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Hadronic QCD Axion Models with Multiple New Fermions

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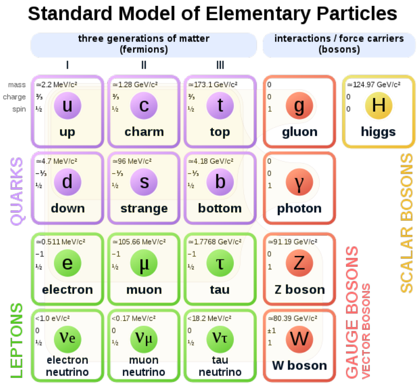
VP & S. Hoof, arXiv:2107.12378 [PRD 104 (2021) 075017]

The KSVZ Model [Kim '79; Shifman,Vainstein,Zakharov '80]



[Wikimedia Commons]

$\rightarrow$ Uncharged under $\mathrm{U}(1)_{\mathrm{PQ}}$

$+$

PQ field

$$\Phi \sim (1,1,0)$$

$$\rightarrow \Phi = \frac{(v_a+\rho_a)}{\sqrt{2}} e^{ia/v_a}$$

Heavy fermion

$$\mathcal{Q} = \mathcal{Q}_L + \mathcal{Q}_R \sim (3,1,0)$$

$$\rightarrow \mathcal{L} \supset -(y_{\mathcal{Q}} \overline{\mathcal{Q}}_L \mathcal{Q}_R \Phi)$$

$$\rightarrow m_{\mathcal{Q}} = y_{\mathcal{Q}} v_a/\sqrt{2}$$

Axion Mass and Interactions

Axion mass

$$m_a \simeq 5.69 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

Axion-photon coupling

$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{2\pi f_a} \left(\frac{E}{N} - 1.92(4) \right)$$

Axion-electron coupling

$$g_{ae} = \frac{3\alpha_{\rm em}^2}{2\pi} \frac{m_e}{f_a} \left[\frac{E}{N} \ln \left(\frac{f_a}{m_e} \right) - 1.92 \ln \left(\frac{\Lambda}{m_e} \right) \right]$$

$\mathrm{U}(1)_{\rm PQ}$ charge — SM gauge dimensions

$$E = \mathcal{X}\, d(\mathcal{C})\, d(\mathcal{I}) \left(\frac{d(\mathcal{I})^2 - 1}{12} + \mathcal{Y}^2 \right)$$

$$N = \mathcal{X}\, d(\mathcal{I})\, T(\mathcal{C})$$

$f_a = v_a/2N = v_a/N_{\rm DW}$

$\mathcal{Q}$ gauge reps. — Dynkin index

$$\left(\frac{E}{N} \right)_{\rm KSVZ} = 0$$

Selection Criteria [Di Luzio,Mescia,Nardi '17]

- A window for preferred models – selection criteria for $\mathcal{Q}$:

Dark Matter Constraints

Constrain $f_a \lesssim 5 \times 10^{11}\,\mathrm{GeV} \Rightarrow$ constraint on $m_{\mathcal{Q}} = y_{\mathcal{Q}} f_a N_{\mathrm{DW}}/\sqrt{2}$

