Axion-assisted electroweak baryogenesis

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w/ John March-Russell

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Baryogenesis

Measured baryon density \[ \eta \equiv \frac{n_B}{s} \sim 10^{-10} \]

One of the better-motivated BSM questions!
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Sakharov criteria

- Violation of B number
- Violation of CP
- Departure from thermal equilibrium
Baryogenesis in EWPT?

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- Violation of B number → Large when EW symmetry is restored!
- Violation of CP → Possible in MSSM or SM extensions?
- Departure from thermal equilibrium → Certainly if EWPT is sufficiently strong
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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...

\[ \mathcal{L}_{CP} = \frac{g^2}{32\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu} \Phi(T, H) \]
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...related via anomaly equation to CS number:

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Biases baryon number during EWPT:

\[ \frac{dn_B}{dt} = -\frac{1}{T} \Gamma_{a}\mu_{CS} \]
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Ultimate baryon asymmetry \( \sim \) const \( \times \alpha_{w}^{5} \delta \Phi \)
Integrate out quarks to generate an effective operator.

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

[The idea in practice: QCD] [Kuzmin, Shaposhnikov, Tkatchev '92]
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Axion vev gives nonzero gluon condensate:

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\]

\[
\delta \Phi \sim \frac{\sin \theta}{m_q^4} f_a^2 \delta m_a^2(T, \nu)
\]

This looks like a chemical potential for CS number, and

[Kuzmin, Shaposhnikov, Tkatchev '92]
Quantitatively...

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

Axion mass in this regime only comes from instanton effects:

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

This is terrible; need \( T_c \sim \Lambda \) for meaningful CP violation
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...but instead have

\[ T_c \sim 100 \text{ GeV} \]

\[ \Lambda \sim 0.2 \text{ GeV} \]
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...but instead have \( T_c \sim 100 \text{ GeV} \), \( \Lambda \sim 0.2 \text{ GeV} \)

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

\[ SU(N)_G \text{ gauge theory w/ bifundamental matter} \]

<table>
<thead>
<tr>
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<th>(SU(N)_G)</th>
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<td>(Q)</td>
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<td>(\bar{Q})</td>
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<td>(U)</td>
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<td>(1/2 + Y_Q)</td>
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<tr>
<td>(\bar{U})</td>
<td>(\Box)</td>
<td>1</td>
<td>(-1/2 - Y_Q)</td>
</tr>
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</table>

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

(I will assume colored multiplets are \(\sim 1\) TeV and irrelevant to the IR phenomenology)
The theory I

Start with vector masses and Higgs couplings:

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

Spectrum has three Dirac fermions w/ $\mu_Q = \mu_U = \mu$

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

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

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

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

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

Nonzero axion vev gives a hidden glue condensate

\[ \frac{\alpha_G}{8\pi} \langle G\tilde{G} \rangle = m^2_a(T) f_G^2 \sin \theta_G \]
Effective theory below the scale $m_Q$

Integrate out the bifundamental matter:

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

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

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

\[ \mathcal{L}_{CP} = j_{CS}^0 \partial_0 \Phi = n_{CS} d\Phi / dt \]
Induced CP violation

Effective operator serves as chemical potential for CS number

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

Leads to CP violating contribution to baryon asymmetry:

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

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

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 \( m_a f_G^2 \sim \Lambda_G^4 \).

But the relevant confinement scale depends on quark masses:

\[
\Lambda_G = \Lambda_{G,\text{UV}} \left( \frac{\Lambda_{G,\text{UV}}}{m_Q} \right)^{\left( \frac{b_1,\text{UV}}{b_1,\text{IR}} - 1 \right)}
\]
First hierarchy: $T_c < \Lambda_G < m_Q$

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$m_a f_G^2 \sim \Lambda_G^4$.

