Deformation of Axion Potentials:
Implications for Spontaneous Baryogenesis, Dark Matter, and Isocurvature Perturbations

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Some Outstanding Issues

dark matter problem:
vast majority of matter content in the universe is not accounted for by Standard Model physics

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universe has an imbalance between baryonic/antibaryonic matter, with a baryon-to-photon ratio

\[ \eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx \frac{n_b}{n_\gamma} \approx 6 \times 10^{-10} \]

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**dark matter problem:**

Vast majority of matter content in the universe is *not accounted for* by Standard Model physics.

⇒ What is the composition of this “dark sector”?

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⇒ What processes in the early universe produce this asymmetry?

Interesting to consider physics that *reveals connections* between these two problems.
Spontaneous Baryogenesis

Typically, baryogenesis can only occur by satisfying **Sakharov conditions**:  
- $B$ (baryon number) and/or $L$ (lepton number) violation  
- $C$ and $CP$ violation  
- departure from thermal equilibrium
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hinges on conservation of CPT symmetry

alternatives exist if CPT spontaneously, e.g., with homogeneous scalar field $\phi$:

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{f} \partial_\mu \phi J^\mu_L \approx \frac{\dot{\phi}}{f} \left( n_\ell - n_{\bar{\ell}} \right) \equiv \mu_{\text{eff}} n_L$$
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alternatives exist if $CPT$ spontaneously, e.g., with homogeneous scalar field $\phi$:

$$L_{\text{eff}} \supset \frac{1}{f} \partial_{\mu} \phi J_{L}^{\mu} \approx \frac{\dot{\phi}}{f} (n_{\ell} - n_{\bar{\ell}}) \equiv \mu_{\text{eff}} n_{L}$$

effective chemical potential $\mu_{\text{eff}} \equiv \dot{\phi} / f$

for lepton number density $n_{L}$  
⇒ opportunity for asymmetry generation even at equilibrium
The $\mu_{\text{eff}} \neq 0$ shifts equilibrium $n_{\text{eq}}^L$ value away from zero:

$$n_{\text{eq}}^L \propto \int \frac{d^3p}{(2\pi)^3} \left[ \frac{1}{e^{(p-\mu_{\text{eff}})/T} + 1} - \frac{1}{e^{(p+\mu_{\text{eff}})/T} + 1} \right] \approx \frac{1}{6} \mu_{\text{eff}} T^2$$

when $L$-violation occurs sufficiently fast $\Gamma_L \gg H$ but in general

$$\dot{n}_L + 3Hn_L = -\Gamma_L (n_{\text{eq}}^L - n_L)$$

$\Rightarrow$ need to specify a source of $L$-violation:

Assume Weinberg operators, corresponding to heavy $M_* \sim \Lambda_{\text{GUT}} \gg T$ right-handed neutrinos:

$$\mathcal{L}_{\text{eff}} \supset -\frac{(LH)^2}{M_*}$$

then the rate is fixed by experiment:

$$\Gamma_L = 4n_{\ell}^\text{eq}\langle \sigma_L v \rangle \sim \mathcal{O}(10^8 \text{GeV}) \left( \frac{T}{10^{13} \text{GeV}} \right)^3.$$
Can the scalar field $\phi$ which drives $\mu_{\text{eff}} = \dot{\phi}/f$ also serve as a candidate for DM?
Spontaneous Baryogenesis via Axions [Kusenko ‘15]

- An **axion-like field** is a natural candidate for $\phi(x)$:
  \[
  \mathcal{L}_{\text{eff}} \supset \frac{1}{f} \partial_{\mu} \phi J_{L}^{\mu} \sim -\frac{\phi}{f} \partial_{\mu} J_{L}^{\mu}
  \]
  \[\Rightarrow \text{recast using } U(1)_{L} \text{ anomalies:}\]
  \[
  -\frac{\phi}{f} \partial_{\mu} J_{L}^{\mu} \rightarrow \frac{\phi}{f} \left( \frac{N_{f} g_{2}^{2}}{8\pi^{2}} W_{\mu\nu} \tilde{W}^{\mu\nu} - \frac{N_{f} g_{1}^{2}}{8\pi^{2}} B_{\mu\nu} \tilde{B}^{\mu\nu} \right)
  \]
  which can readily arise [e.g., string axion models]

- With typical $V(\phi) \sim \Lambda^{4} \cos(\phi/f)$ potential, **successful baryogenesis requires heavy** $m_{\phi} \gtrsim 10^{5}$ GeV $\Rightarrow$ axion decays and is **not suitable DM candidate**
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**interesting route forward:**

consider physics that “deforms” effective potential and **flattens** $V_{\text{eff}}(\phi)$ at its minimum