$\mathcal{Q}$ Lifetimes

$\mathcal{Q}$ to decay to SM with $\tau_{\mathcal{Q}} \leq 10^{-2}\,\mathrm{s}$

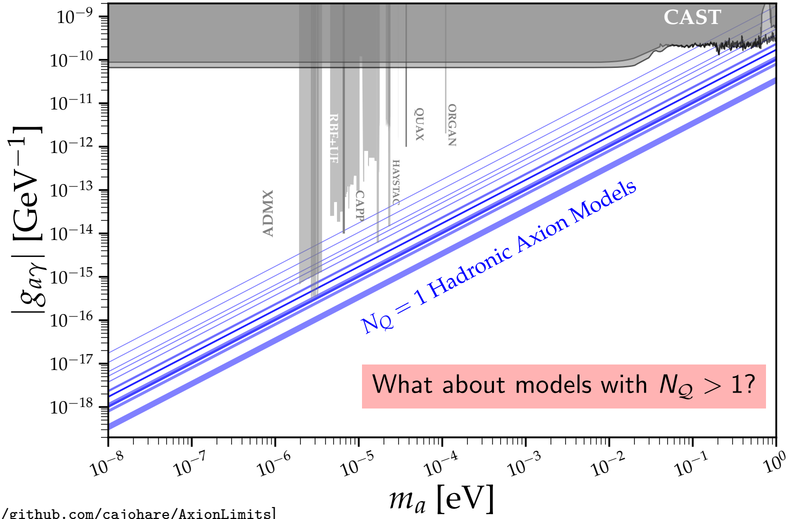
$\rightarrow$ Restrict $d\,(\mathcal{O}) \leq 5$ for post-inflationary $\mathrm{U}(1)_{\mathrm{PQ}}$ breaking scenario

Landau Poles

Avoid LPs below $10^{18}\,\mathrm{GeV}$, i.e. only representations with $\Lambda_{\mathrm{LP}} > 10^{18}\,\mathrm{GeV}$ allowed

- 15 $\mathcal{Q}$ representations fulfil the criteria $(m_{\mathcal{Q}} = 5 \times 10^{11}\,\mathrm{GeV})$

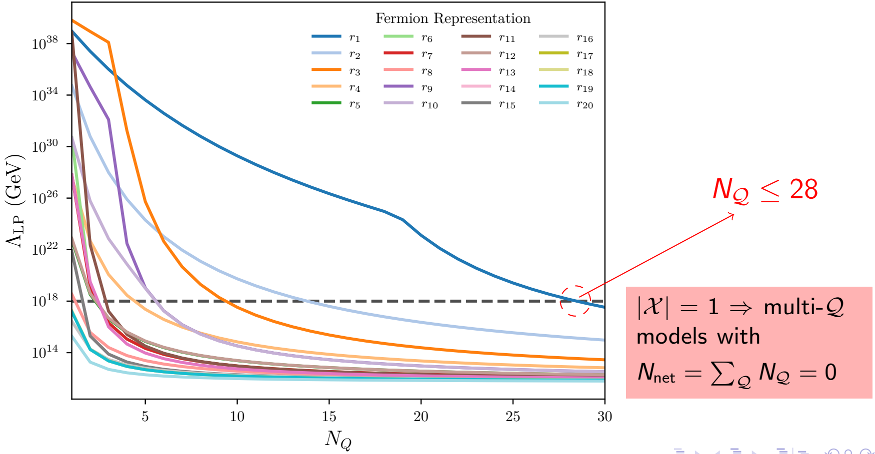
The $N_Q = 1$ Window



[Ciaran O'Hare: https://github.com/cajohare/AxionLimits]

Adding More Fermions

For given $m_\mathcal{Q}$ and LP threshold, possible to find maximum $N_\mathcal{Q}$ allowed:



$|\mathcal{X}| = 1 \Rightarrow$ multi-$\mathcal{Q}$ models with $N_{\rm net} = \sum_\mathcal{Q} N_\mathcal{Q} = 0$

Selection Criteria

Dark Matter Constraints

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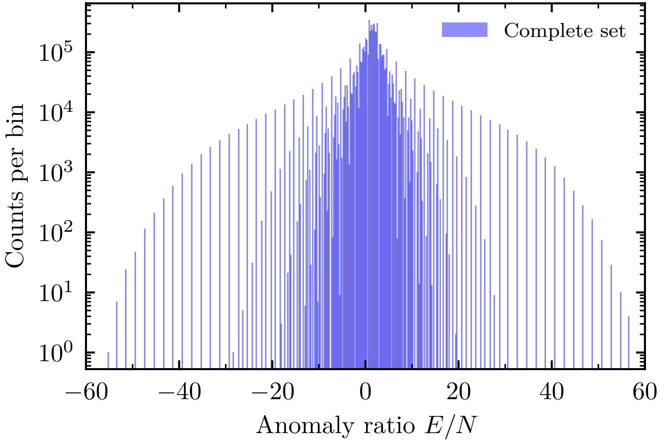
$N \neq 0$

