Axion-assisted electroweak baryogenesis

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based on arXiv:1007.0019
w/ John March-Russell

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Baryogenesis

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One of the better-motivated BSM questions!

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- Violation of CP
- Departure from thermal equilibrium

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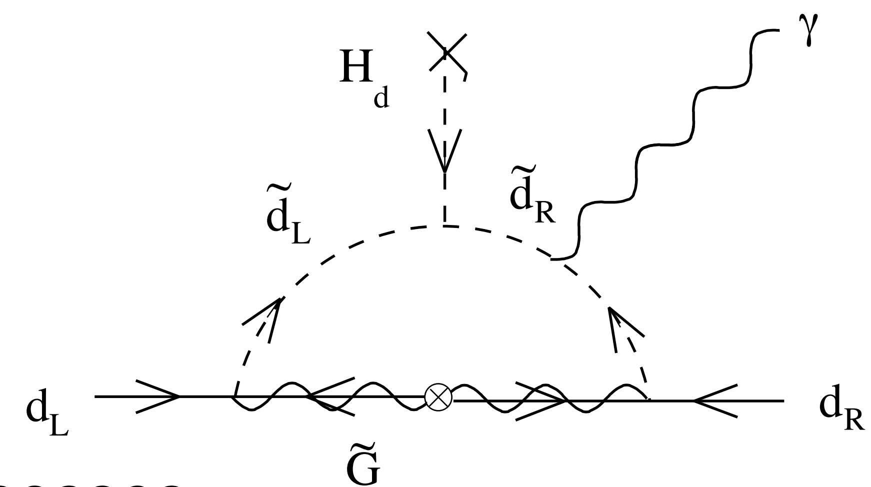
Certainly there are countless other mechanisms with these ingredients, but the EWPT is such a compellingly natural part of our cosmological history

We'll focus on the source of CP violation

The question of CP violation

- A natural ingredient of the SM, but relation to baryogenesis is less clean...
- CP violation intrinsic to SM, but effects suppressed by Jarlskog invariant; effective CP violation in weak interactions is 10^{-20}
- Can do it in MSSM with CP-violating soft masses; or by adding dimension-six operators by hand, but these are fairly tightly constrained by neutron/electron EDMs and CP-violating FCNC processes.



- A little tension: want CP violation large during baryogenesis, but very small now?
- Wouldn’t it be nice if we could somehow relax CP violation to satisfy current bounds?

Dynamical relaxation of CP violation

- We know of one such example: the strong CP angle in QCD with an axion!
- CP violation large in early universe, before axion relaxes.
- Axion relaxes starting around confinement; present value satisfies neutron EDM limits $\theta_{QCD} < 10^{-9}$
- Unsurprisingly, this is not a completely new idea...

The basic idea

Induce an effective, CP-violating operator...

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Biases baryon number during EWPT: $\dfrac{dn_B}{dt} = -\dfrac{1}{T}\Gamma_a \mu_{CS}$

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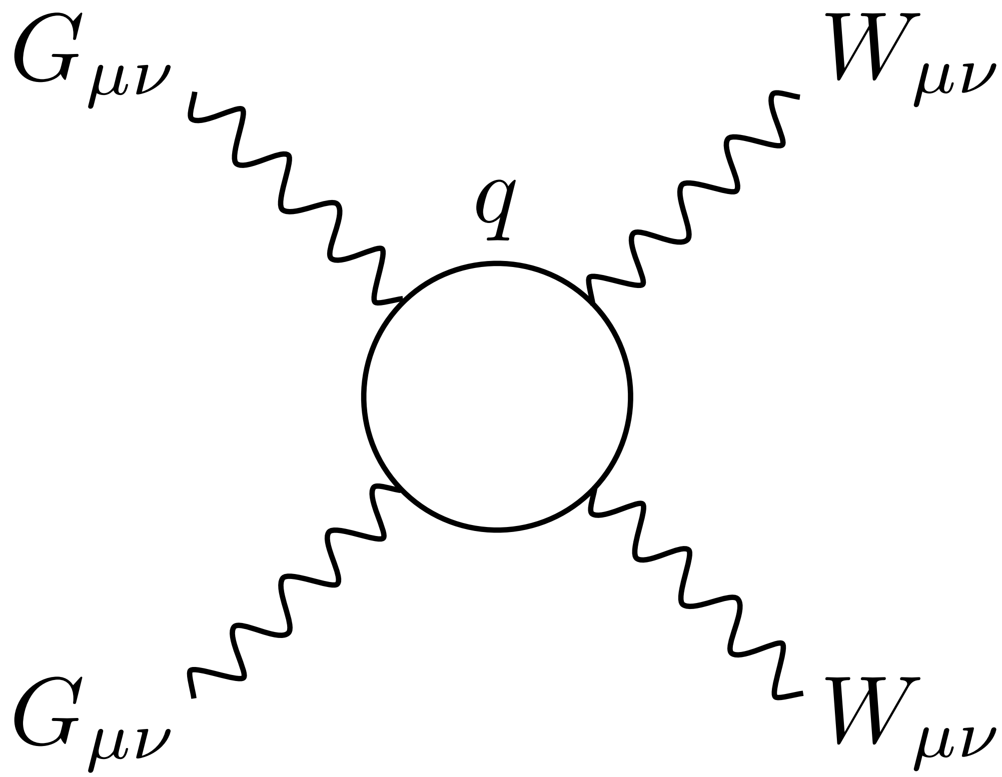
Ultimate baryon asymmetry $\sim \mathrm{const} \times \alpha_w^5 \delta\Phi$

The idea in practice: QCD

[Kuzmin, Shaposhnikov, Tkatchev '92]

