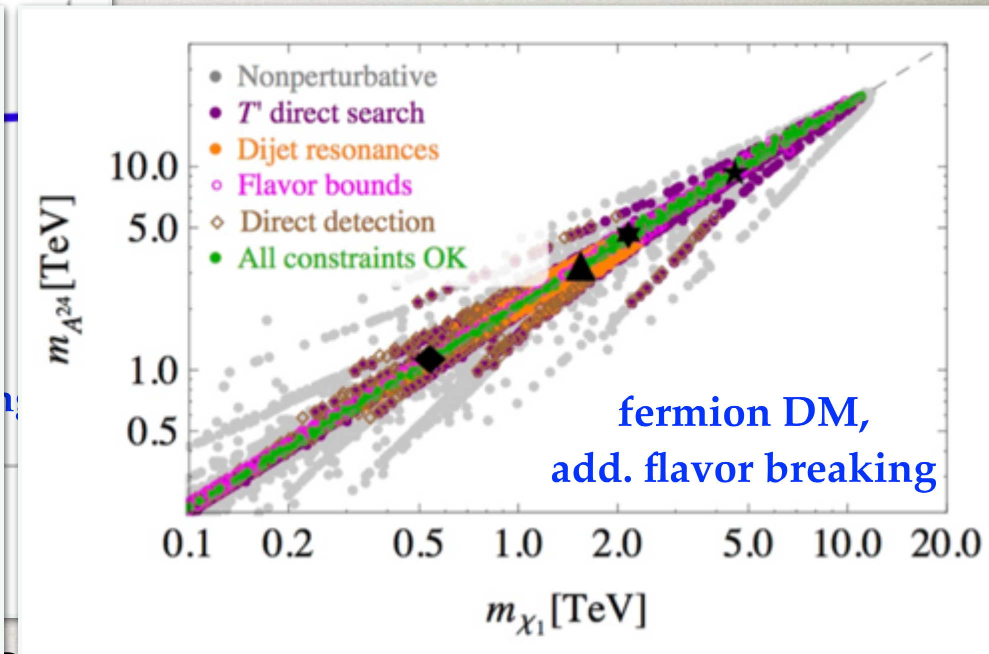

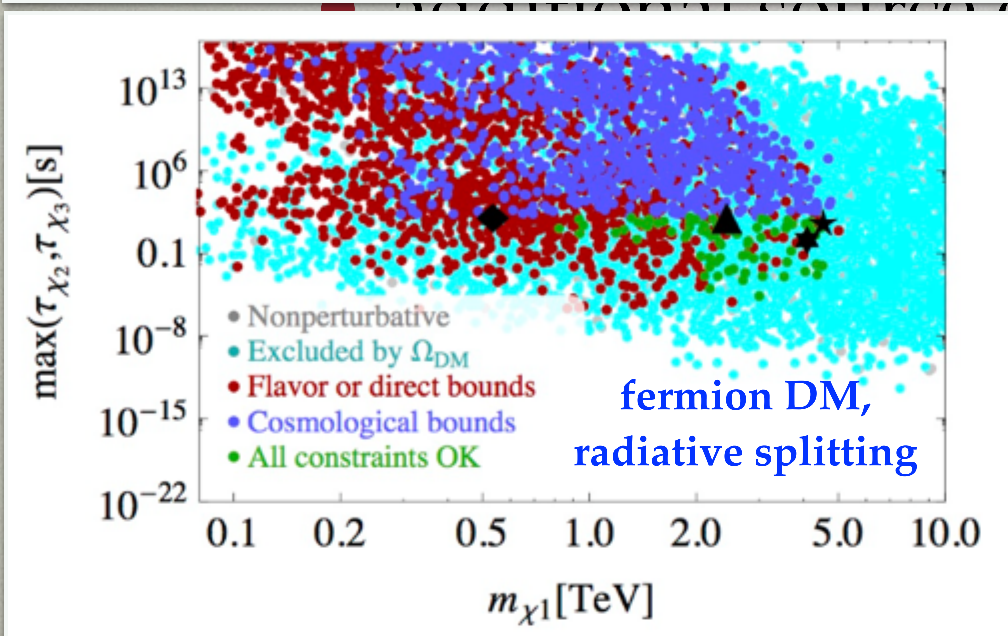

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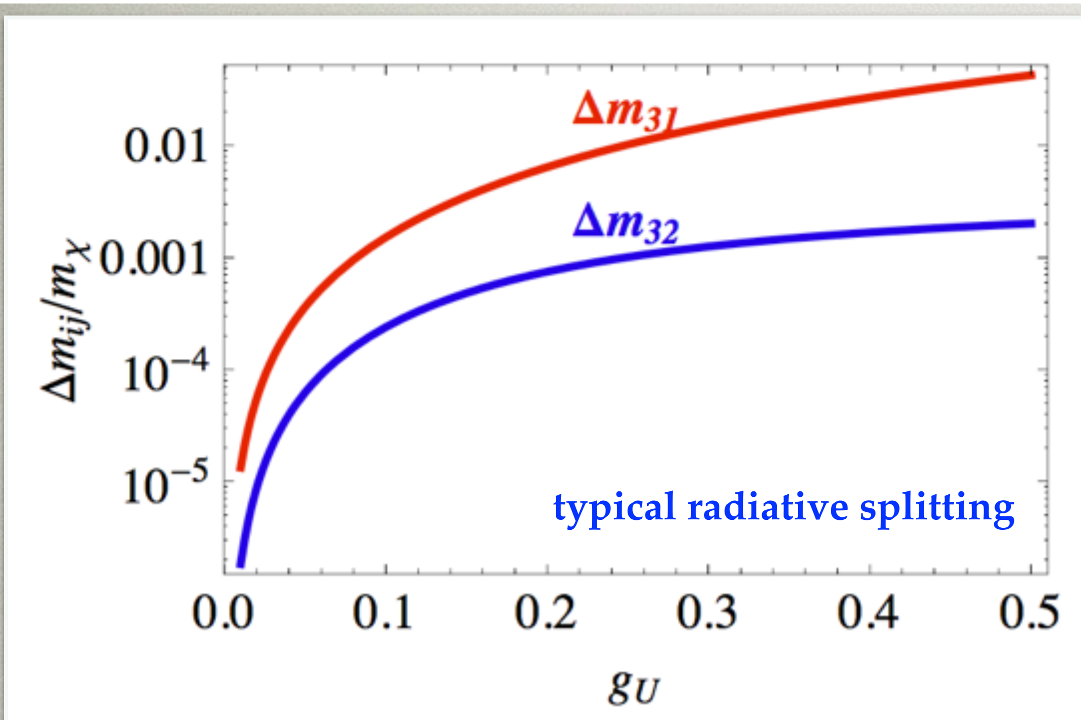