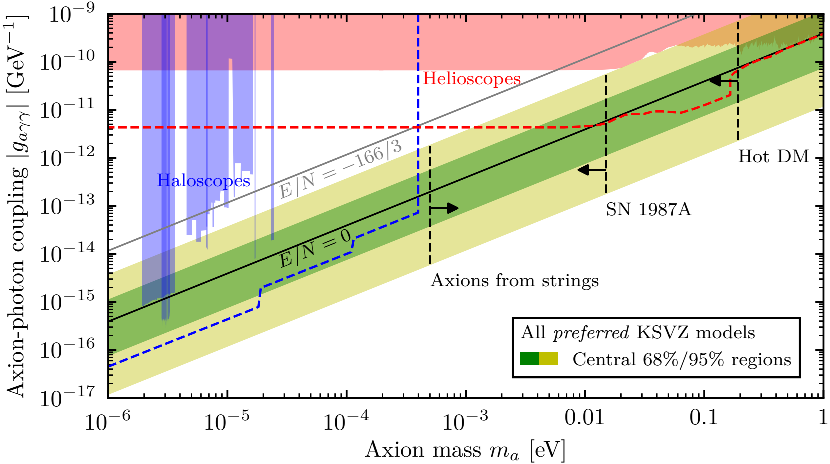
The model should provide a solution to the Strong CP problem.

Anomaly Ratio Distributions

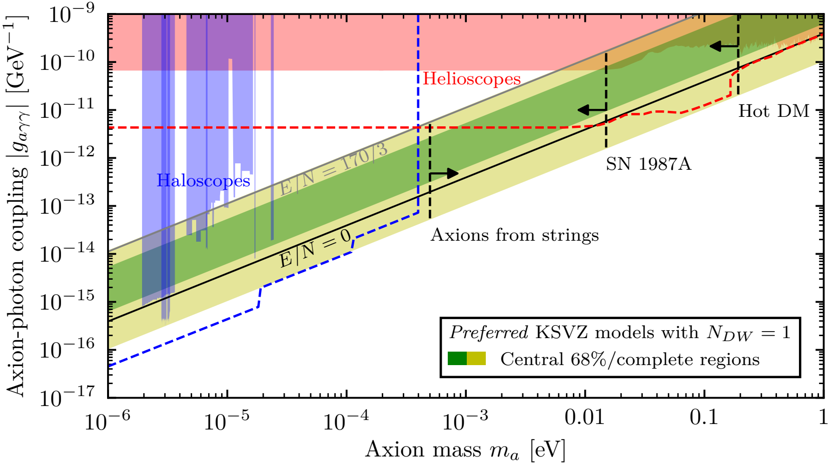


- 5,753,012 non-equivalent models $\rightarrow \approx 1.42\%$ models photophobic $(|E/N - 1.92| < 0.04)$
- 820 different E/N values $\rightarrow$ 11 within 1σ of 1.92(4)
- Largest $|g_{a\gamma\gamma}|$: $N_{\mathcal{Q}} = 8$ model with $E/N = -166/3$