Integrate out quarks to generate an effective operator



$$\sim \frac{7\alpha_3\alpha_2}{6480}\frac{1}{m_q^4}(G\tilde{G})(W\tilde{W})$$

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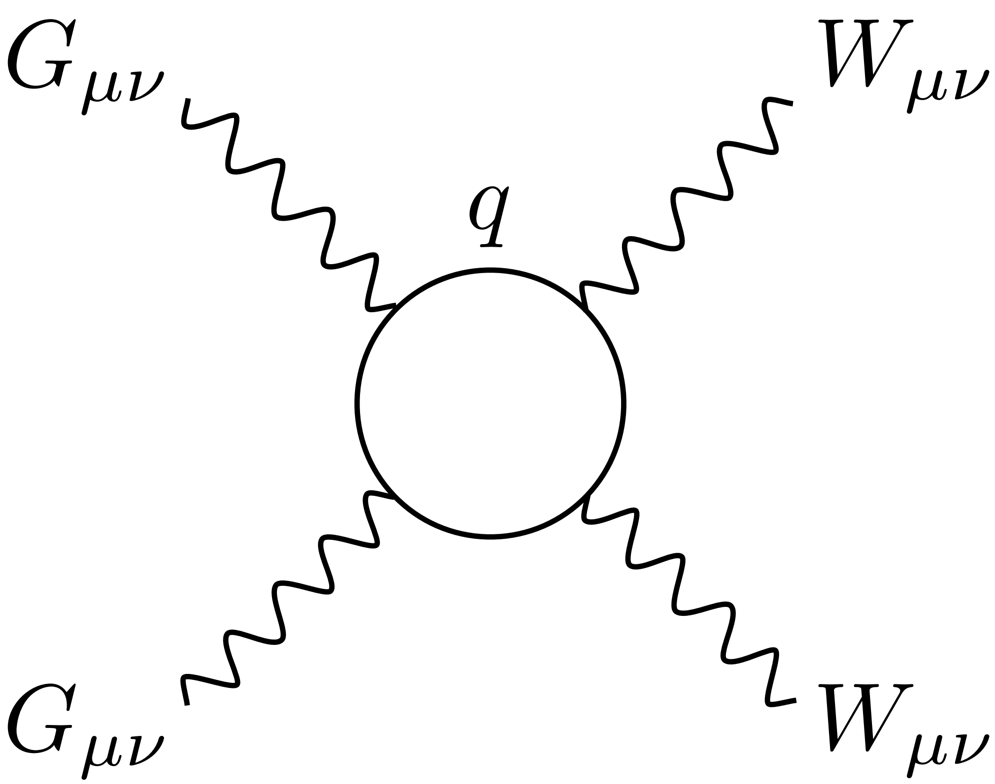

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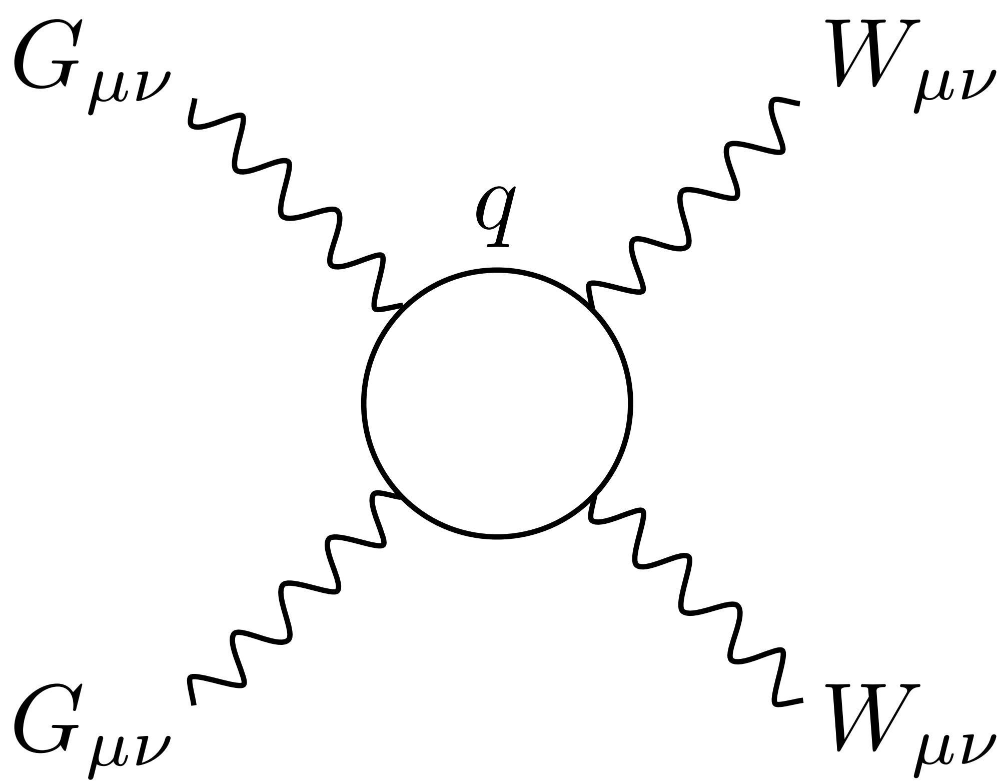

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$$\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle = m_a^2(T) f_a^2 \sin\theta$$

This looks like a chemical potential for CS number, and

$$\delta\Phi \sim \frac{\sin\theta}{m_q^4} f_a^2\, \delta m_a^2(T,v)$$

Quantitatively...

Quantitative result depends on change in axion mass during EWPT...