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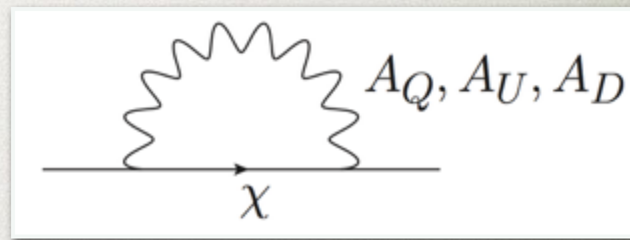

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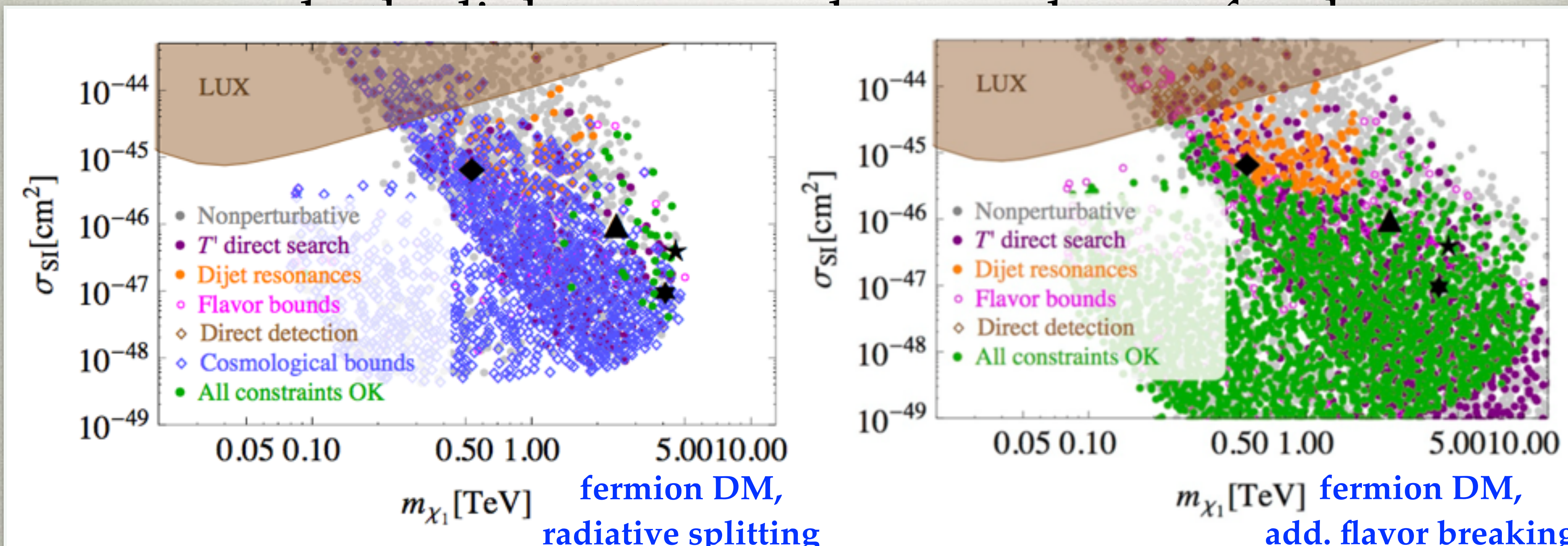
RELIC ABUNDANCE AND DIRECT SEARCHES

- only the lightest gauge boson relevant for the DM interactions
  - approximately T_8 diagonal in $SU(3)_i$
  - DM annihilates to $t'\bar{t}'$, $t\bar{t}$, jj
- viable set of benchmarks seem to require $m_\chi \sim m_A/2$
- there is a lower bound on m_χ due to flavor and collider constraints on flavored gauge bosons
- direct detection mostly below the bounds

RELIC ABUNDANCE AND DIRECT SEARCHES



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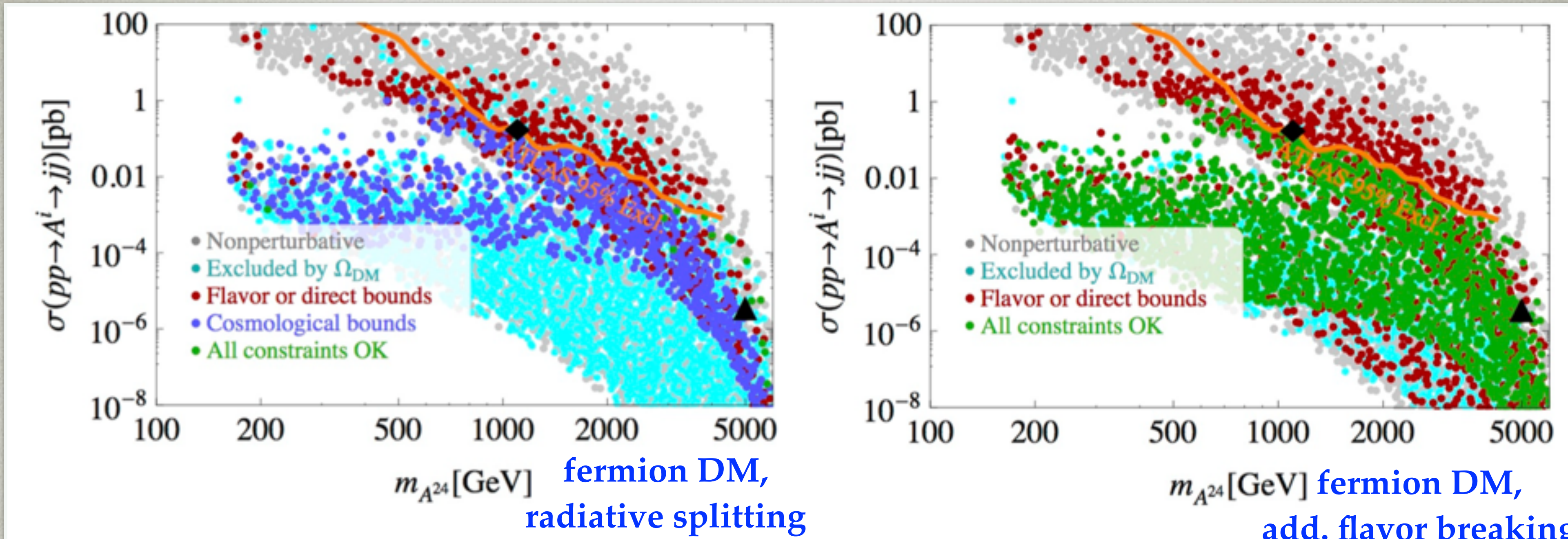
OTHER SEARCHES

- at colliders can search for extra states of the model
  - lightest FGB from di-jets
  - searches for exotic quarks from $t' \to bW, tZ, th$ CMS, 1311.7667
- can search for deviations in FCNCs
  - meson mixing from lightest FCB exchange
  - $b \to s\gamma$ from loops with exotic quarks



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recapitulating DM from flavor triality

- the flavor symmetry of the quark sector can be the origin of DM stability
  - DM needs to be part of a flavor multiplet
- one can search for extra states at colliders and through FCNCs

ASYMMETRIC DM & FLAVOR

ASYMMETRIC DM

- asymmetric DM addresses the coincidence problem
  - Ω_{DM}~5 Ω_{baryon}
  - is there a link between the two abundances?

