Axial Vector Z' and Anomaly Cancellation

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consider pure axial vectorial Z',

i.e. $q_{f,L} = -q_{f,R}$

rich phenomenology

generating anomaly free fermions spectrum:

SM is Anomaly Free

$$\mathcal{A}_{WWB} := \sum_{f_L/\text{w SU(2)}} d_3[f_L]Y[f_L] - \sum_{f_R/\text{w SU(2)}} d_3[f_R]Y[f_R] = 0$$

$$\mathcal{A}_{ggB} := \sum_{f_L/\text{w SU(3)}} d_2[f_L]Y[f_L] - \sum_{f_R/\text{w SU(3)}} d_2[f_R]Y[f_R] = 0$$

$$\mathcal{A}_{GGB} := \sum_{f_L} d_2[f_L]d_3[f_L]Y[f_L] - \sum_{f_R} d_2[f_R]d_3[f_R]Y[f_R] = 0$$

$$\mathcal{A}_{BBB} := \sum_{f_L} d_2[f_L]d_3[f_L](Y[f_L])^3 - \sum_{f_R} d_2[f_R]d_3[f_R](Y[f_R])^3 = 0$$

where d_N is the dimension of the representation under SU(N), and Y is the hypercharge.

U(1)' Anomaly Free Conditions

Analogously with the SM anomaly cancellation condition, there are $\mathcal{A}_{WWZ'}$, $\mathcal{A}_{ggZ'}$, $\mathcal{A}_{GGZ'}$, and $\mathcal{A}_{Z'Z'Z'}$ and two additional

Cancellations from U(1) and U(1)'.

$$
\begin{aligned}
\mathcal{A}_{Z'Z'B} &:= \sum_{f_L} d_2[f_L] d_3[f_L] Y[f_L] (z[f_L])^2 - \sum_{f_R} d_2[f_R] d_3[f_R] Y[f_R] (z[f_R])^2 \\
&= 0 \\
\mathcal{A}_{BBZ'} &:= \sum_{f_L} d_2[f_L] d_3[f_L] z[f_L] (Y[f_L])^2 - \sum_{f_R} d_2[f_R] d_3[f_R] z[f_R] (Y[f_R])^2 \\
&= 0
\end{aligned}
$$

Exotics and Anomaly Free

In the case of a pure Axial vector coupling to both the SM and DM:

$z_q^{(i)} := z_Q^{(i)} = -z_u^{(i)} = -z_d^{(i)}$; $z_l^{(i)} := z_L^{(i)} = -z_e^{(i)}$; $z_{\mathrm{DM}} := z_{\chi_L} = -z_{\chi_R}$

Field Name	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)$	Notation
Q_L^i, $Q'_{L,R}$	$1/3$	2	3	$(3,2)_{(1/3,\ z)}$
u_R^i, $u'_{L,R}$	$4/3$	1	3	$(3,1)_{(4/3,\ z)}$
d_R^i, $d'_{L,R}$	$-2/3$	1	3	$(3,1)_{(-2/3,\ z)}$
L_L^i, $L'_{L,R}$	-1	2	1	$(1,2)_{(-1,\ z)}$
e_R^i, $e'_{L,R}$	-2	1	1	$(1,1)_{(-2,\ z)}$
ν_R, $\chi_{L,R}$	0	1	1	$(1,1)_{(0,\ z)}$
H	1	2	1	$(1,2)_{(1,\ z)}$

Straightforwardly, anomaly cancellation is solved by a general and unique set of equations:

$$z_{Q'_R} = z_{Q'_L} + 2z_{\mathrm{SM}}, \quad z_{u'_R} = 7z_{\mathrm{SM}} + z_{u'_L},$$

$$z_{d'_R} = z_{d'_L} + z_{\mathrm{SM}}, \quad z_{L'_R} = z_{L'_L} + 6z_{\mathrm{SM}}, \quad z_{d'_L} \neq 2z_{Q'_L} + \frac{101}{2} z_{\mathrm{SM}} + 14 z_{u'_L},$$

$$z_{e'_L} = \frac{1}{3}(z_{d'_L} + 6z_{L'_L} - 2z_{Q'_L} - 28z_{\mathrm{SM}} - 14z_{u'_L}),$$