Axion mass in this regime only comes from instanton effects:

$$\delta\Phi \simeq \sin\theta \frac{f_\pi^2 m_\pi^2}{T_c^3}\left(\frac{\Lambda}{T_c}\right)^9$$

This is terrible; need $T_c \sim \Lambda$ for meaningful CP violation

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Strong CP won't work.

The next best thing?

Try the silliest possible generalization: a confining sector with a higher confinement scale.

What are the necessary ingredients?

- A confining gauge group with strong CP angle
- Some means of communicating to the SM
- Significant time-dependence during EWPT
- An axion for the new group

May sound a bit hokey, but the results are appealing.

A simple (nonsupersymmetric) model

$SU(N)_G$ gauge theory w/ bifundamental matter

	$SU(N)_G$	$SU(2)_L$	$U(1)_Y$
Q	$\square$	2	Y_Q
$\overline{Q}$	$\overline{\square}$	2	$-Y_Q$
U	$\square$	1	$1/2 + Y_Q$
$\overline{U}$	$\overline{\square}$	1	$-1/2 - Y_Q$

(anomaly-free; if you want unification, add colored multiplets to fill out $\mathbf{5} + \overline{\mathbf{5}}$)

(I will assume colored multiplets are ~1 TeV and irrelevant to the IR phenomenology)

The theory I

Start with vector masses and Higgs couplings:

$$\mathcal{L}_G \supset -\mu_Q Q\overline{Q} - \mu_U U\overline{U} - \lambda H^\dagger Q\overline{U} - \lambda' H\overline{Q}U + \text{ h.c.}$$

Spectrum has three dirac fermions w/

$$\mathcal{M} = \begin{pmatrix} \mu_Q & \frac{1}{\sqrt{2}}\lambda v(T) \\ \frac{1}{\sqrt{2}}\lambda' v(T) & \mu_U \end{pmatrix}$$

For $\mu_Q = \mu_U = \mu$ $\quad m_Q(T) = \mu,\ \mu \pm \sqrt{\frac{\lambda\lambda'}{2}} v(T)$

The theory II

Symmetries allow a theta term for the hidden gauge group

$$\mathcal{L}_G \supset -\frac{\alpha_G \theta_G}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}.$$

...and include a hidden group axion w/ usual coupling

$$\supset \frac{\alpha_G}{8\pi} \frac{a_G}{f_G} G\tilde{G}$$

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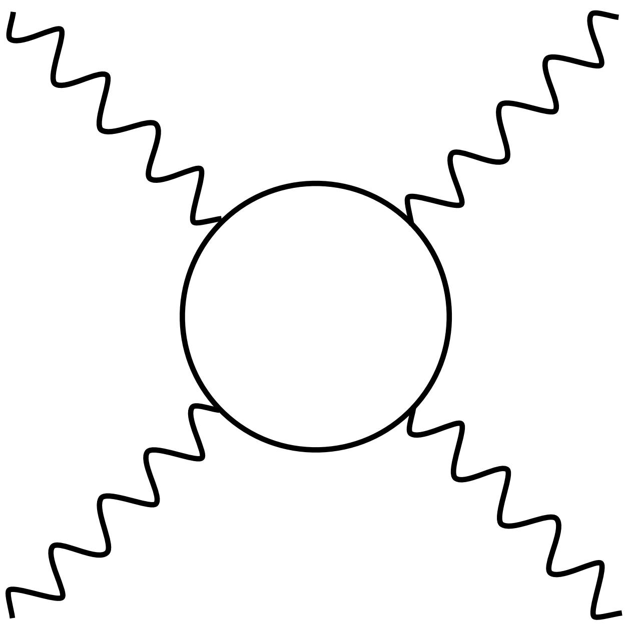
Hidden group confinement leads to axion mass, evolution of the axion vev

Nonzero axion vev gives a hidden glue condensate

$$\frac{\alpha_G}{8\pi} \langle G\tilde{G} \rangle = m_a^2(T) f_G^2 \sin\theta_G$$

Effective theory below the scale m_Q



Integrate out the bifundamental matter:

$$\mathcal{L}_{eff} \sim \frac{\alpha_W \alpha_G}{64\pi^2} \frac{1}{m_Q^4} W_{\mu\nu} \tilde{W}^{\mu\nu} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Axion vev leads to an effective operator

$$\sim \frac{g^2}{32\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu} \left[\sum_i \frac{1}{m_{Q,i}^4(T)} m_a^2(T) f_G^2 \sin\theta_G \right].$$

Induced CP violation

Effective operator serves as chemical potential for CS number

$$\mathcal{L}_{CP} = \frac{g^2}{32\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu}\Phi(T,H)$$

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$$\mathcal{L}_{CP} = \frac{g^2}{32\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu} \Phi(T, H)$$

$$\longrightarrow \quad \mathcal{L}_{CP} = j^0_{CS} \partial_0 \Phi = n_{CS} d\Phi/dt$$

Leads to CP violating contribution to baryon asymmetry:

$$\delta\Phi(T, H) \sim \delta \left(\sum_i \frac{m_a^2(T)}{m_{Q,i}^4(T)} \right) f_G^2 \sin\theta_G$$

Depends on change in quark, axion masses during EWPT

Estimating the asymmetry

Clearly the result depends on the hierarchy of parameters:

1. $T_c < \Lambda_G < m_Q$ → Confinement before EWSB, no light quarks
2. $T_c < m_Q < \Lambda_G$ → Confinement before EWSB, light quarks
3. $\Lambda_G < T_c < m_Q$ → Confinement after EWSB, no light quarks

(“confinement after EWSB, light quarks” is excluded by Tevatron)