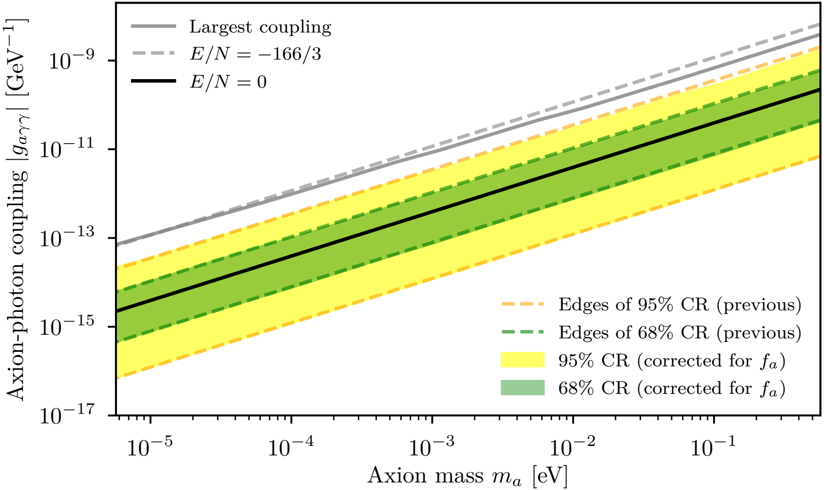
Hadronic Axion Bands



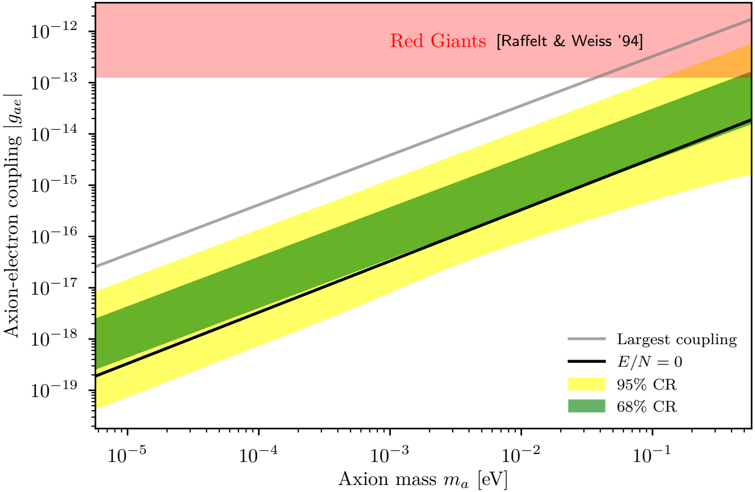
$N_{DW} = 1$ Models


Axion-photon coupling $|g_{a\gamma\gamma}|$ [GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Helioscopes
Haloscopes
E/N = 170/3
E/N = 0
Hot DM
SN 1987A
Axions from strings
Preferred KSVZ models with $N_{DW} = 1$
Central 68%/complete regions
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
Axion mass m_a [eV]

Different $m_{\mathcal{Q}}$, Correction for f_a



Axion-electron Coupling



What Next?

- Non-universal coupling of $\mathcal{Q}$ to Φ, i.e. distinguishable $\mathcal{Q}$s with different $m_{\mathcal{Q}}$
- Non-universal PQ field – multi-axion models, essentially different $m_{\mathcal{Q}}$ for each $\mathcal{Q}$
- Enhanced coupling, e.g. via clockwork mechanism [Farina,Pappadopulo,Rompineve,Tesi '17]
- A catalogue of DFSZ extensions with generation-dependent $\mathrm{U}(1)_{\mathrm{PQ}}$ charges and nine Higgs doublets

Summary

- Hadronic axion models = SM + PQ scalar + heavy chiral fermion(s)
- Extend the hadronic model by allowing multiple $\mathcal{Q}$ in different representations
- Selection criteria to restrict the models to a preferred window
$\Rightarrow N_{\mathcal{Q}} \leq 28$ $(m_{\mathcal{Q}} = 5 \times 10^{11}\,\mathrm{GeV},\ \Lambda_{\mathrm{LP}} > 10^{18}\,\mathrm{GeV}) \rightarrow$ finite number of models
- 820 different E/N values
- Statistical interpretation of the distributions allows to determine density of models in parameter space; central 95% region of $|E/N - 1.92(4)| \rightarrow [0.06, 17.30]$
- Models with $N_{\mathrm{DW}} = 1$ – trivially solve the DW problem; none photophobic