$$z_{e'_R} = \frac{1}{3}(z_{d'_L} + 6z_{L'_L} - 2z_{Q'_L} - 37z_{\mathrm{SM}} - 14z_{u'_L}),$$

$$\begin{aligned} z_{L'_L} = \quad & \frac{1}{\Omega}\Big(-8z_{d'_L}^2 - 4z_{d'_L}z_{Q'_L} - 32z_{Q'_L}^2 - 74z_{d'_L}z_{\mathrm{SM}} + 58z_{Q'_L}z_{\mathrm{SM}} \\ & -404z_{\mathrm{SM}}^2 - 28z_{d'_L}z_{u'_L} + 56z_{Q'_L}z_{u'_L} + 469z_{\mathrm{SM}}z_{u'_L} + 133z_{u'_L}^2 \Big) \ , \end{aligned}$$

where $\Omega = 606z_{\mathrm{SM}} + 168z_{u'_L} - 12z_{d'_L} + 24z_{Q'_L}$

If $z_{\mathrm{SM}} = z_{Q'_L} = 1$ and $z_{u'_L} = -z_{Q'_R} = -3$:

$$z_{u'_R} = 4, \quad z_{d'_L} = 3, \quad z_{d'_R} = 4, \quad z_{L'_L} = -9,$$

$$z_{L'_R} = -3, \quad z_{e'_L} = -13, \quad z_{e'_R} = -16.$$

Name	n_G	Lepto-phobic/philic?
♯1. Universal Model	3	✗
♯2. /w DM Model	3	✗
♯3. *L*-phobic Model	3	Leptophobic
♯4. *L*-philic Model	3	Leptophilic
♯5. 1G-Model	1	N/A
♯6. *t*-*b*-Model	1	Leptophobic

Field	$\sharp 1$	$\sharp 2$	$\sharp 3$	$\sharp 4$	$\sharp 5$	$\sharp 6$
$z[Q_L]$	1	1	1	0	1	1
$z[u_R]$	-1	-1	-1	0	-1	-1
$z[d_R]$	-1	-1	-1	0	-1	-1
$z[L_L]$	1	1	0	1	1	0
$z[e_R]$	-1	-1	0	-1	-1	0
$z[\chi_L]$	-	9	9	-9/4	1	1
$z[\chi_R]$	-	-9	-9	9/4	-1	-1

Field	♯1	♯2	♯3	♯4	♯5	♯6
$z[Q'_L]$	1	1	1	-	-	-
$z[Q'_R]$	3	-1	0	-	1	1
$z[u'_L]$	-3	-2	-2	-2	-1	-1
$z[u'_R]$	4	3	-1	5/2	-	-
$z[d'_L]$	3	-6	-2	2	-1	-1
$z[d'_R]$	4	5	11	-5/2	-	-
$z[L'_L]$	-9	-82/3	-49/12	-157/48	-	-
$z[L'_R]$	-3	-28/3	95/12	-13/48	1	0
$z[e'_L]$	-13	-100/3	103/6	-85/24	-1	0
$z[e'_R]$	-16	-127/3	67/6	-121/24	-	-
$z[\nu_R]$	-	-	-	-	1	1
$N[\nu_R]$	-	-	-	-	2	2

SM Fermions

For axial vector couplings $z[\bar{Q}_L u_R] = 2z_0$ and $z[\bar{Q}_L d_R] = 2z_0$, the gauge invariant mass operator $H^\dagger \bar{Q}_L u_R$ requires that $z[H^\dagger] = -2z_0$.
However, $H\bar{Q}_L d_R$ breaks down U(1)' gauge invariance. There are two ways out:

- Type II Two Higgs Doublet Model
- EFT higher dimension operators $\frac{1}{\Lambda} S H^\dagger Q_L \bar{u}_R$. S is a SM singlet and gets vev $\langle S \rangle \equiv v'$ to break U(1)' (Froggatt-Nielson).

- $m_{Z'} \simeq g'v'$; $m_S \simeq \lambda_S v'$ (λ_S is the S quartic coupling.)

