Spontaneous Baryogenesis in Continuum-Clockwork Axion Models

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[IBS-CTPU]

[arXiv:1811.10655]

collaborators on this work:

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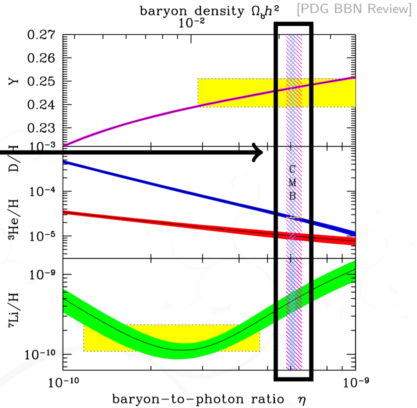
Outstanding Issues

matter-antimatter asymmetry:

need to explain 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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- ◦ B and/or L violation
- ◦ C and CP violation
- ◦ departure from thermal equilibrium

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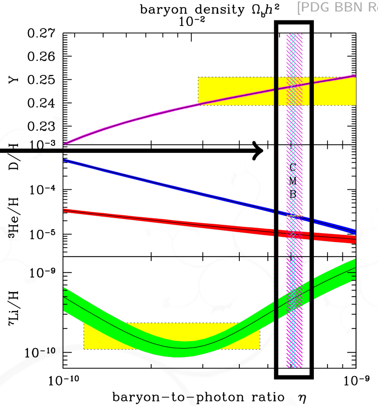

[PDG BBN Review]

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alternatives exist if $\not{CPT}$ spontaneously, *e.g.*, with homogeneous scalar field ϕ:

$$\mathcal{L}_{\text{eff}} \supset \underbrace{\frac{1}{f}\partial_\mu\phi}_{\text{NG boson}} \overbrace{J^\mu_L}^{\text{lepton current}} \approx \frac{\dot{\phi}}{f}(n_\ell - n_{\bar{\ell}}) \equiv \mu_{\text{eff}} n_L$$

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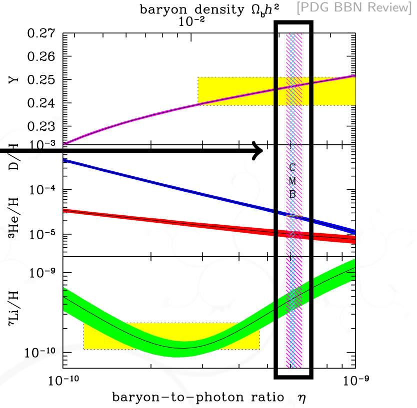

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lepton current

NG boson

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_L^{eq} value away from zero:

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

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

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

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

Assume Weinberg operator, 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 for L-violation is fixed:

$$\Gamma_L = 4 n_\ell^{\text{eq}} \langle \sigma_{\Delta L = 2} v \rangle \sim \mathcal{O}(10^8 \text{GeV}) \left(\frac{T}{10^{13} \text{GeV}} \right)^3$$

Spontaneous Baryogenesis via Axions [Kusenko '15]

- An **axion-like field** is a natural candidate for $\phi(x)$:

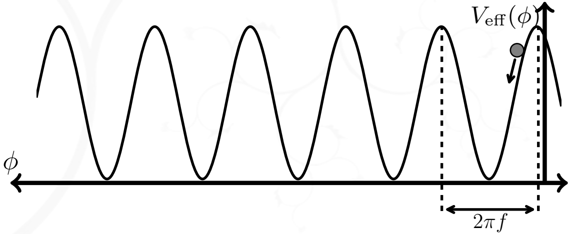
$$\mathcal{L}_{\rm eff} \supset \frac{1}{f}\partial_\mu \phi J^\mu_L \sim -\frac{\phi}{f}\partial_\mu J^\mu_L$$