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[Graph showing deformation of effective potential]
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**interesting route forward:**
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\[
\Rightarrow \text{can appear via non-canonical kinetic terms}
\]
Non-Canonical Kinetic Term

• Consider an angular field \( \theta(x) \) with non-trivial non-canonical factor \( Z(\theta) \):

\[
\mathcal{L} = \frac{Z(\theta)}{2} f^2 (\partial_\mu \theta)^2 - \Lambda^4 U(\theta)
\]

\[
\equiv \frac{1}{2} (\partial_\mu \phi)^2 - V_{\text{eff}}(\phi)
\]

\( \phi/f \equiv \int \sqrt{Z(\theta)} d\theta \) canonically-normalized
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$$\equiv \frac{1}{2} (\partial_\mu \phi)^2 - V_{\text{eff}}(\phi)$$

The angular field $\theta$ is canonically-normalized through the relation

$$\phi/f \equiv \int \sqrt{Z(\theta)} \, d\theta$$

⇒ in canonical basis $Z(\theta)$ has the effect of deforming effective potential $V_{\text{eff}}(\phi)$:

$$\frac{\partial V_{\text{eff}}}{\partial \phi} = \frac{1}{\sqrt{Z}} \frac{\Lambda^4}{f} \frac{\partial U}{\partial \theta}$$

$$\frac{\partial^2 V_{\text{eff}}}{\partial \phi^2} = \frac{1}{Z} \frac{\Lambda^4}{f^2} \left( \frac{\partial^2 U}{\partial \theta^2} - \frac{1}{2Z} \frac{\partial Z}{\partial \theta} \frac{\partial U}{\partial \theta} \right)$$

⇒ attractive features for $V_{\text{eff}}(\phi)$ can be re-interpreted as features for $Z(\theta)$.
Non-Canonical Kinetic Term

\[ Z = O(1) \]

\[ Z \gg 1 \]

\[ Z = O(1) \]

\[ Z \approx \frac{1}{\theta^2 n} \]

\[ Z \approx \frac{1}{\epsilon^2 n} \]
Non-Canonical Kinetic Term

- Take, for example, an approximate form

\[ Z(\theta) \approx \begin{cases} 
1 & \text{for } |\theta| = \mathcal{O}(1) \\
1/\theta^{2n} & \text{for } \epsilon \lesssim |\theta| < \mathcal{O}(1) \\
1/\epsilon^{2n} & \text{for } |\theta| \gtrsim \epsilon 
\end{cases} \]

where \( n \in \mathbb{Z}^+ \) and small \( \epsilon > 0 \)
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where \( n \in \mathbb{Z}^+ \) and small \( \epsilon > 0 \)

- The field goes through several periods:
  - at early times axion \textbf{slowly rolls}:
    \[ \dot{\phi} \simeq - \frac{1}{5H} \frac{\partial V_{\text{eff}}}{\partial \phi} \]
  - as it falls into \( Z(\theta) \simeq 1/\theta^{2n} \) region, field follows “\textbf{tracking}” trajectory:
    \[ w_\phi \rightarrow \frac{1 + w - n}{n} \]
  - eventually exits tracking region and undergoes \textbf{coherent oscillations}
    \[ w_\phi \rightarrow 0 \]
Non-Canonical Kinetic Term

- Take, for example, an approximate form

\[ Z(\theta) \approx \begin{cases} 
1 & \text{for } |\theta| = O(1) \\
1/\theta^{2n} & \text{for } \epsilon \lesssim |\theta| < O(1) \\
1/\epsilon^{2n} & \text{for } |\theta| \gtrsim \epsilon 
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\[ \Omega_\phi h^2 \approx \frac{\epsilon^{2(1-n)}}{g_{*S}^{1/4}} \sqrt{m_\phi} \left( \frac{f}{10^{12} \text{ GeV}} \right)^2 \]

 insensitive to misalignment angle
Can we build explicit models which furnish such $Z(\theta)$?
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**EXAMPLE:** continuum-clockwork axions

*i.e.*, realization of clockwork mechanism with 5D axion
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**clockwork mechanism:** [Choi et al. ‘14] [Kaplan, Rattazzi ‘15] [Choi, Im ‘15]

- Consider $N + 1$ pNGBs $\theta_j$ with “nearest-neighbor” interactions ($q > 1$):
  \[
  \mathcal{L} \supset - \sum_{j=0}^{N-1} \mu^2 f^2 \cos (\theta_{j+1} - q\theta_j)
  \]
  \[\Rightarrow U(1)^{N+1} \text{ broken down to } U(1)_{CW} : \theta_j \rightarrow \theta_j + \alpha q^j \]

- remaining massless field $\phi$ has an overlap with each $\theta_j$:
  \[\langle \phi | \theta_j \rangle \propto q^{-N} \text{ for } N \gg 1 \]

Any couplings $q^{-N}\phi O_{SM}$ exponentially suppressed
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**EXAMPLE:** *continuum-clockwork axions*  
i.e., realization of clockwork mechanism with 5D axion

\[ N \to \infty \textit{continuum limit:} \]

identify $y \equiv j \epsilon$ with extra spatial coordinate

\[ \epsilon = \frac{\pi R}{N} \to 0 \]

size = $\pi R$
Can we build explicit models which furnish such $Z(\theta)$?