Exotic Fermion Masses

Model $\sharp 1$

$z[H]=2$, $z[S_1]=1$ and $z[S_4]=4$

$$\mathcal{L}_{\rm SMY} \supset y_u^i H \bar{Q}_L u_R + \frac{y_d^i}{\Lambda} S_4 H^\dagger \bar{Q}_L d_R + \frac{y_l^i}{\Lambda} S_4 H^\dagger \bar{L}_L e_R$$

$$\mathcal{L}_{\rm Ex} \supset y_{Q'} S_1^2 Q_L' \bar{Q}_R' + \frac{y_{u'}}{\Lambda^2} S_4^2 S_1^\dagger u_L' \bar{u}_R' + y_{d'} S_1 d_L' \bar{d}_R' + \frac{y_{L'}}{\Lambda^2} S_4 {S_1}^2 L_L' \bar{L}_R' + \frac{y_{e'}}{\Lambda} S_4 S_1^\dagger e_L' \bar{e}_R'$$

$$L_{\rm UV} \supset y_\psi H^\dagger \bar{L}_L \psi_L + y_\psi' S_4 \bar{\psi}_L e_R + m_\psi \bar{\psi}_L \psi_R$$

where $\Lambda = \frac{m_\psi}{y_\psi y_\psi'}$ and ψ_L, ψ_R in the representation $(1,1)_{-2,3}$

Mass Generation For Mirror Construction

In order to have above EW massive mirror exotics, additional U(1)' neutral charged exotics fermions are introduced:

$$\mathcal{L}_{Mir} \supset S\bar{Q}'_L Q'_R + S\bar{u}'_L u'_R + S\bar{d}'_L d'_R + S\bar{L}'_L L'_R + S\bar{e}'_L e_R \ .$$

where $z[Q'_L] = z[u'_R] = z[d'_R] = z[L'_L] = z[e'_R] = 0$ and $z[S] = -1$

The Non-Perturbative Limit

$U(1)'$ coupling strength $\alpha' \equiv g'^2/4\pi$ runs with the energy scale Q is given by

$$\frac{d\alpha'^{-1}}{d\ln Q} = -\frac{b}{2\pi} \qquad \text{with} \quad b = \sum_f \frac{2}{3} z_f^2 + \sum_s \frac{1}{3} z_s^2$$

If the new fermions enter at the scale M, the running of g' to some UV scale Λ is described by

$$\alpha'^{-1}(\Lambda) = \alpha'^{-1}(m_{Z'}) - \int_{m_{Z'}}^{M} \frac{b_{Z'}}{2\pi}\,\mathrm{d}\ln Q - \int_{M}^{\Lambda} \frac{b_{Z'} + b_M}{2\pi}\,\mathrm{d}\ln Q$$