Nussinov 1985; Barr 1991; Kaplan 1992; Kaplan, Luty, Zurek, 0901.4117; +many refs.

- could be explained if m_{DM}~5 m_{proton}
  - exact relation depends on thermal history and B-L charge of χ
    - for χ Dirac fermion, no other states below EW scale

Bishara, JZ, 1408.3852

$$m_\chi = \{6.2, 3.1, 2.1\}\text{GeV}, \qquad \text{for} \quad (B-L)_\chi = \{1,2,3\},$$

  - requires asymmetric interactions that freeze out above EW phase transition

ASYMMETRIC OPERATORS

Bishara, JZ, 1408.3852

fixed by flavor symmetries

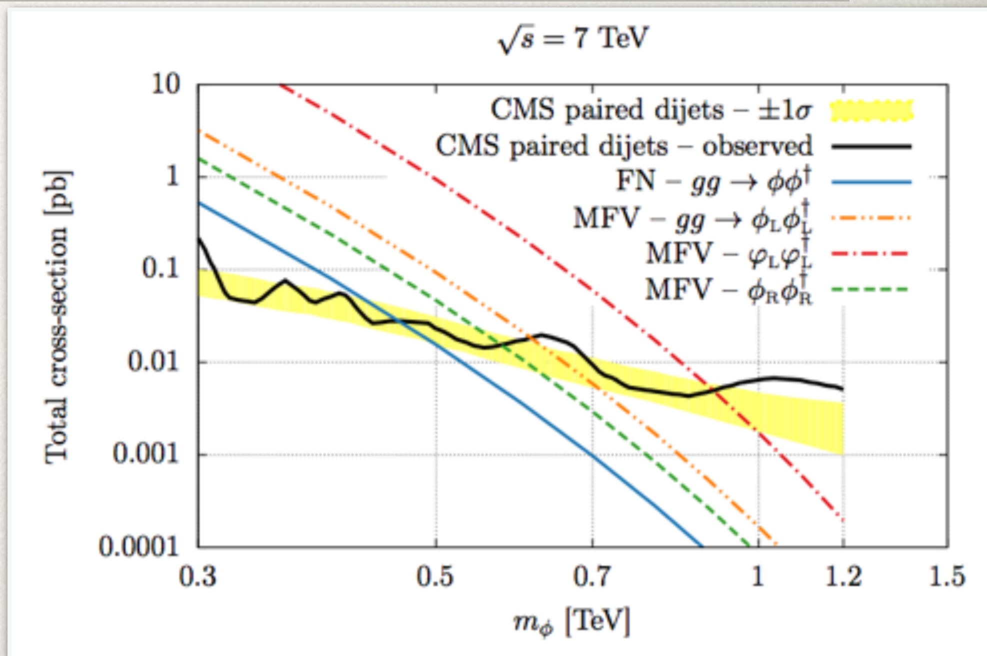
- such asymmetric operators could be linear in χ
  - for instance for B=2 DM, schematically $\mathcal{O}_{\text{asymm.}} \sim \frac{C}{\Lambda^6}\chi(qq)^3,$
  - also lead to DM decay
- is it possible O_{asymm} is suppressed enough that DM metastable?
  - i.e. we have accidental Z_2?
  - the required scale depends on the origin of flavor
- the suppression scales that give $\tau=10^{26}\,s$

without flavor $\Lambda \gtrsim 7$ TeV

ADM model			MFV			FN		
B	Dim.	m_χ [GeV]	decay	τ [s]	Λ [TeV]	decay	τ [s]	Λ [TeV]
1	6	6.2	$\chi \to bus$	10^{26}	4.0×10^6	$\chi \to bus$	10^{26}	8.1×10^8
2	10	3.1	$\chi \to udsuds$	10^{26}	0.63	$\chi \to udsuds$	10^{26}	2.5
3	15	2.1	forbidden	∞	–	forbidden	∞	–

SEARCHES

- colored mediators inevitable
  - can be searched for at the LHC through pair prod. or single product.



  - $\phi \to tb$, $\phi' \to bj$, $\phi'' \to jj$
  - the lowering of scale using flavor model crucial that they can be in LHC reach
- also searches through low energy FCNCs

Flavor violation & DM searches

THE AIM

Kamenik, JZ, 1107.0623

- most of the time flavor breaking irrelevant in DM searches
    - is there an instant where it is important?

FV AND DM

- FV couplings can be important
  - when DM couplings to quarks are chirality flipping
  - since then couplings to two different EW representations
    - typically in two different flavor representations as well
- numerically, the FV couplings can dominate in mono tops

DIRECT PRODUCTION

- use EFT for DM interactions with quarks

$$\mathcal{L}_{\text{int}} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- only interested in interactions with quarks