First hierarchy: $T_c < \Lambda_G < m_Q$

Axion mass is parametrically $m_a^2 f_G^2 \sim \Lambda_G^4.$

But the relevant confinement scale depends on quark masses:

$$\Lambda_G = \Lambda_{G,UV} \left(\frac{\Lambda_{G,UV}}{m_Q} \right)^{(b_{1,UV}/b_{1,IR}-1)}$$

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Ultimately this leads to

$$\delta\Phi = \sin\theta_G \left(10 - \frac{8}{11N}\right) \left(\frac{\lambda\lambda' v \delta v}{\mu^2}\right) \left(\frac{\Lambda_{G,UV}}{\mu}\right)^{(4-24/11N)}$$

Second hierarchy: $T_c < m_Q < \Lambda_G$

Axion mass is parametrically $m_a^2 f_G^2 \sim m_Q \Lambda_G^3.$

Resulting asymmetry is simply

$$\delta\Phi \simeq 10 \sin\theta_G \lambda\lambda' v \delta v \frac{\Lambda_G^3}{\mu^5}$$

(this will prove to be an uninteresting limit)

Third hierarchy: $\Lambda_G < T_c < m_Q$

In this case the axion still acquires mass from instantons!

May estimate using dilute instanton gas approximation

$$m_a^2 f_G^2 \approx \Lambda_G^4 \left(\frac{\Lambda_G}{T} \right)^{\frac{1}{3}(11N-12)}$$

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Also incorporate dependence of Λ_G on m_Q

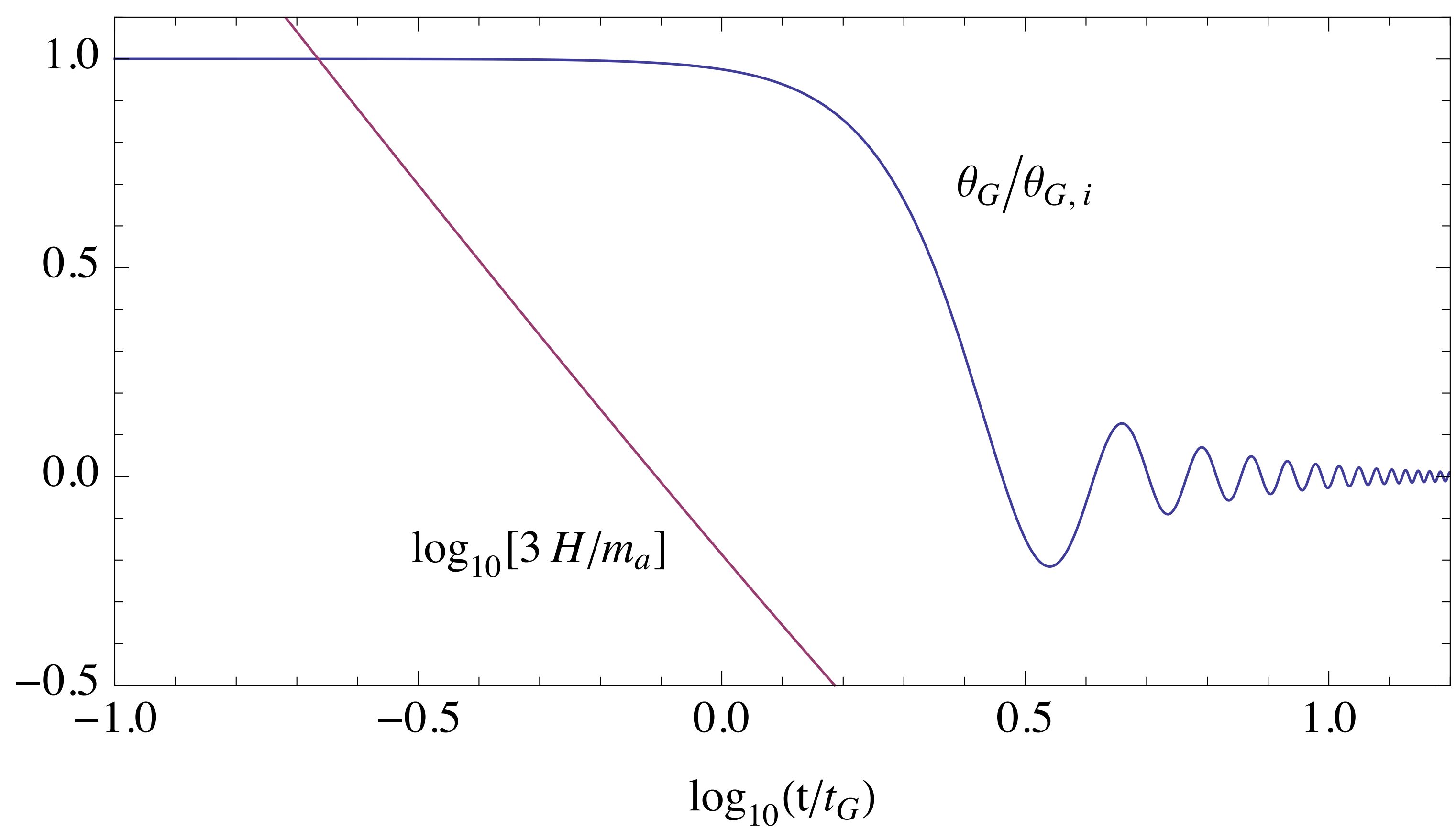
$$\delta\Phi \simeq \frac{28}{3}\sin\theta_G \left(\frac{\lambda\lambda' v\delta v}{\mu^2}\right)\left(\frac{\Lambda_{G,UV}}{\mu}\right)^2 \left(\frac{\Lambda_{G,UV}}{T}\right)^{\frac{11N}{3}-4} .$$