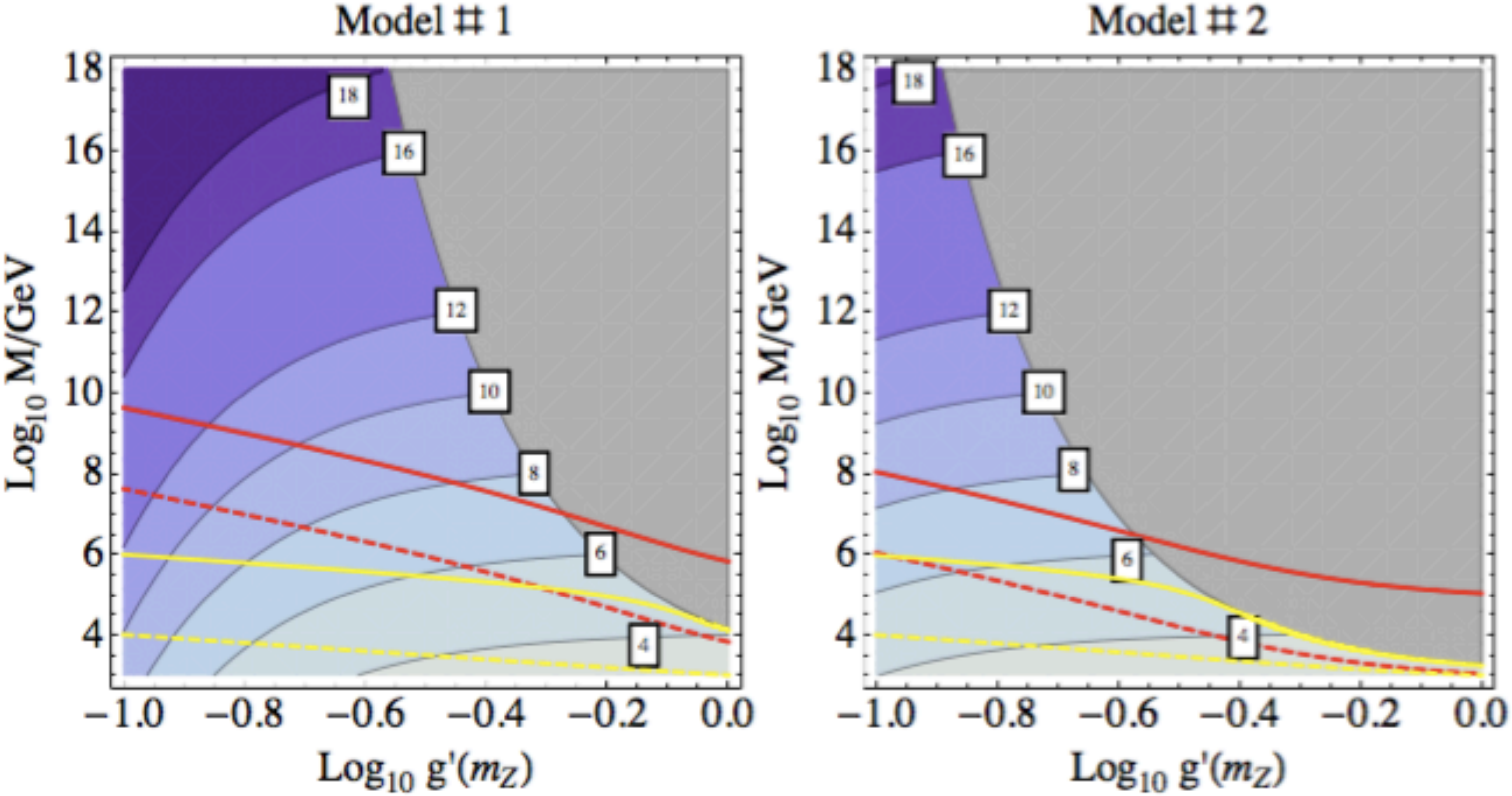
where $b_{Z'}$ the sum is over the SM states and DM.

The Non-Renormalizable Limit

The scale limit $\Lambda_{\not R}$ for an anomaly EFT theory maintaining renormalizable without introducing exotics to cancel anomaly at scale M is: (Preskill 1991)