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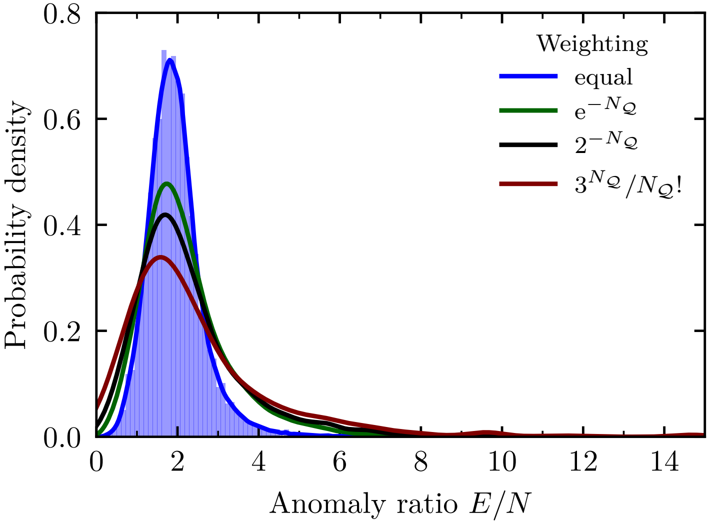
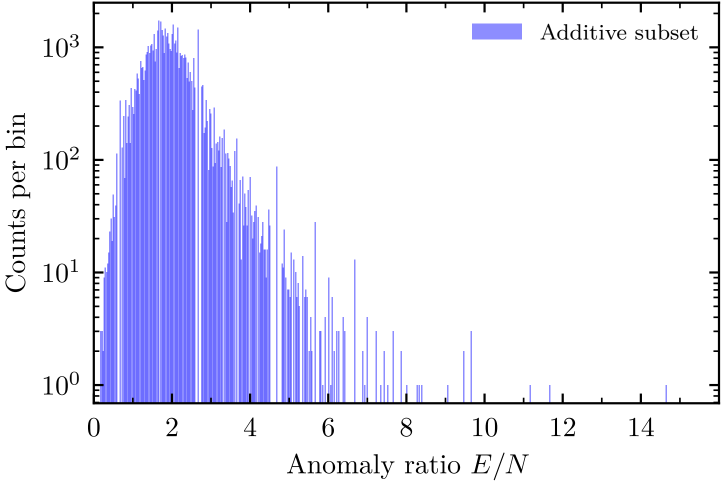
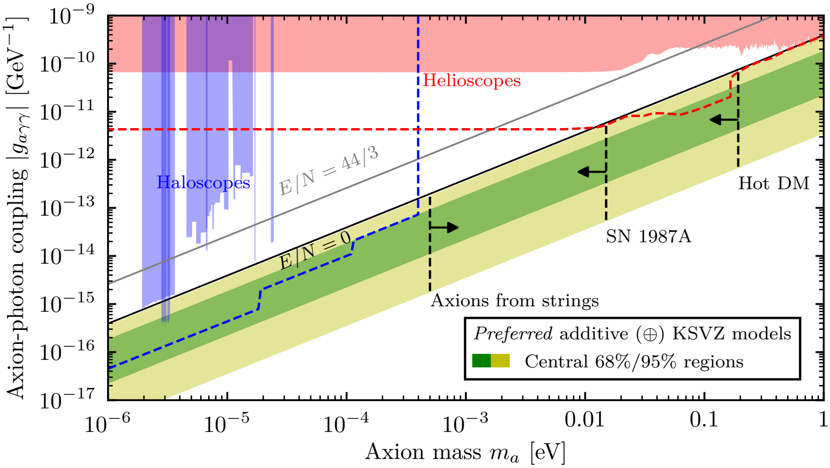
Weighting the Models