$$\mathcal{J}^{\mu}_{V,A} = \bar{\chi}\gamma^{\mu}\{1,\gamma_5\}\chi$$

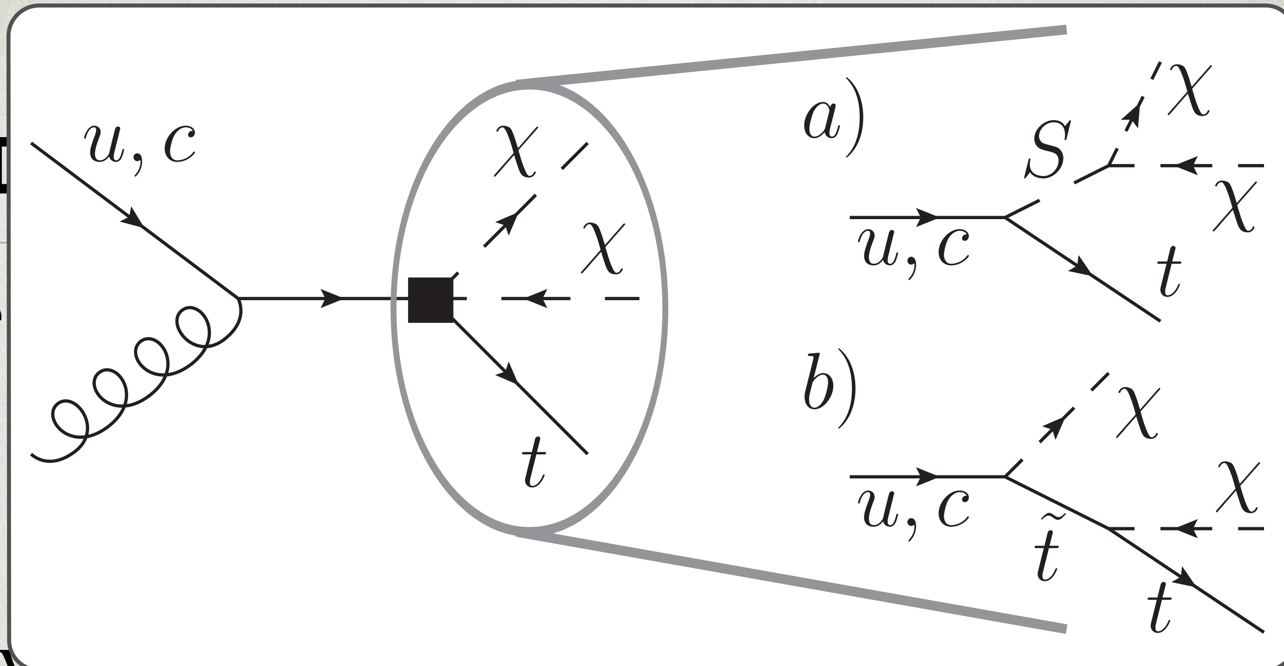
$$\mathcal{O}^{ij}_{1a} = (\bar{Q}^i_L \gamma_\mu Q^j_L)\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{2a} = (\bar{u}^i_R \gamma_\mu u^j_R)\mathcal{J}^\mu_a, \qquad \mathcal{O}^{ij}_{3a} = (\bar{d}^i_R \gamma_\mu d^j_R)\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{4a} = (\bar{Q}^i_L H u^j_R)\mathcal{J}_a\,, \qquad \mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R)\mathcal{J}_a\,,$$

$$\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$$

- full set includes other ops.



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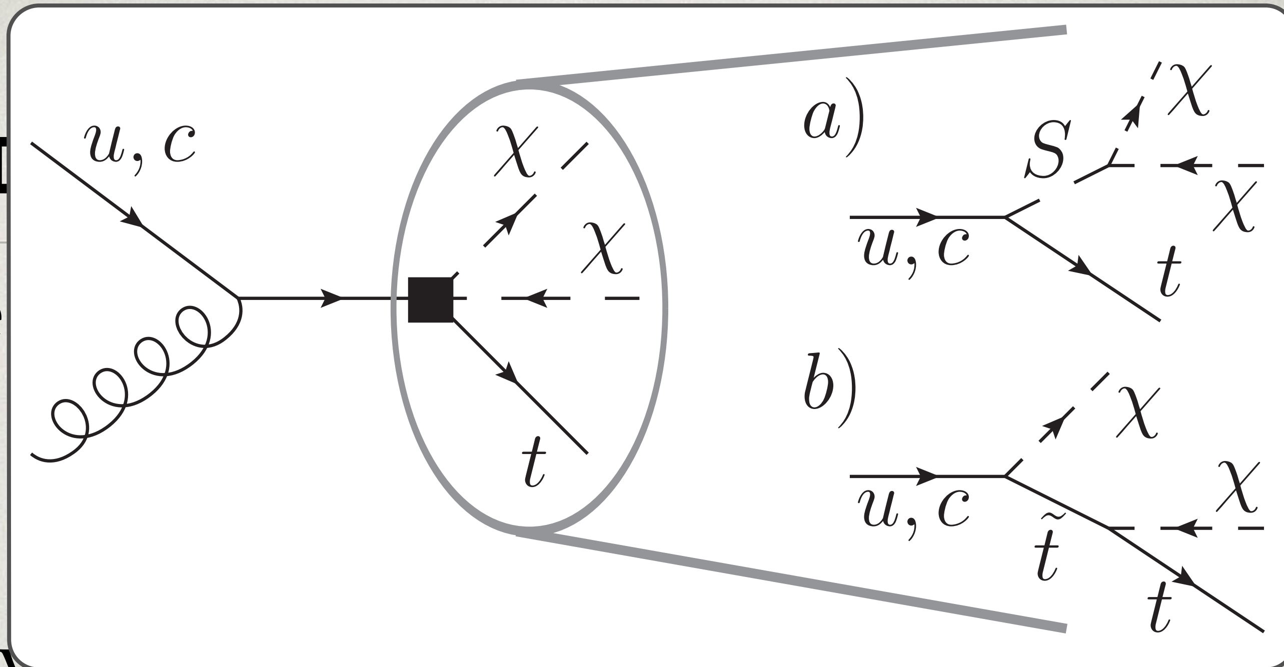

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- full set includes other ops.

HORIZONTAL SYMMETRIES EXAMPLE

- an example: abelian horizontal symm.

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

- the yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

- in the same way the couplings to DM

chirality preserving

$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

chirality flipping

- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor

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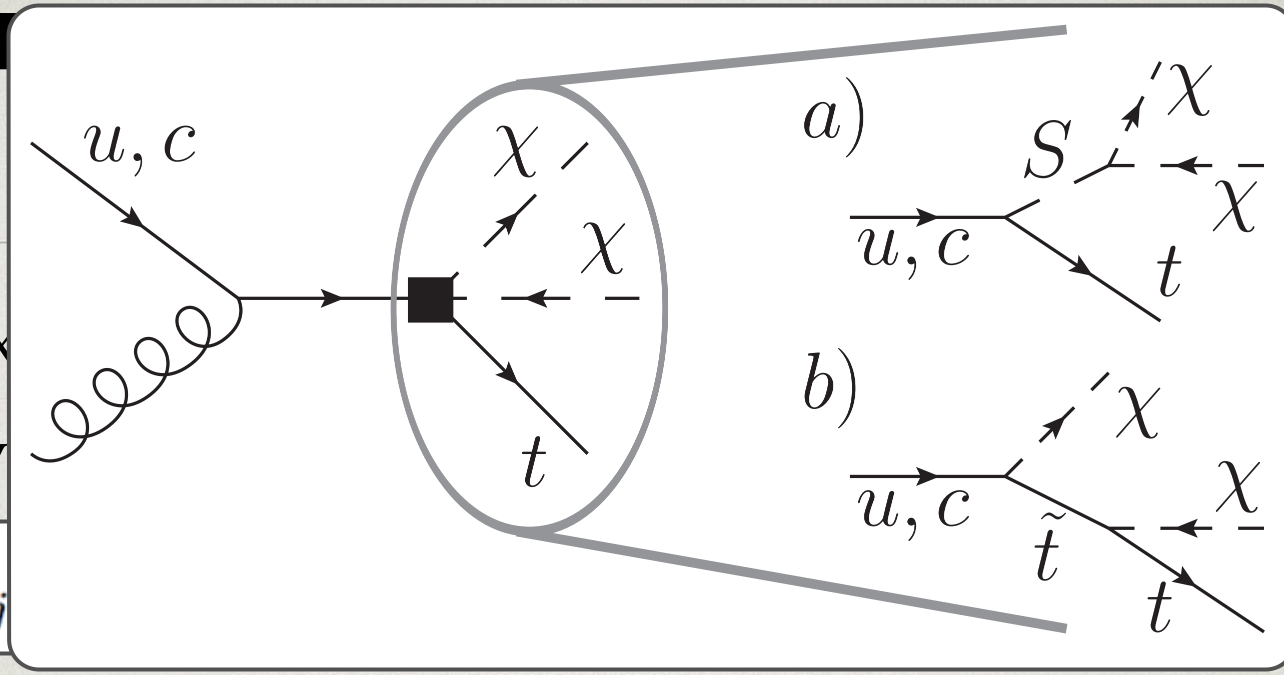