Cosmological evolution

Another important effect to account for: cosmological evolution of the axion

Axion vev begins to evolve when $m_a \gtrsim 3H$

Not sure what happens when oscillation begins; need to ensure that some CP violation remains by EWPT



Cosmological evolution II

A conservative limit: require that the axion vev not pass through zero before T_c

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These regimes are more interesting

1. $T_c < \Lambda_G < m_Q$
2. $T_c < m_Q < \Lambda_G$
3. $\Lambda_G < T_c < m_Q$

Cosmological evolution III

Also has implications for the size of f_G

$$f_G = 10^{12}\ \mathrm{GeV} \to \Lambda_G \lesssim 1\ \mathrm{GeV}$$

$$f_G = 10^{16}\ \mathrm{GeV} \to \Lambda_G \lesssim 300\ \mathrm{GeV}$$

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Cosmological evolution III

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~~$f_G = 10^{12}$ GeV $\rightarrow \Lambda_G \lesssim 1$ GeV~~

$f_G = 10^{16}$ GeV $\rightarrow \Lambda_G \lesssim 300$ GeV !!!!!

Of course, we know that GUT-scale PQ scale requires the initial angle to be small in order to avoid DM overdensity; puts us in the anthropic axion range.

In this case, requires $\theta_{G,i} \lesssim 0.01$

Constraints

How constrained is this scenario?

- Collider constraints on hidden sector
- PEWC constraints on bifundamental matter
- Cosmological constraints on the hidden sector
- Cosmological constraints on the hidden axion

Leads to (mild) limits on

$$\mu,\ \Lambda_G,\ \theta_i,\ f_G$$

that constrain new physics to lie near the weak scale, within LHC reach.

Collider constraints

Hidden sector quarks: CDF Run II limits on uncolored fermions w/ Higgs coupling

$$m_Q \gtrsim 200\ \mathrm{GeV}$$

(if colored, limit is $m_Q \gtrsim 250\ \mathrm{GeV}$)

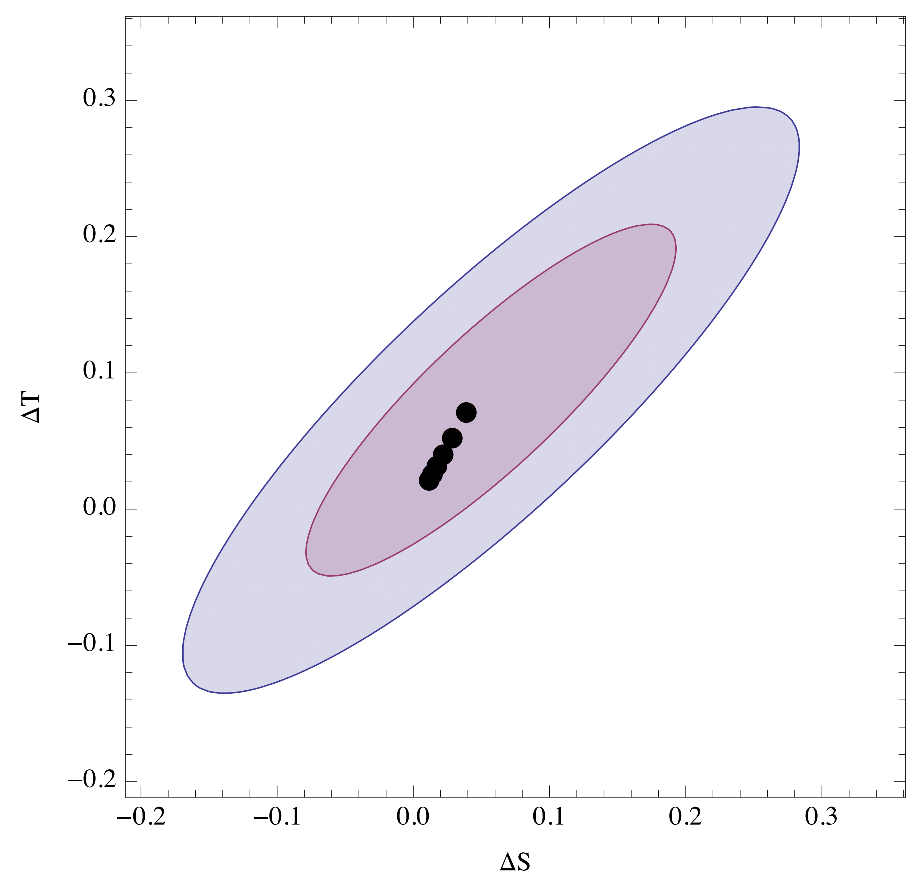
Implies $\mu \gtrsim 300\ \mathrm{GeV}$ for $\frac{1}{\sqrt{2}}\lambda v \sim 100\ \mathrm{GeV}$