$\Rightarrow$ recast using $U(1)_L$ anomalies:

$$-\frac{\phi}{f}\partial_\mu J^\mu_L \longrightarrow \frac{\phi}{f}\Big(\underbrace{\frac{N_f g_2^2}{8\pi^2} W_{\mu\nu}\widetilde{W}^{\mu\nu}}_{\text{weak}} - \underbrace{\frac{N_f g_1^2}{8\pi^2} B_{\mu\nu}\widetilde{B}^{\mu\nu}}_{\text{hypercharge}} \Big)$$

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 **suitable DM candidate**



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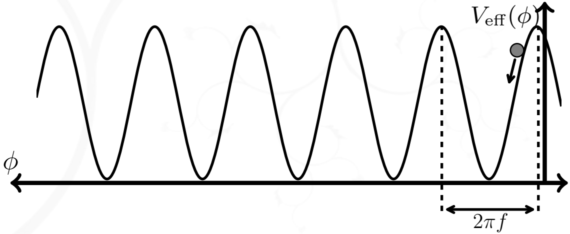

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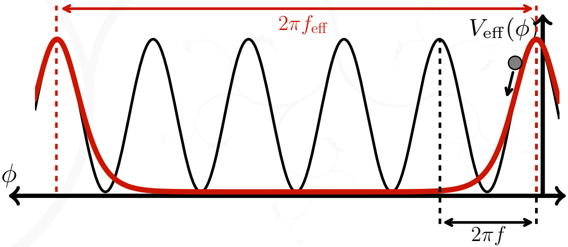

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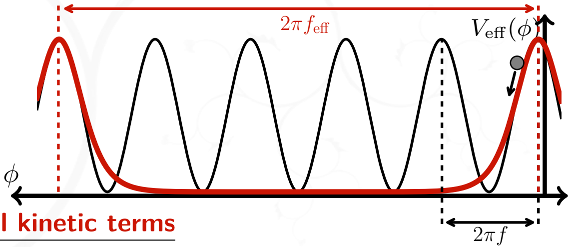

$\Rightarrow$ can appear via **non-canonical kinetic terms**

Non-Canonical Kinetic Term

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

$$\begin{aligned}\mathcal{L} &= \frac{Z(\theta)}{2} f^2 (\partial_\mu \theta)^2 - \Lambda^4 U(\theta) \\ &\equiv \underbrace{\frac{1}{2} (\partial_\mu \phi)^2 - V_{\text{eff}}(\phi)}_{\text{canonically-normalized}}\end{aligned}$$

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

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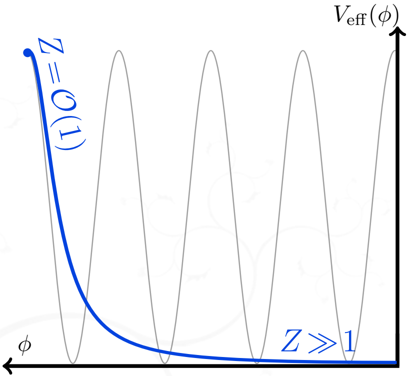
canonically-normalized

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

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

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

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



$\Rightarrow$ attractive features for $V_{\text{eff}}(\phi)$ can be re-interpreted as features for $Z(\theta)$

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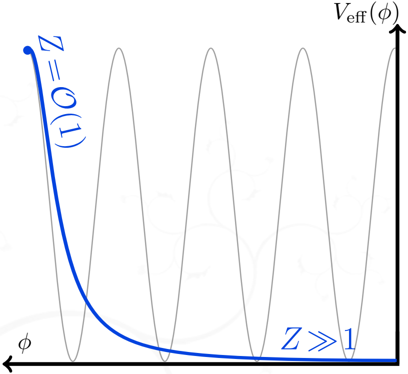
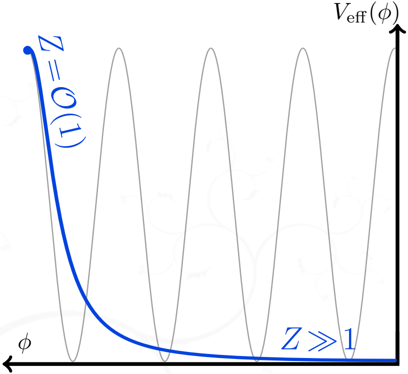