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$(Y_u)_{ij}$

8; hep-ph/9310320

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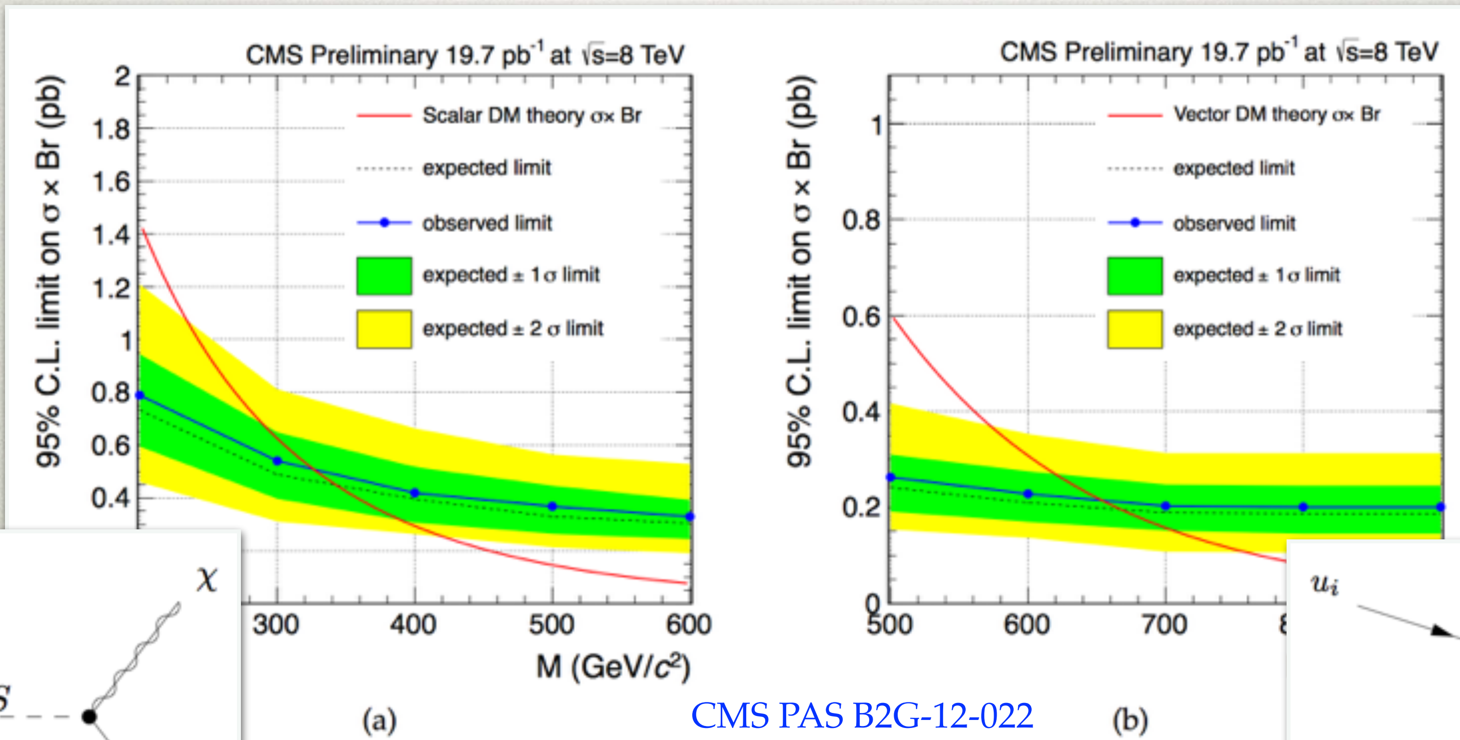
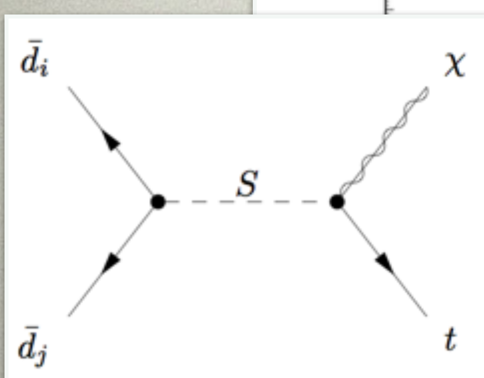
MONOTOP EXPERIMENTAL RESULTS

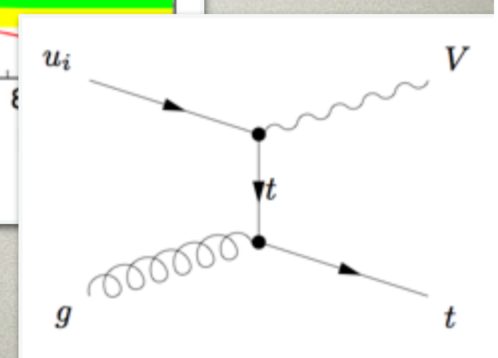
- CMS results on monotop searches
  - couplings set to 0.1
  - uses hadronic tops: 3j+MET channel

CMS 1410.1149;
improves CDF 1202.5653;
see also ATLAS 1410.5404



(a) CMS PAS B2G-12-022 (b)





Andrea, Fuks, Maltoni, 1106.6199

CONCLUSIONS

- have shown three examples where flavor important for understanding DM
  - (meta-)stability of DM
  - monotop signals

BACKUP SLIDES

GENERAL FLAVORED DM

Bishara, Greljo,Kamenik, Stamou, JZ, 1505.03862

- basic requirement for flavored DM stable due to Z_3^{QUD}
  - G_F is a good symmetry in the UV
  - broken by spurions ϕ_{vev} in representations with zero flavor triality
    - $(n_{vev} - m_{vev}) mod\ 3 = 0$
      - e.g., any vev in adjoint or bi-fundamental ok
  - stable color singlet(s) in representations with nonzero flavor triality
    - $(n_\chi - m_\chi) mod\ 3 \neq 0$