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Then can motivate action for bulk field $\theta(x, x^5)$:

$$S = \frac{f_5^3}{2} \int d^5 x \left[ (\partial_\mu \theta)^2 - (\partial_y \theta - m \sin \theta)^2 \right]$$

$\Rightarrow$ effective 4D theory for zero-mode $\theta \equiv \theta(x, 0)$ has non-canonical kinetic term:

$$Z(\theta) = \frac{f_5^3}{m} \frac{1}{\coth(\pi m R) - \cos \theta}$$

$$\approx \frac{2}{1 + 2e^{-2\pi m R} - \cos \theta}$$

$R \equiv$ size of extra dimension

$m \equiv$ scale of bulk/boundary masses
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for moderate $m R$ satisfies our minimal requirements

$R \equiv$ size of extra dimension

$m \equiv$ scale of bulk/boundary masses
Continuum-Clockwork Axion

- The canonical axion potential is then deformed:

\[
V_{\text{eff}}(\phi) = \Lambda^4 \{1 - \cos \theta\} = \frac{2\Lambda^4 [u(\phi)]^2}{1 + [u(\phi)]^2}
\]

so curvature is suppressed as \( \phi \to 0 \)

\[
\Rightarrow m^2_\phi = \left. \frac{\partial^2 V_{\text{eff}}}{\partial \phi^2} \right|_{\phi=0} = e^{-2\pi m R} \cdot \frac{\Lambda^4}{f^2}
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\[ \Rightarrow m_{\phi}^2 = \left. \frac{\partial^2 V_{\text{eff}}}{\partial \phi^2} \right|_{\phi=0} = e^{-2\pi m R} \cdot \frac{\Lambda^4}{f^2} \]
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larger curvature drives baryogenesis more efficiently

small curvature suppresses decays, allows for \( \Omega_\phi \sim \Omega_{\text{DM}} \)

\[ |\langle \phi \rangle| \approx \pi f_{\text{eff}} \quad \langle \phi \rangle \approx 0 \]
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\]

- The interactions \( \sim \theta [F_{\mu\nu} \tilde{F}^{\mu\nu}]_{\text{SM}} \) also get modified such that axion decay widths are **also suppressed** by

\[
\Gamma_{\phi} \propto \frac{1}{Z(0)} \frac{m_{\phi}^3}{f^2} = e^{-2\pi m R} \cdot \frac{m_{\phi}^3}{f^2}
\]
Early Dynamics

The axion $\Omega_\phi$, radiation $\Omega_R$, inflaton $\Omega_\varphi$, and lepton $Y_L$ abundances:

increasingly deformed with $m_R$
Early Dynamics

The axion $\Omega_\phi$, radiation $\Omega_R$, inflaton $\Omega_\varphi$, and lepton $Y_L$ abundances:

\[
\frac{Y_L}{Y_L^{eq}} \approx \frac{1}{3} \sqrt{\frac{1}{5} \frac{m_\phi M_p}{T_{dec}^2} e^{\pi m R/2}}
\]

The clockwork factor $m_R > 0$ *enhances* generation of asymmetry while retaining *light axion field*
Viable Regions

- **decays suppressed** not only by small effective mass $m_\phi = \Lambda^2 e^{-\pi mR}/f$, but also by suppressed couplings

$$\Gamma_\phi \sim \frac{m_\phi^3}{f^2} e^{-2\pi mR}$$

- **abundance** at $mR \gtrsim \mathcal{O}\text{(few)}$ falls as tracking epoch is elongated:

$$\frac{\Omega_\phi}{\Omega_{\text{obs DM}}} \approx \left[ \frac{f_{\text{eff}}}{10^{13}\text{GeV}} \frac{12}{mR} \right]^2 \sqrt{\frac{m_\phi}{0.53\text{eV}}}$$

and rendered **insensitive** to initial misalignment angle.
Viable Regions

the baryon asymmetry $\eta_B$ and axion abundance $\Omega_\phi$ can be achieved simultaneously in observed amounts:

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**constraints from **isocurvature?**

at first glance, presents a concern for this type of scenario
Isocurvature Perturbations