Non-Canonical Kinetic Term

- Take, for example, an approximate form

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

where $n \in \mathbb{N}$ and small $\epsilon > 0$



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- The field goes through several periods:
  - assuming $\Lambda^2/f \ll H$ at early times the axion **slowly rolls** with velocity

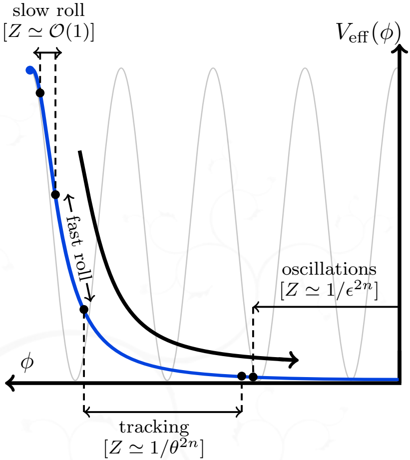
$$\dot{\phi} \simeq -\frac{1}{5H}\frac{\partial V_{\text{eff}}}{\partial \phi}$$

  - as it falls into $Z(\theta) \simeq 1/\theta^{2n}$ region the field follows **"tracking"** trajectory:

$$w_\phi \longrightarrow \frac{1+w-n}{n}$$

  - eventually axion exits tracking region and commences **coherent oscillations**

$$w_\phi \longrightarrow 0$$



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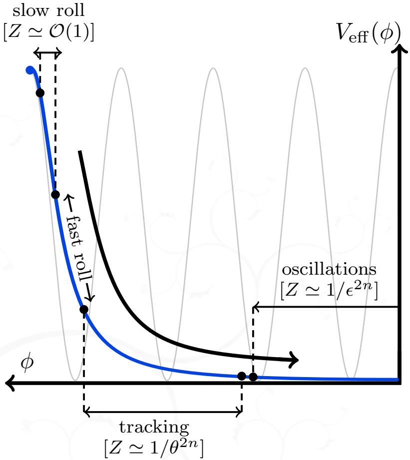


$$\Omega_\phi h^2 \approx \frac{\epsilon^{2(1-n)}}{g_{*S}^{1/4}}\sqrt{\frac{m_\phi}{7\ \text{eV}}}\left(\frac{f}{10^{12}\ \text{GeV}}\right)^2$$

insensitive to misalignment angle

Can we build explicit models which furnish such $Z(\theta)$?

EXAMPLE: continuum-clockwork axions

discrete clockwork mechanism: [Choi *et al.* '14] [Kaplan, Rattazzi '15] [Choi, Im '15]

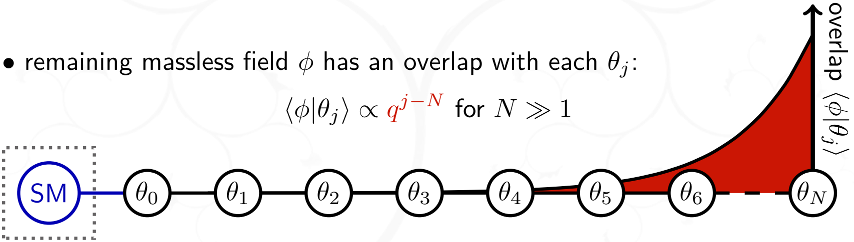
- Consider $N+1$ Nambu-Goldstone bosons θ_j and introduce some "nearest-neighbor" interactions ($q > 1$):

$$\mathcal{L} \supset -\sum_{j=0}^{N-1} \mu^2 f^2 \cos\left(\theta_{j+1} - q\theta_j\right)$$