GAUGED FLAVOR SYMMETRY

Grinstein, Redi, Villadoro, 1009.2049
Bishara, Greljo,Kamenik, Stamou, JZ, 1505.03862

- fully gauged G_F
  - spontaneously broken by vevs

$$Y_u \sim (\bar{3}, 3, 1) \qquad Y_d \sim (\bar{3}, 1, 3)$$

  - to ensure anomaly cancellation a set of chiral fermions

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

  - mass term (after EWSB and flavor breaking)

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

flavor symmetric mixing | breaks flavor after SSB | flavor symmetric mixing

SM YUKAWAS

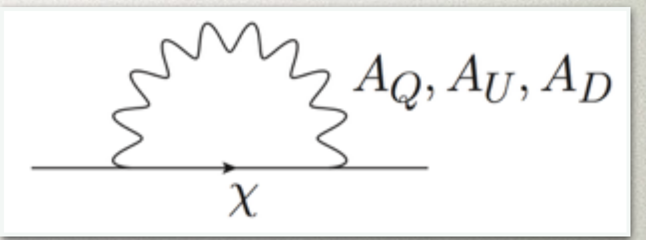
- the SM Yukawas are generated after $Y_{u,d}$ obtain vevs and Ψ_i integrated out

$$y_u = \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle} \qquad y_d = \frac{\lambda_d M_d}{\lambda'_d \langle Y_d \rangle}$$

- note that the SM Yukawas are non-analytic in spurions $\langle Y_{u,d} \rangle$
  - the model is not of the usual MFV-type
  - FGBs inverse mass hierarchy $m_A{}^2 \sim (y_{ui} y_{uj})^{-1}$
  - low energy observables have MFV structure

RADIATIVE SPLITTING

- if mass degeneracy broken only by radiative corrections
  - in the limit of $m_\chi \ll m_A$

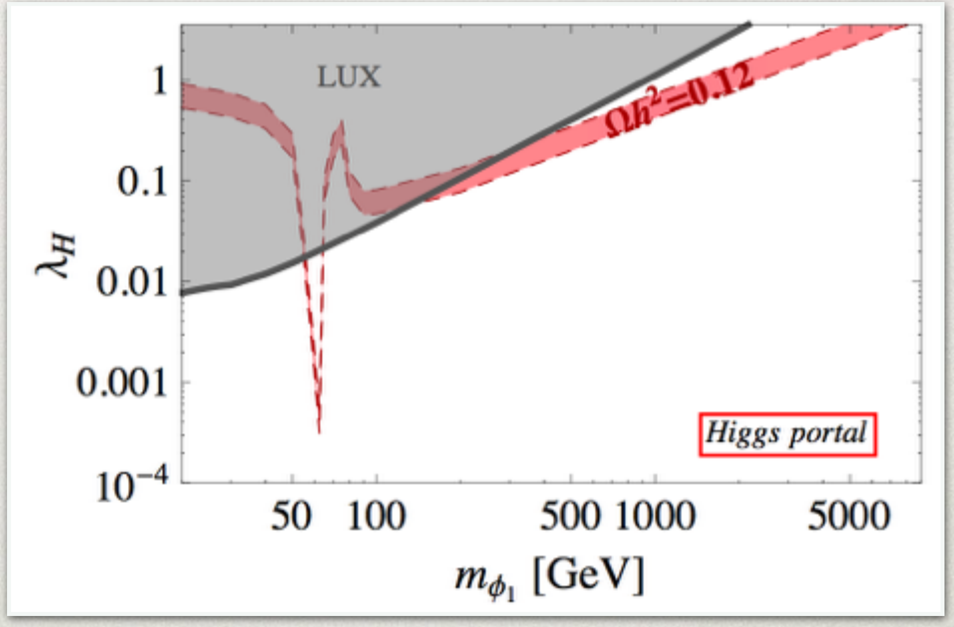


$$\mathcal{L}^{\rm DM}_{\rm break} = -\frac{m_\chi g_U^2}{16\pi^2}\bar{\chi}\lambda^a(\log \mathcal{M}_A^2/\mu^2)^{ab}\lambda^b\chi,$$

- typical splitting ~*few GeV* to ~few 10GeV
  - long enough lifetimes that problems with BBN
- χ_1 the lightest state

HIGGS PORTAL

- the scalar flavored DM behaves exactly like Higgs portal DM



- the DM multiplet split at tree level

$$\mathcal{L} \supset \kappa(\phi^\dagger \lambda^a \phi)\mathrm{Tr}(Y_u^\dagger \lambda^a Y_u)$$

- the only remnant of gauged flavor symmetries at low eng. is the stability of DM

SCALAR FLAVORED DM

- introduce a scalar in fundamental of $SU(3)_U$

$$\phi \sim (1,3,1)$$

- dominant interaction with the SM through Higgs portal

$$\mathcal{L}_{\rm int}^{\rm DM} = \lambda_H (\phi^\dagger \phi)(H^\dagger H)$$

  - FGB exchanges are sub-leading
  - no longer required $m_\chi \sim m_A/2$

ASYMMETRIC DM

- cosmological history of the ADM

$T \gg T_{\mathrm{EWPT}}$	$B \longleftrightarrow \Delta\chi$	Asymmetric operators in equilibrium. Baryon asymmetry transferred to DM.
$T_f > T_{\mathrm{EWPT}}$	$B \not\longleftrightarrow \Delta\chi$	Asymmetric operators freezeout. DM number separately conserved.
$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow \mathrm{SM}, \gamma_d\gamma_d, \ldots$	Symmetric component of DM is efficiently annihilated away.

from a slide by F. Bishara, talk at Notre Dame

- note: more complicated cosmological histories possible

see e.g., Falkowski, Ruderman, Volansky, 1101.4936

OUR AIM

Bishara, JZ, 1408.3852

- for a subset of ADM models
  - the Z_2 that ensures the stability is *accidental* and *approximate*
- as a result
  - DM is metastable
  - decay times potentially close to its present observational bound $\tau \gtrsim 10^{26} s$
- the mediators can be below TeV
  - realistic flavor structure essential

DM MASS

- the relation Ω_{DM}~5.4 Ω_{baryon} fixes the DM mass

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  - assuming SM visible sector

$$m_\chi = m_p \frac{\Omega_\chi}{\Omega_B} \frac{B}{B-L} \frac{B-L}{\Delta\chi} = (12.5 \pm 0.8)\mathrm{GeV} \frac{1}{(B-L)_\chi^{\mathrm{sum}}}$$

$$(B-L)_\chi^{\mathrm{sum}} \equiv \sum_i \hat{g}_\chi^i (B-L)_\chi^i$$

- for instance, for a Dirac fermion g_χ=2

$$m_\chi = (6.2 \pm 0.4)\mathrm{GeV} \frac{1}{(B-L)_\chi},$$

$$m_\chi = \{6.2, 3.1, 2.1\}\mathrm{GeV}, \qquad \text{for} \quad (B-L)_\chi = \{1, 2, 3\},$$

- note: for *B*=3 DM cannot decay
  - accidental Z_2 (which is exact if *B* is exact)

ASYMMETRIC DM

- cosmological history of the ADM

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$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow {\rm SM}, \gamma_d\gamma_d, \ldots$	Symmetric component of DM is efficiently annihilated away.