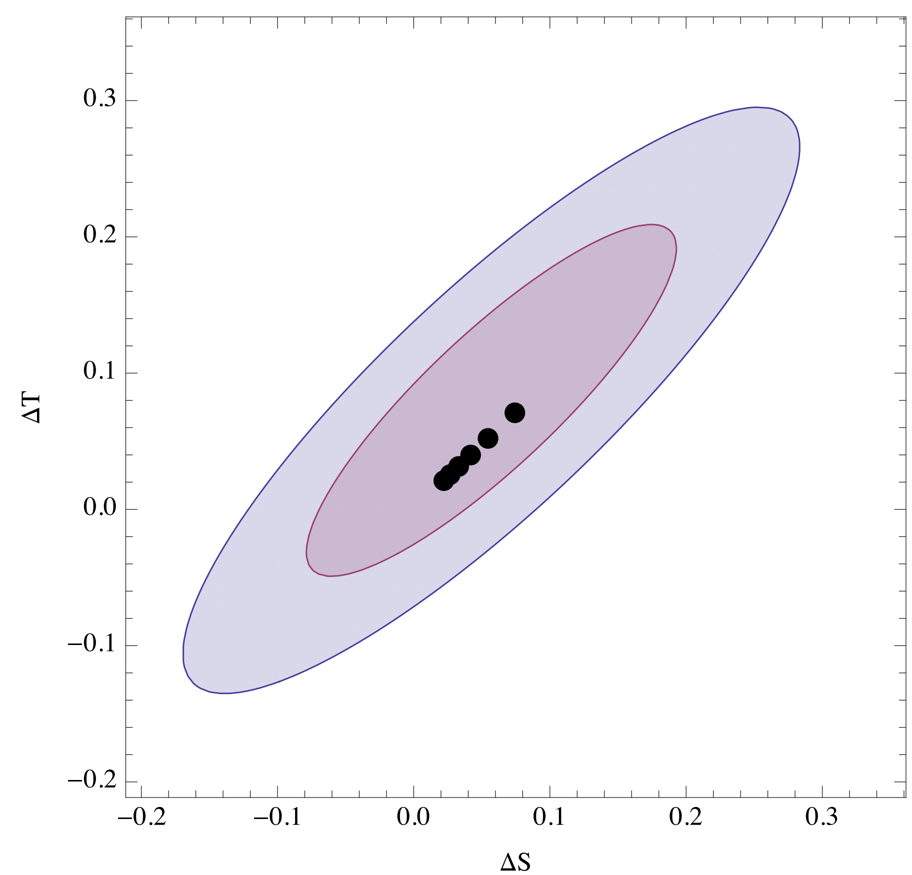
Λ_G not strongly constrained (and too large in this scenario to be macroscopically “quirky”)

Precision electroweak constraints

Contribution to ΔS from, e.g., $\sim \frac{Ngg'}{16\pi^2}\frac{\lambda\lambda'\mu\mu'}{m_Q^4}H^\dagger H W_{\mu\nu}B^{\mu\nu}$

But these contributions decouple as $\left(\frac{\lambda v}{\mu}\right)^2$





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Surprisingly safe! Scenario is basically a variation on quirk cosmology.
Lightest quarks stable, but annihilate rapidly

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Glueballs decay rapidly into Higgs, EW bosons:

$$\tau \sim 10^{-18}\ \mathrm{s} \times \left(\frac{m_Q}{300\ \mathrm{GeV}}\right)^4 \left(\frac{100\ \mathrm{GeV}}{\Lambda_G}\right)^7 .$$

...so no problems with BBN

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Contributes to DM density

$$\Omega_a h^2 \sim 10^7 \left(\frac{f_G}{M_P}\right)\left(\frac{\Lambda_G}{T_i}\right)\left(\frac{a_{G,i}}{f_G}\right)^2$$

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Abundance limit

$$\theta_i = 1 \rightarrow f_G \lesssim 10^{12}\ \mathrm{GeV}$$

$$\theta_i = 0.01 \rightarrow f_G \lesssim 10^{16}\ \mathrm{GeV} \longleftarrow$$ plausibly anthropic

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If we fold all these constraints together, what do we get?

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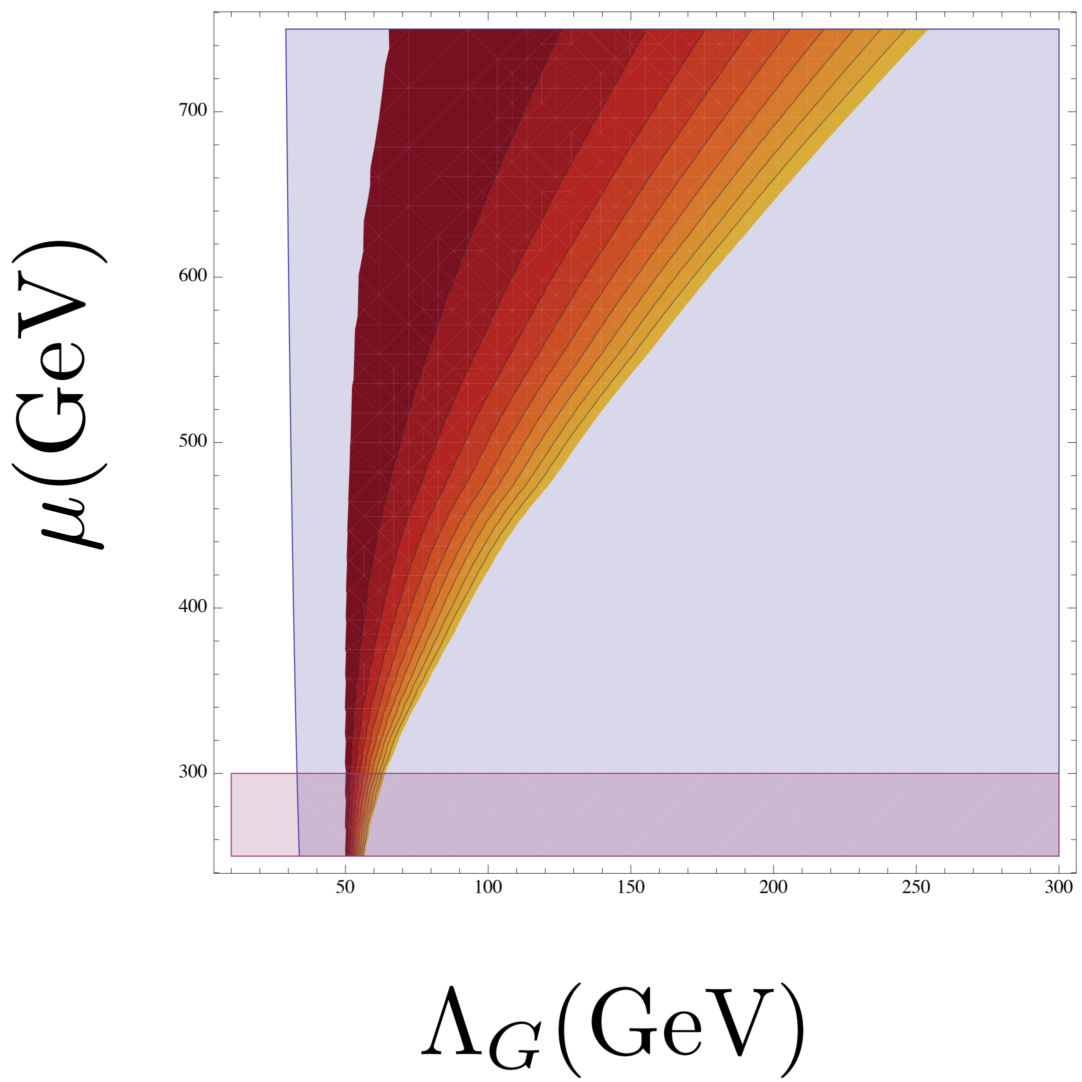