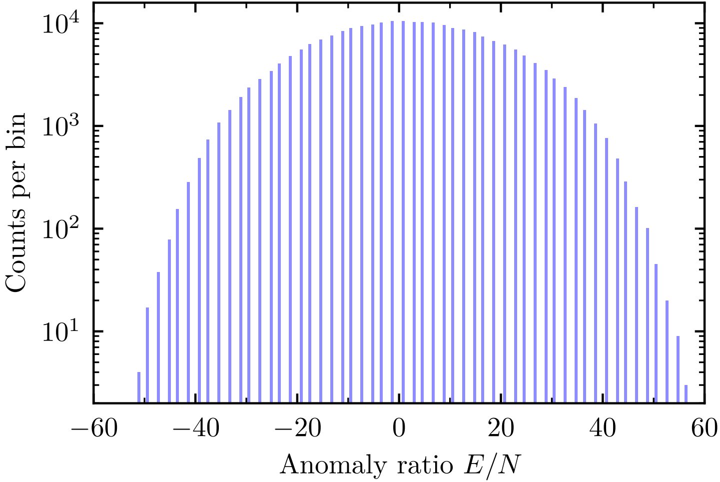
Additive Subset



Additive Subset



$N_{DW} = 1$ Anomaly Ratio Distribution



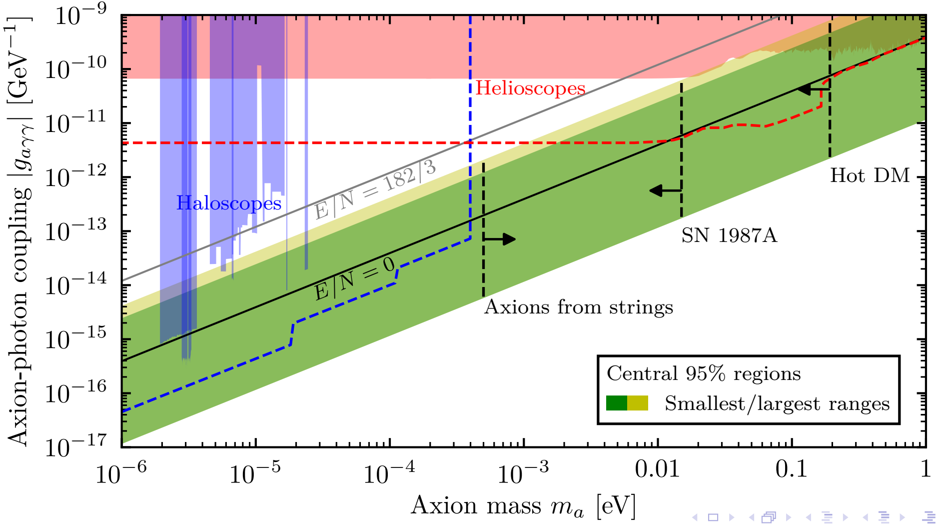
Effect of Varying m_Q

m_Q (GeV)	$\max(N_Q)$	#models	$\widehat{E/N}$	$\overline{E/N}$	med(E/N)	photophobic	95% CR
10^7	15	29,926	$-94/3$	1.51	1.58	1.15%	[0.06, 14.76]
$5 \cdot 10^7$	16	46,334	$-94/3$	1.50	1.56	1.30%	[0.06, 13.29]
10^8	17	65,904	$-94/3$	1.45	1.50	1.25%	[0.06, 14.75]
$5 \cdot 10^8$	18	124,523	$-100/3$	1.52	1.67	1.52%	[0.06, 14.76]
10^9	19	177,836	$-112/3$	1.44	1.54	1.33%	[0.06, 15.27]
$5 \cdot 10^9$	21	330,867	$-118/3$	1.42	1.41	1.36%	[0.06, 15.25]
10^{10}	22	494,428	$-130/3$	1.45	1.56	1.37%	[0.06, 16.73]
$5 \cdot 10^{10}$	24	1,140,142	$-136/3$	1.38	1.50	1.44%	[0.06, 14.68]
10^{11}	25	1,950,978	$-142/3$	1.42	1.52	1.40%	[0.06, 17.24]
$5 \cdot 10^{11}$	28	5,753,017	$-166/3$	1.44	1.52	1.42%	[0.06, 17.30]
10^{12}	29	9,214,494	$-178/3$	1.40	1.47	1.42%	[0.06, 18.74]