- symmetric annihilation needs to be efficient
  - have nothing new to say, a number of scenarios proposed

see e.g., Bhattacherjee, Matsumoto, Mukhopadhyay, Nojiri, 1306.5878; March-Russell, McCullough, 1106.4319; Lin, Yu, Zurek, 1111.0293

FREEZE-OUT OF ASYMMETRIC INTERACTIONS

- asymmetric operators, schematic form for B=2

$$\mathcal{O}_{\text{asymm.}} \sim \frac{C}{\Lambda^6}\chi(qq)^3,$$

- leads to asymmetric $2\to 5$ interactions in the early universe
  - the freeze-out should be above EW phase transition
  - gives lower bounds:
    - Λ>730 GeV (Froggatt-Nielsen flavor model)
    - Λ>400 GeV (MFV breaking)
- naively expect that asymmetric mediators not much heavier
  - then self-consistent framework (need small m_χ for metastable DM)
    - at very high Λ the direct relation between m_χ and m_p is lost
  - however, easy to think of models with very massive mediators

ADM AND MFV

- take as an example *B=1* fermionic ADM
  - two types of asymm. operators

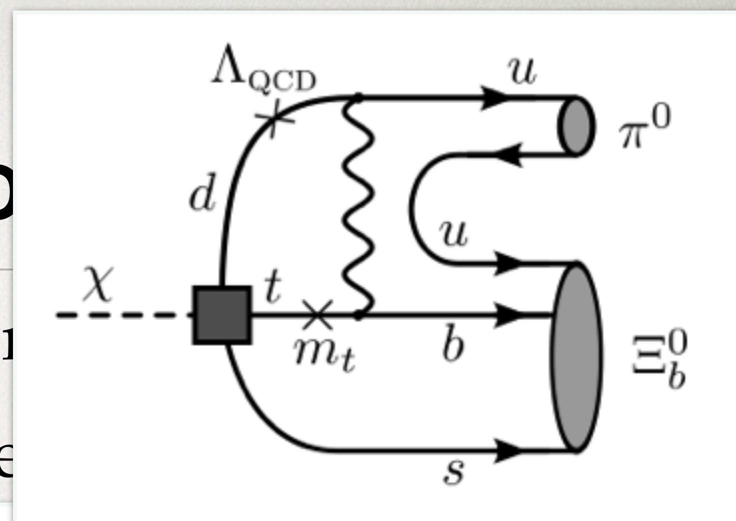
$$\mathcal{O}_1^{(B=1)} = \left(\chi\, u^c_\alpha Y_U^\dagger Y_D\right)_K \left(d^c_{N\beta} d^c_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}$$
$$\to \left(\chi\, u^c_{\text{MASS}} Y_U^{\text{diag}\dagger} V_{\text{CKM}}^\dagger Y_D^{\text{diag}}\right)_{K\alpha}\left([d^c_{\text{MASS}}]_{N\beta}\,[d^c_{\text{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_2^{(B=1)} = \left(\chi\, q^*_{K\alpha i}\right)\left([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j}\right)\epsilon^{ij}\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}$$
$$\to \left(\chi\, u^*_{\text{MASS}} V_{\text{CKM}}^\dagger\right)_{K\alpha}\left([d^c_{\text{MASS}} Y_D^{\text{diag}\dagger}]_{N\beta}[d^*_{\text{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},$$

  - from here an NDA estimate for decay width

$$\Gamma_\chi^{(1)} \sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\left(\frac{1}{16\pi^2}\frac{m_t\Lambda_{\text{QCD}}}{m_W^2}\right)^2\frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}\text{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.0\cdot 10^6\text{TeV}}{\Lambda}\right)^4,$$
$$\Gamma_\chi^{(2)} \sim \frac{|y_b V_{ub}|^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}\text{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.3\cdot 10^7\text{TeV}}{\Lambda}\right)^4,$$

ADM AND

- take as an example *B=1* ferr
  - two types of asymm. ope



$$\mathcal{O}_1^{(B=1)} = (\chi\, u^c_\alpha Y_U^\dagger Y_D)_K (d^c_{N\beta} d^c_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma}$$

$$\to (\chi\, u^c_{\rm MASS} Y_U^{{\rm diag}\dagger} V_{\rm CKM}^\dagger Y_D^{\rm diag})_{K\alpha} ([d^c_{\rm MASS}]_{N\beta} [d^c_{\rm MASS}]_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma},$$

$$\mathcal{O}_2^{(B=1)} = (\chi\, q^*_{K\alpha i})([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j}) \epsilon^{ij} \epsilon^{KNM} \epsilon^{\alpha\beta\gamma}$$

$$\to (\chi\, u^*_{\rm MASS} V_{\rm CKM}^\dagger)_{K\alpha} ([d^c_{\rm MASS} Y_D^{{\rm diag}\dagger}]_{N\beta} [d^*_{\rm MASS}]_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma},$$

  - from here an NDA estimate for decay width

$$\Gamma_\chi^{(1)} \sim \frac{(y_t y_b)^2}{8\pi} \left(\frac{m_\chi}{\Lambda}\right)^4 \left(\frac{1}{16\pi^2} \frac{m_t \Lambda_{\rm QCD}}{m_W^2}\right)^2 \frac{m_\chi}{16\pi^2} = 6.6 \cdot 10^{-51} {\rm GeV} \left(\frac{y_b}{0.024}\right)^2 \left(\frac{4.0 \cdot 10^6 {\rm TeV}}{\Lambda}\right)^4,$$

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FN MODELS

- U(1) Froggatt-Nielsen (FN) models of spontaneously broken horizontal symmetries
  - quarks carry horizontal charges $H(q_i)$, …
- the two B=1 operators

$$\mathcal{O}_1^{(B=1)} = (\chi\, d_K^c)\,(u_N^c d_M^c) \to (\chi\,[d^c_{\rm MASS}]_K)\,([u^c_{\rm MASS}]_N [d^c_{\rm MASS}]_M),$$
$$\mathcal{O}_2^{(B=1)} = (\chi\, q_{Ki}^*)(d_N^c q_{Mj}^*)\epsilon^{ij} \to (\chi\,[u^*_{\rm MASS}]_K)\,([d^c_{\rm MASS}]_N [d^*_{\rm MASS}]_M)\,,$$

$$\mathcal{L} = \sum_i \frac{C_i}{\Lambda^{(D_i-4)}}\mathcal{O}_i.$$

  - have Wilson coefficients

$$C_1 \sim \lambda^{|H(d_K^c)+H(u_N^c)+H(d_M^c)|}, \qquad C_2 \sim \lambda^{|-H(q_K)+H(d_N^c)-H(q_M)|}.$$