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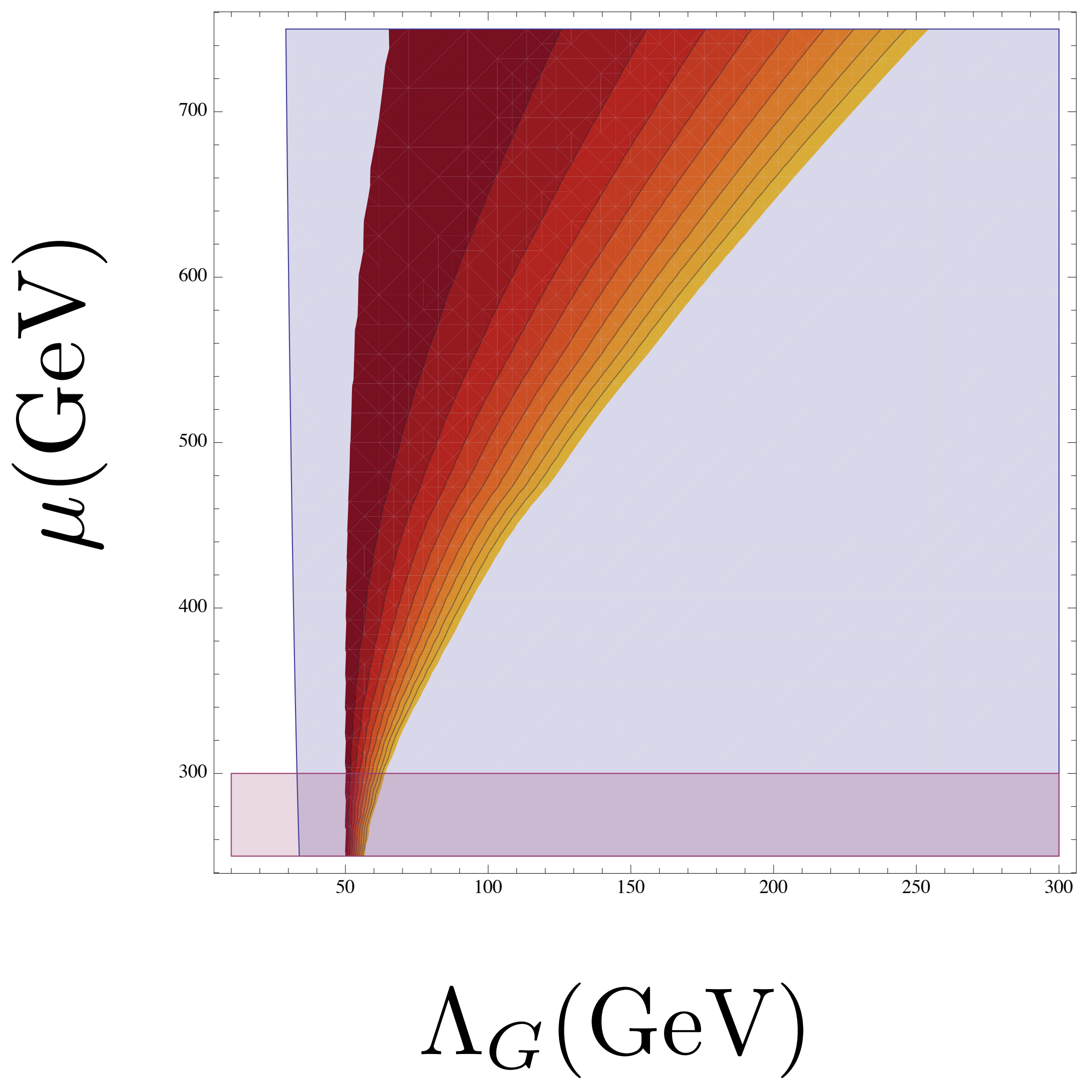
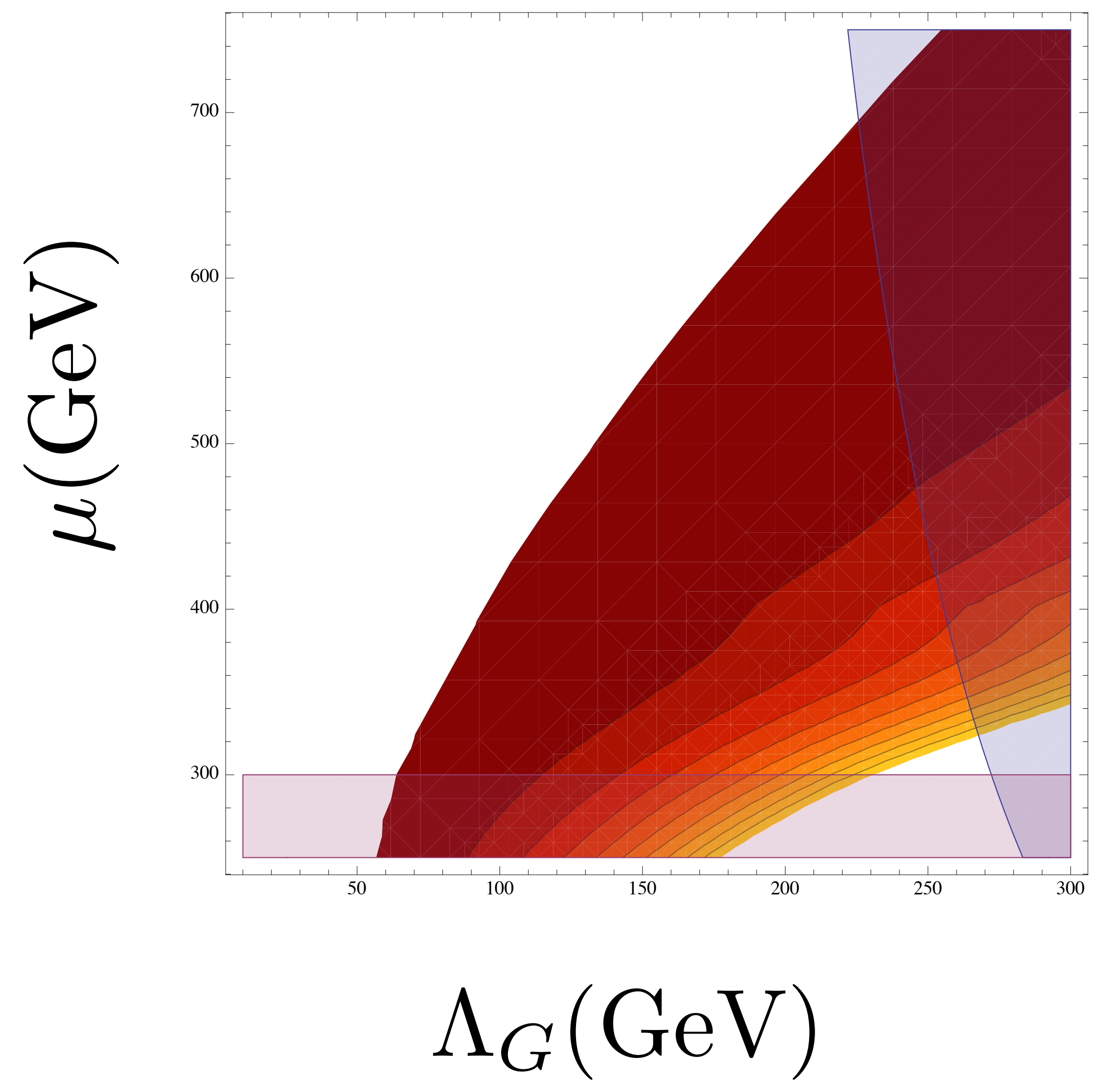