The axion is subject to de-Sitter quantum fluctuations during inflation

\[ \delta \phi = \frac{H_I}{2\pi} \]

In our model, ultimately manifested in isocurvature mode two ways:

1. **axion-photon** isocurvature

\[ S_{\phi \gamma} \equiv \frac{\delta \phi}{1 + w_\phi} - \frac{3}{4} \delta \gamma \]

2. **baryon-photon** isocurvature

\[ S_{B\gamma} \equiv \frac{\delta n_B}{n_B} - \frac{3}{4} \delta \gamma \]

both show significant departures from standard \((mR = 0)\) case
• If asymmetry were generated at equilibrium, then

\[ n_B \propto \dot{T}^2 \propto \frac{[V'_\text{eff}(\phi)]^2}{\sqrt{1 - \frac{V_{\text{eff}}}{2\Lambda^4} V_{\text{eff}}/2\Lambda^4}} \]

\[ \Rightarrow \text{perturbation after decoupling:} \]

\[ \frac{\delta n_B}{n_B} \approx \left\{ 2 \frac{V''_{\text{eff}}(\phi)}{V'_{\text{eff}}(\phi)} - \frac{1}{2} \frac{V'_{\text{eff}}(\phi)}{V_{\text{eff}}(\phi)} \left[ 1 - \frac{V_{\text{eff}}}{\Lambda^4} \right] \right\} \delta \phi \]

inflection points/cancelations in terms can drive \( \to 0 \)

• Serves as a good benchmark for our \textbf{out-of-equilibrium} generation, since numerics show only up to \( \mathcal{O}(10) \) suppression of this result
Isocurvature Perturbations
Axion Component

- The tracking behavior in axion field implies a non-trivial evolution in $S_{\phi \gamma}$

\[
\frac{1}{2} \frac{d[(1 + w_\phi)S_{\phi \gamma}]}{d \log a} = \Gamma
\]

\[-2 [(1 + w_\phi)S_{\phi \gamma}] - \Gamma = \frac{d\Gamma}{d \log a}
\]

where it is coupled to the intrinsic entropy perturbation:

pressure perturbation

\[
\Gamma \equiv \frac{\delta P_\phi / \rho_\phi - c_\phi^2 \delta \phi}{1 - c_\phi^2}
\]

adiabatic sound speed

⇒ can be solved analytically to show amplitude of $S_{\phi \gamma} \propto 1/\sqrt{a}$ falls while axion follows tracking trajectory
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⇒ can be solved analytically to show amplitude of $S_{\phi \gamma} \propto 1/\sqrt{a}$ \textbf{falls} while axion follows \textit{tracking trajectory}

\[
\Rightarrow \text{axion dynamics lead generically to a } \textit{suppression}
\]

of the axion $S_{\phi \gamma}$ and baryon $S_{B \gamma}$ isocurvature modes
The baryonic and axionic contributions to the isocurvature mode are exactly correlated and \textbf{CMB observations place a bound} on

$$
\mathcal{P}_{SS}(k_*) \equiv \left[ \frac{\Omega_B}{\Omega_{CDM}} S_{B\gamma} + \frac{\Omega_\phi}{\Omega_{CDM}} S_{\phi\gamma} \right]^2 \lesssim 7.98 \cdot 10^{-11}
$$

’excluded by decays

excluded by isocurvature

\begin{align*}
\frac{Y_B}{Y_{B\text{obs}}} & \geq 1 - 10^{-2} \\
\frac{m_R}{\mathrm{GeV}} & = 10^{-3} - 10^{-6} \\
\Omega_\phi/\Omega_{CDM} & = 10^{-16} - 10^{-12} \\
\Omega_B/\Omega_{CDM} & = 10^{-10} - 10^{-8} \\
\end{align*}
The baryonic and axionic contributions to the isocurvature mode are exactly correlated and **CMB observations place a bound** on

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P_{SS}(k_*) = \left[ \frac{\Omega_B}{\Omega_{CDM}} S_{B\gamma} + \frac{\Omega_\phi}{\Omega_{CDM}} S_{\phi\gamma} \right]^2 \lesssim 7.98 \cdot 10^{-11}
\]

isocurvature **suppressed** by tracking dynamics and cancelations in \( S_{B\gamma} \); **interesting regions remain viable**
TAKE-AWAY MESSAGE:

The early dynamics of an **axion-like field** can induce the **observed baryon asymmetry** — via a spontaneous baryogenesis mechanism — while also serving as a **viable dark matter** candidate.

Using an explicit model (**continuum-clockwork axion**) we showed viability of this idea; however, **model-building possibilities** exist for scenarios in which similar non-canonical terms appear.
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THANK YOU FOR YOUR ATTENTION!