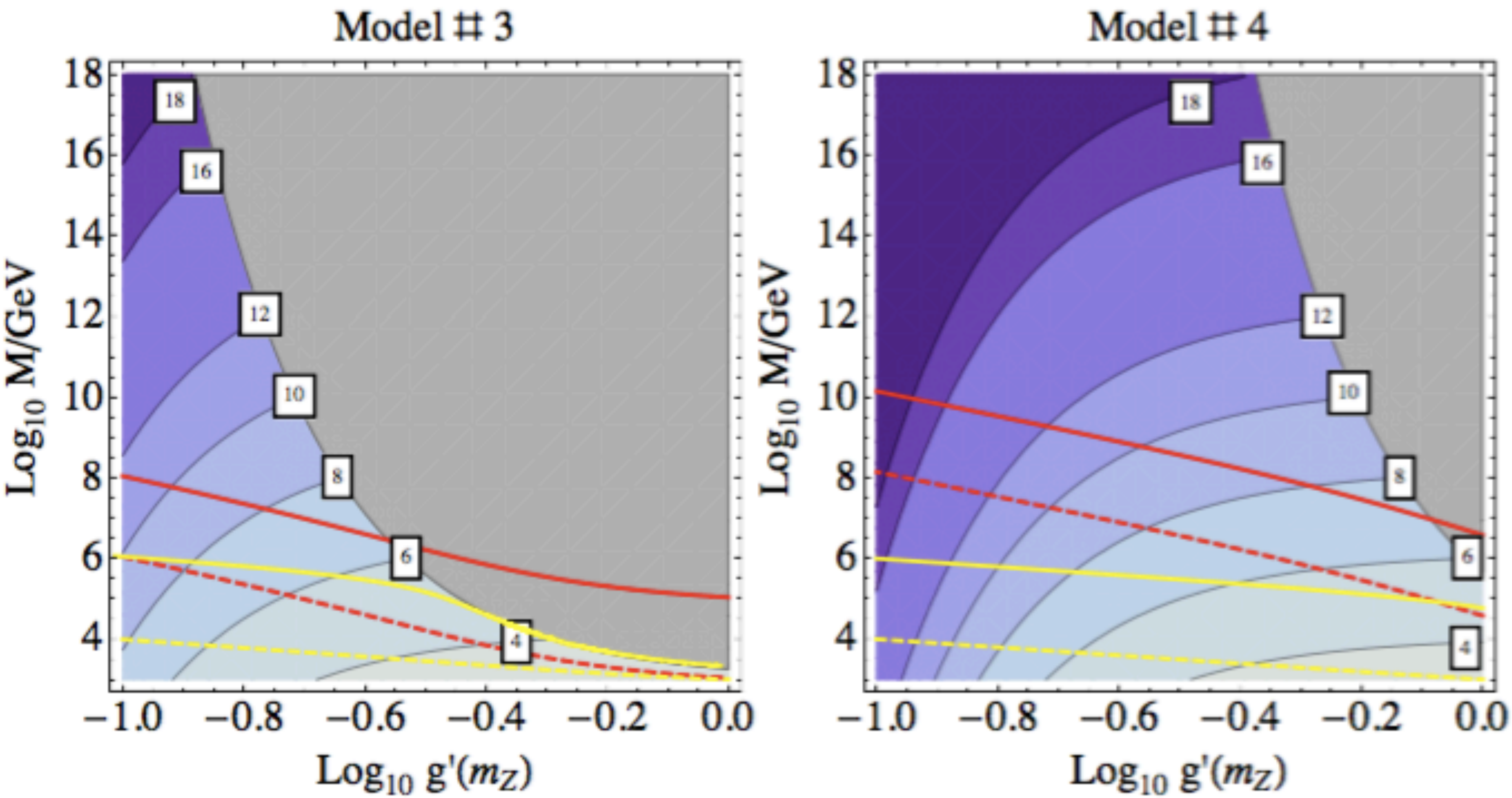
$$M < m_{Z'} \left(\frac{64\pi^3}{|g_{\not R}^3 \mathcal{A}_{Z'Z'Z'}|} \right) \equiv \Lambda_{\not R}$$

where $g_{\not R} \equiv g(\Lambda_{\not R})$ and $\mathcal{A}_{Z'Z'Z'} = \mathrm{Tr}[z^3]$ is the $\mathrm{U}(1)'^3$ anomaly coefficient calculated in the EFT below the scale of the exotics M.