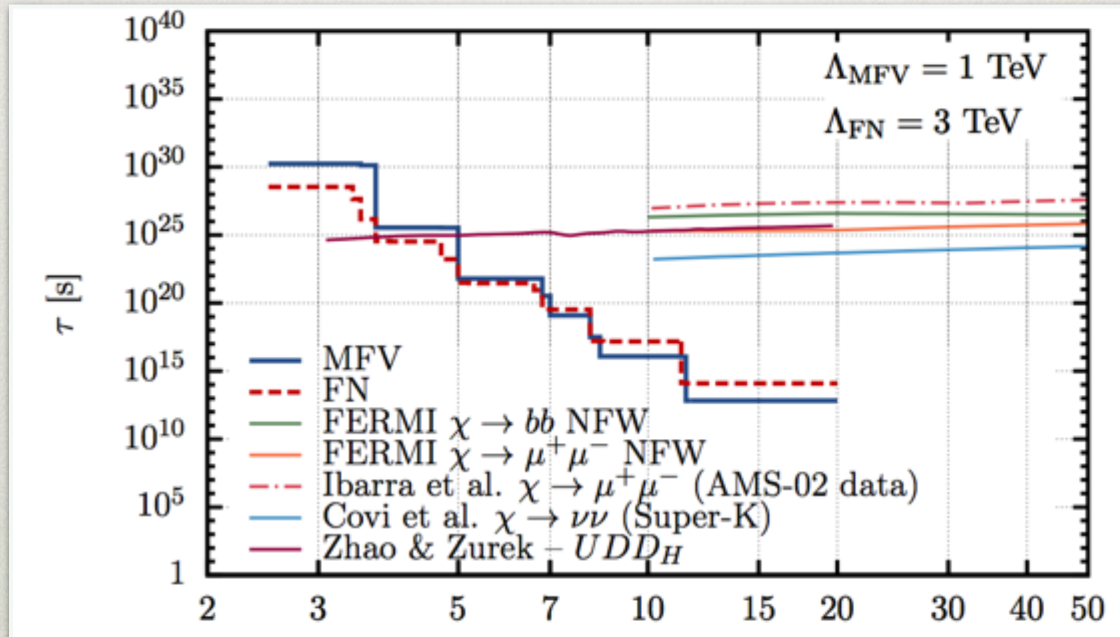
  - expansion parameters $\lambda \sim 0.2$
  - we use the phenomenologically viable assignments:

$$H(q, d^c, u^c) \Rightarrow \begin{array}{c} \\ q \\ d^c \\ u^c \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} 3 & 2 & 0 \\ 3 & 2 & 2 \\ 3 & 1 & 0 \end{pmatrix} \end{array},$$

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

INDIRECT DETECTION CONSTRAINTS

- the most relevant indirect constraints from antiproton flux and gamma ray spectra



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- for *3.1GeV B=2* DM the bounds are

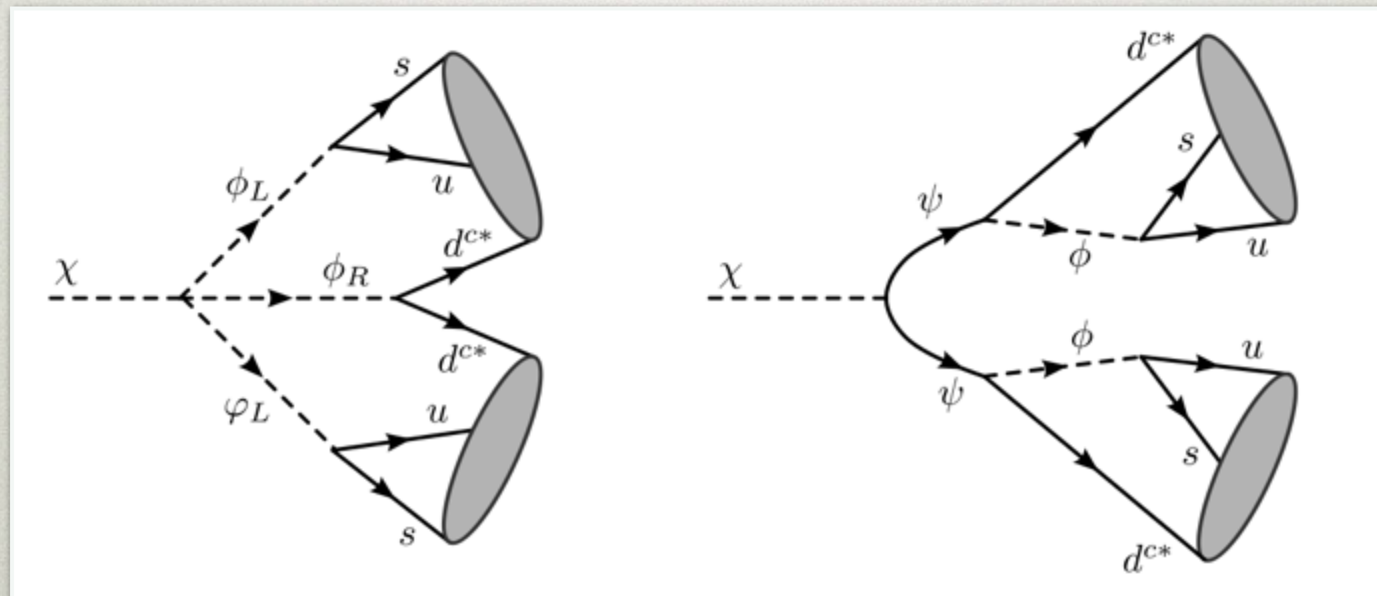
$$\Lambda_{\rm MFV} \gtrsim 0.49 \text{ TeV} \qquad \Lambda_{\rm FN} \gtrsim 1.9 \text{ TeV},$$

MEDIATOR MASS

- these bounds imply for the mass of asymmetric mediators
  - MFV: $m_{mediator}$ >490 (210, 90)GeV
  - FN: $m_{mediator}$ >1900 (830, 360)GeV
  - if asymmetric operators are generated at tree(1-loop,2-loop)-level
- these mediators can be searched for at the LHC
- note: without flavor structure the bound would be Λ>7.3 TeV
  - out of LHC reach

MEDIATOR MODELS

- for LHC pheno. consider two toy-model completions
  - MFV model with scalar mediators
  - FN model with fermionic and scalar mediators



FLAVOR BOUNDS

- typical FCNC bounds