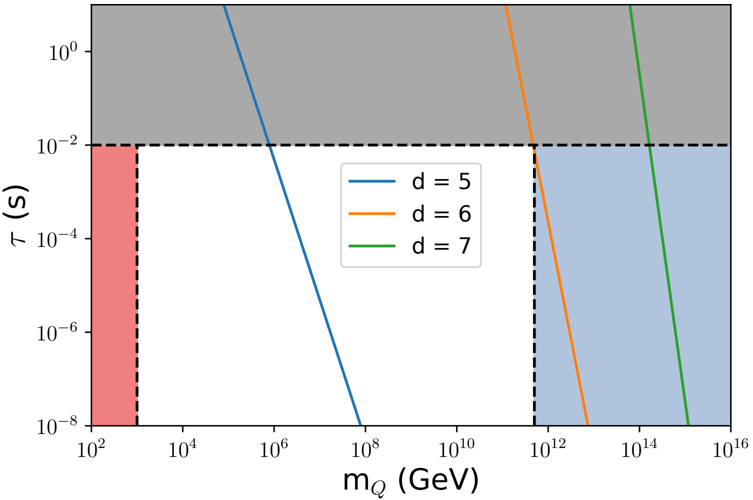
Effect of Varying the LP Threshold

	$\Lambda_{LP} > 10^{16}$ GeV	10^{17} GeV	10^{18} GeV	10^{19} GeV
$m_Q = 10^7$ GeV	$[0.06, 16.74]$	$[0.06, 14.75]$	$[0.06, 14.76]$	$[0.06, 11.26]$
10^8 GeV	$[0.06, 17.25]$	$[0.06, 15.25]$	$[0.06, 14.75]$	$[0.06, 12.78]$
10^9 GeV	$[0.06, 17.23]$	$[0.06, 15.30]$	$[0.06, 15.27]$	$[0.06, 12.77]$
10^{10} GeV	$[0.07, 19.27]$	$[0.06, 18.22]$	$[0.06, 16.73]$	$[0.06, 13.32]$

Effect of Varying the LP Threshold



Q Lifetime



10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
τ (s)
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
m_Q (GeV)
d = 5
d = 6
d = 7

Landau Poles

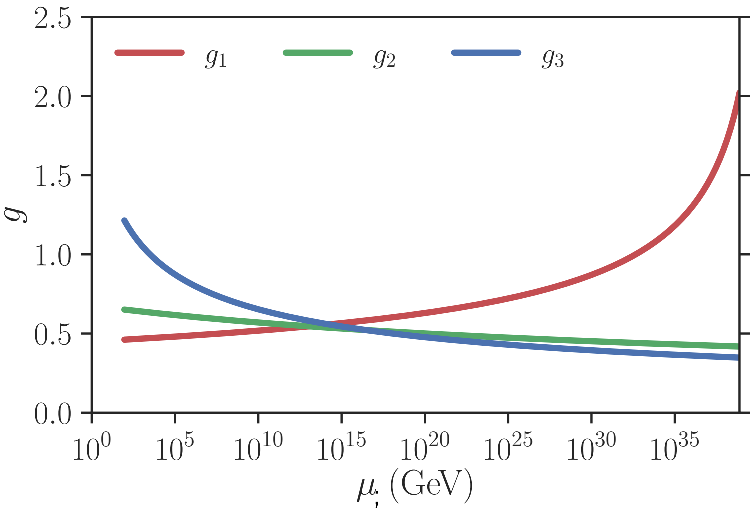
$$\frac{\mathrm{d}}{\mathrm{dt}}\alpha_i^{-1} = -a_i - \frac{b_{ij}}{4\pi}\alpha_j$$

$$a_i = -\frac{11}{3}\,C_2(G_i) + \frac{4}{3}\sum_F \kappa\,T(F_i) + \frac{1}{3}\sum_S \eta\,T(S_i)$$