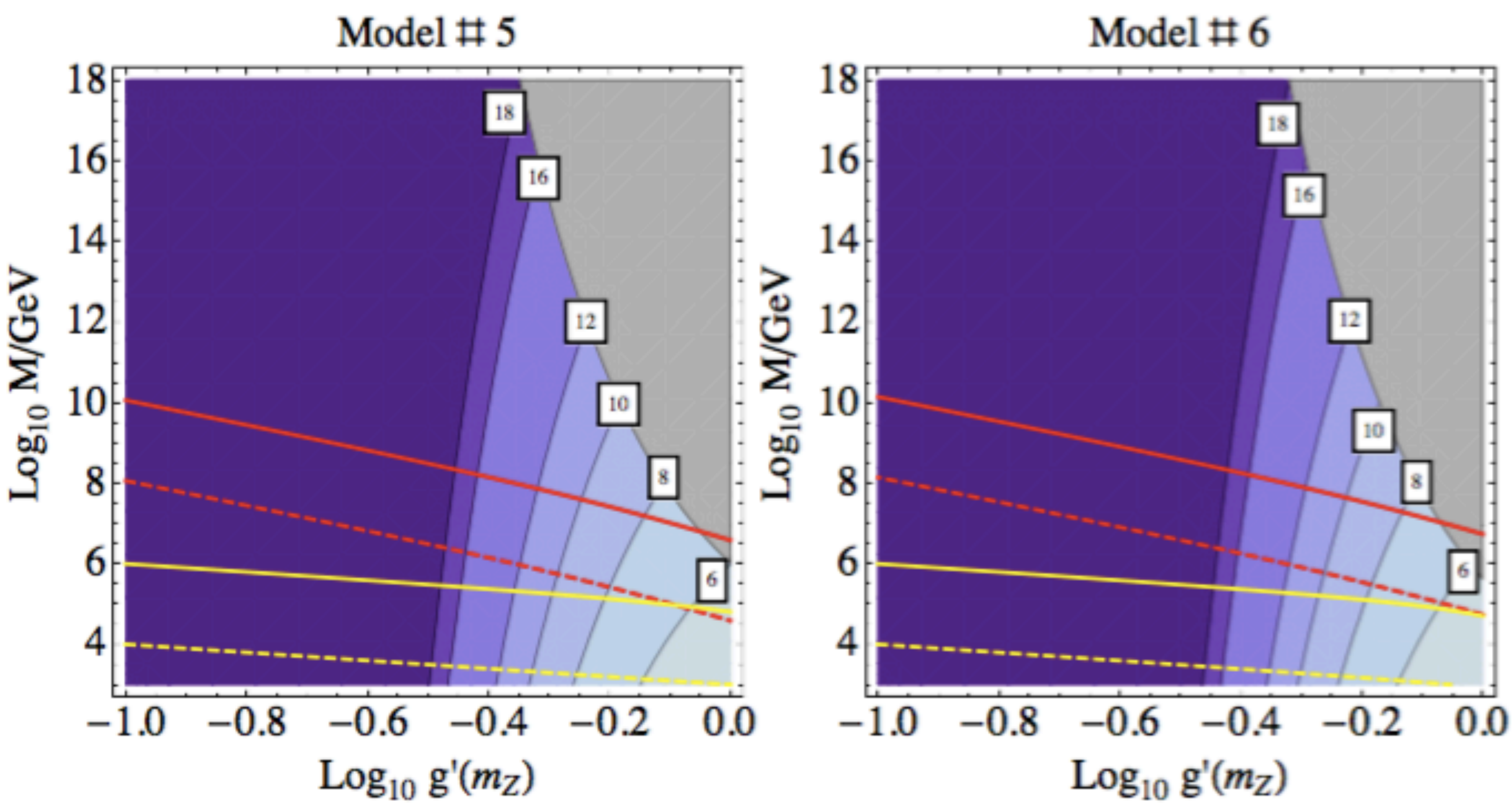


Purple contours: g' runs non-perturbative. Grey region: $\Lambda_{\not P} < M$. Red curves: $\Lambda_{\not R}$ for $m_{Z'} \sim 1$ TeV(dashed), and 100 TeV(solid). Yellow curves: Unitarity for $m_{Z'} \sim 1$ TeV(dashed), and 100 TeV(solid).