But the relevant confinement scale depends on quark masses:

$$\Lambda_G = \Lambda_{G,UV} \left( \frac{\Lambda_{G,UV}}{m_Q} \right)^{(b_1,UV/b_1,IR-1)}$$

Ultimately this leads to

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

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

Resulting asymmetry is simply

\[
\delta \Phi \sim 10 \sin \theta_G \lambda \lambda' \nu \delta \nu \frac{\Lambda_G^3}{\mu^5}
\]

(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

\[ m_a^2 f_G^2 \approx \Lambda_G^4 \left( \frac{\Lambda_G}{T} \right)^{\frac{1}{3}} (11N - 12) \]
Third hierarchy: $\Lambda_G < T_c < m_Q$

In this case the axion still acquires mass from instantons!

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

Also incorporate dependence of $\Lambda_G$ on $m_Q$

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

(this is often quite a bit after \( m_\alpha = 3H \))
Cosmological evolution II

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

(this is often quite a bit after $m_a = 3H$)

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 $f_G$

\[ f_G = 10^{12} \text{ GeV} \rightarrow \Lambda_G \lesssim 1 \text{ GeV} \]

\[ f_G = 10^{16} \text{ GeV} \rightarrow \Lambda_G \lesssim 300 \text{ GeV} \]
Cosmological evolution III

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\[
\begin{align*}
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\end{align*}
\]

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

\[ m_Q \gtrsim 200 \text{ GeV} \]

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

Implies \( \mu \gtrsim 300 \text{ GeV} \) for \( \frac{1}{\sqrt{2}} \lambda v \sim 100 \text{ GeV} \)

\[ \Lambda_G \] not strongly constrained (and too large in this scenario to be macroscopically “quirky”)
Precise electroweak constraints

Contribution to $\Delta S$ from, e.g.,
\[ \sim \frac{N gg'}{16\pi^2} \frac{\lambda \lambda' \mu \mu'}{m_Q^4} H^\dagger H W_{\mu\nu} B^{\mu\nu} \]

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

How safe is the new sector? Don’t want to assume unusually low reheating!
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Surprisingly safe! Scenario is basically a variation on quirk cosmology.
Lightest quarks stable, but annihilate rapidly

[Jacoby, Nussinov ’07, Kang, Luty ’08]
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Glueballs decay rapidly into Higgs, EW bosons:

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

...so no problems with BBN
Cosmological constraints II

What about the new axion?
Limits on the axion familiar from QCD axion cosmology:
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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

- $\theta_i = 1 \rightarrow f_G \lesssim 10^{12}$ GeV
- $\theta_i = 0.01 \rightarrow f_G \lesssim 10^{16}$ GeV

Plausibly anthropic
Parameter space for AAEB

If we fold all these constraints together, what do we get?
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\[ f_G = 10^{16} \text{ GeV}, \theta_i = 0.01 \]
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?
Hidden sector dynamics is classic pure-glue hidden valley
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New physics within LHC reach; what would we expect to see?
Hidden sector dynamics is classic pure-glue hidden valley

- Hidden sector quarks produced via gauge bosons, Higgs
- Bound states decay rapidly to hidden sector glueballs
- Glueball decays are prompt and visible
- Decays into electroweak bosons, Higgs
- Final states rich in jets, leptons, photons
Prospects for detection II

Dark matter in this scenario is some combination of hidden and visible sector axions

Not ideal from the perspective of direct detection, but axion searches are sensitive to hidden sector axion
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Not ideal from the perspective of direct detection, but axion searches are sensitive to hidden sector axion.

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:

\[ W_G = \mu_Q Q\bar{Q} + \mu_U U\bar{U} + \lambda H_u Q\bar{U} + \lambda' H_d Q\bar{U} \]

Especially natural if \( \mu_Q, \mu_U \) come from the same physics that sets the SM \( \mu \) 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]
A nice bonus

2) This conveniently solves the little hierarchy problem.

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

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

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

• Signatures are essentially those of “quirk” or “hidden valley” scenarios, but...
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*From a model-builder’s perspective, provides a reason for hidden valleys at the weak scale*