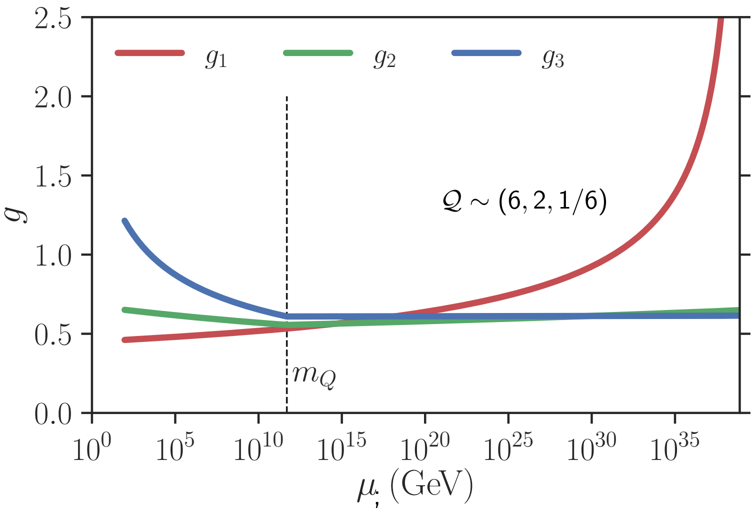
$$b_{ij} = \left[-\frac{34}{3}\left(C_2(G_i)\right)^2 + \sum_F \left(4C_2(F_i) + \frac{20}{3}C_2(G_i)\right)\kappa\,T(F_i) + \sum_S \left(4C_2(S_i) + \frac{2}{3}C_2(G_i)\right) \cdot \eta\,T(S_i)\right]\delta_{ij} + 4\left(1-\delta_{ij}\right)\left[\sum_F \kappa\,C_2(F_j)\,T(F_i) + \sum_S \eta\,C_2(S_j)\,T(S_i)\right]$$

;

Landau Poles



Landau Poles



The Allowed $\mathcal{Q}$s [Di Luzio,Mescia,Nardi '17]

R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{R_Q}_{LP}$[GeV]	E/N	N_{DW}
R_1: $(3,1,-\frac{1}{3})$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	2/3	1
R_2: $(3,1,+\frac{2}{3})$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	8/3	1
R_3: $(3,2,+\frac{1}{6})$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	5/3	2
R_4: $(3,2,-\frac{5}{6})$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	17/3	2
R_5: $(3,2,+\frac{7}{6})$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	29/3	2
R_6: $(3,3,-\frac{1}{3})$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	14/3	3
R_7: $(3,3,+\frac{2}{3})$	$\overline{Q}_R q_L H$	$6.6\cdot 10^{27}(g_2)$	20/3	3
R_8: $(3,3,-\frac{4}{3})$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	44/3	3
R_9: $(\overline{6},1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$2.3\cdot 10^{37}(g_1)$	4/15	5
R_{10}: $(\overline{6},1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$5.1\cdot 10^{30}(g_1)$	16/15	5
R_{11}: $(\overline{6},2,+\frac{1}{6})$	$\overline{Q}_R \sigma q_L \cdot G$	$7.3\cdot 10^{38}(g_1)$	2/3	10
R_{12}: $(8,1,-1)$	$\overline{Q}_L \sigma e_R \cdot G$	$7.6\cdot 10^{22}(g_1)$	8/3	6
R_{13}: $(8,2,-\frac{1}{2})$	$\overline{Q}_R \sigma \ell_L \cdot G$	$6.7\cdot 10^{27}(g_1)$	4/3	12
R_{14}: $(15,1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$8.3\cdot 10^{21}(g_3)$	1/6	20
R_{15}: $(15,1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$7.6\cdot 10^{21}(g_3)$	2/3	20