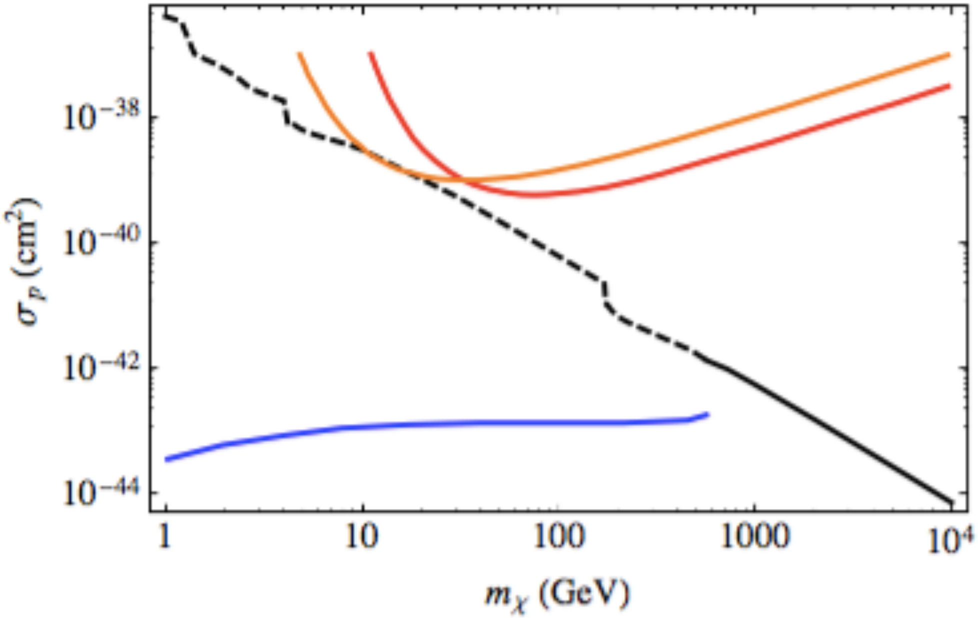
$M \lesssim v' \simeq m_{Z'}/g'$



Model ♯ 3
Model ♯ 4
Log10 M/GeV
Log10 g'(mZ)
18
16
14
12
10
8
6
4
−1.0
−0.8
−0.6
−0.4
−0.2
0.0

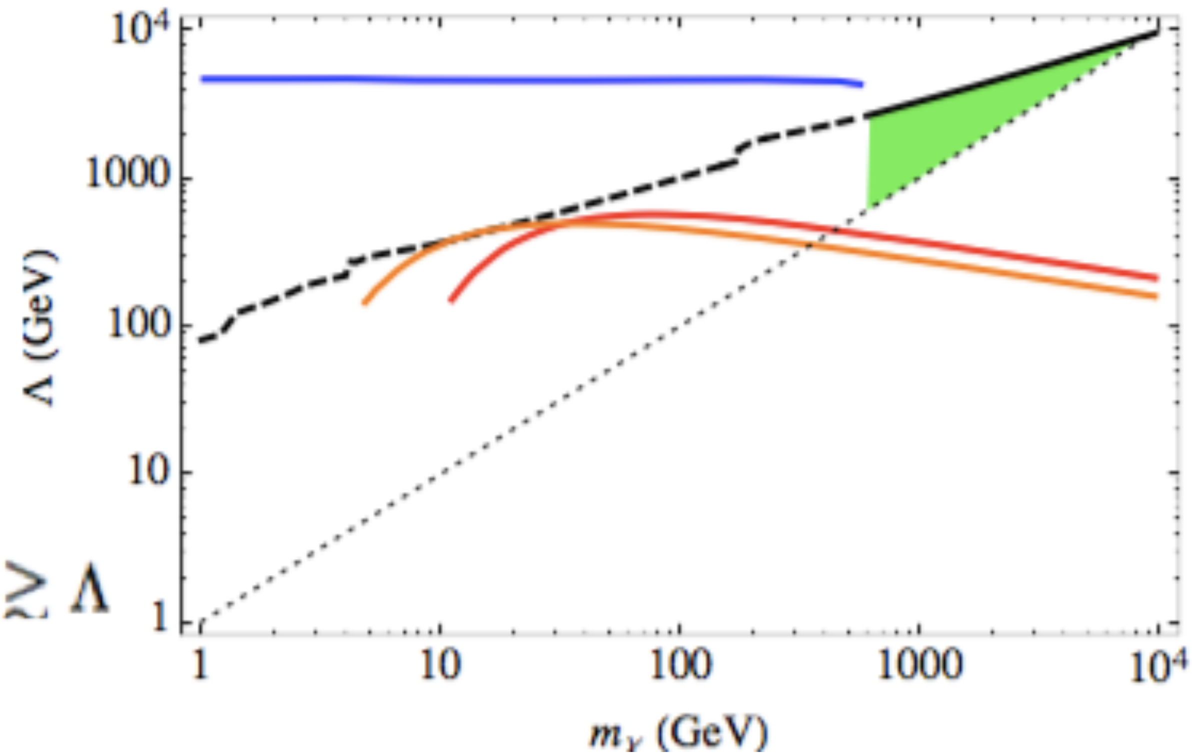


Model ♯ 5
Model ♯ 6
18
16
14
12
10
8
6
4
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Log10 M/GeV
Log10 g'(mZ)



$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma^5 f$

PICO60 (RED) [32], PICO2L (ORANGE) [33], and CMS monojet searches (BLUE) [39].



The thin DOTTED LINE indicates the regime $m_\chi \gtrsim \Lambda$

Summary and more coming

- Systematic construction of extra spectrum for Anomaly cancellation.
- Where are the new exotics?
- Mass structure
- More on t-b-philic DM work