$f_G = 10^{16}$ GeV, $\theta_i = 0.01$



Hidden sector physics at a TeV

The various limits push us into an interesting space:
both confinement scale and quark masses are below a TeV

$$\Lambda_G, \mu \text{ too large} \rightarrow \text{axion relaxes too quickly}$$

$$\Lambda_G \text{ too small} \rightarrow \text{insufficient CP violation}$$

$$\mu \text{ too small} \rightarrow \text{collider limits}$$

GUT-scale anthropic axion most favored

PEWC, hidden sector cosmology limits automatically satisfied in this region

Prospects for detection

New physics within LHC reach; what would we expect to see?

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- Decays into electroweak bosons, Higgs
- Final states rich in jets, leptons, photons

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No “smoking gun”, though weak-scale hidden valley would be suggestive (and no such hidden valley would falsify)

Best indication would be hidden valley + parameters consistent with strong EWPT + no obvious signs of new CPV

A supersymmetric model

The straightforward generalization:

$$W_G = \mu_Q Q\overline{Q} + \mu_U U\overline{U} + \lambda H_u Q\overline{U} + \lambda' H_d \overline{Q} U$$

Especially natural if μ_Q, μ_U come from the same physics that sets the SM μ term

All the previous discussion goes through, with two additions:

1) Now you have an axino, possibly interesting?

and...

A nice bonus

2) This conveniently solves the little hierarchy problem.

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Radiative corrections from vector-like fourth generation lift the Higgs mass

[Martin '09, Graham, Rajendran, Saraswat '09]

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Radiative corrections from vector-like fourth generation lift the Higgs mass

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But no reason this generation can’t be charged under a new gauge group!

Conveniently, the range of quark masses necessary for this to work coincides with the range over which AAEB is efficient

Conclusion

- A mechanism for producing large CP violation during baryogenesis, consistent with small CP violation in the present era.
- Requires confining gauge group, bifundamental quarks, and a hidden axion.
- Efficient CP violation during EWPT forces confinement scale and quark masses to within LHC reach
- Supersymmetric version is conveniently free of little hierarchy problems
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From a model-builder’s perspective, provides a reason for hidden valleys at the weak scale