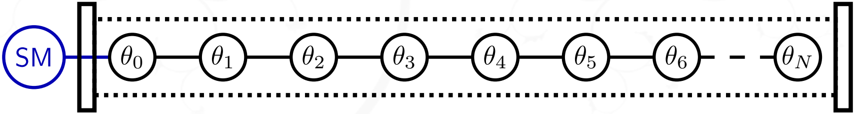
$\Rightarrow U(1)^{N+1}$ broken down to $U(1)_{\rm CW} : \theta_j \to \theta_j + \alpha q^j$

- remaining massless field ϕ has an overlap with each θ_j:

$$\langle \phi | \theta_j \rangle \propto q^{j-N} \text{ for } N \gg 1$$

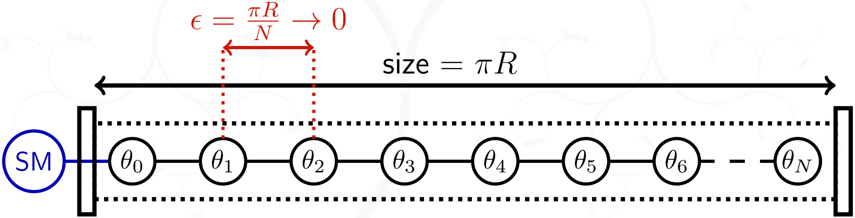


any couplings $q^{-N}\phi\mathcal{O}_{\rm SM}$ **exponentially suppressed**


SM
θ_0
θ_1
θ_2
θ_3
θ_4
θ_5
θ_6
θ_N

consider $N \to \infty$ **continuum limit**:

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



Continuum-Clockwork Axion

- In extra-dimensional scenario, can motive action for angular field $\theta(x, y)$:

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

- A massless 4D mode $\phi(x)$ is again found in the spectrum:

$$\tan\left[\frac{\theta(x, y)}{2}\right] = e^{my} u\left[\phi(x)\right]$$

where $u[\phi]$ is defined to enforce canonical normalization.

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- By integrating out the higher KK modes and the extra dimension we can construct an **effective action** for the zero-mode:

$$\mathcal{S}_{\text{eff}} \;\approx\; \frac{1}{2} \int d^4x \frac{f_5^3}{m} \frac{(\partial_\mu \theta)^2}{\coth(\pi m R) - \cos\theta}$$

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In other words, a non-canonical kinetic term appears with

$$Z(\theta) \; = \; \frac{f_5^3}{m} \frac{1}{\coth(\pi m R) - \cos\theta} \; \simeq \; \frac{2}{1 + 2\epsilon^2 - \cos\theta}$$

for small $\epsilon \equiv e^{-\pi m R}$, which ***satisfies our minimal requirements***.

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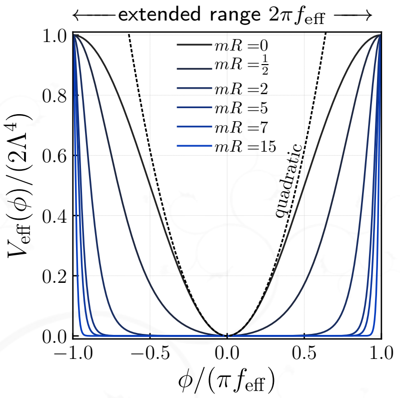
- Any small deviation in boundary masses generates a potential for the zero-mode:

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

so curvature is **suppressed** as $\phi \to 0$

$$\Rightarrow \quad m_\phi^2 \equiv \left.\frac{\partial^2 V_{\text{eff}}}{\partial \phi^2}\right|_{\phi=0} = e^{-2\pi m R} \cdot \frac{\Lambda^4}{f^2}$$



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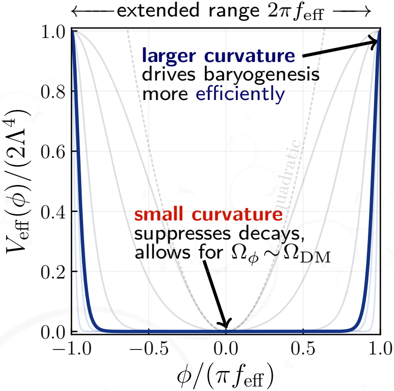

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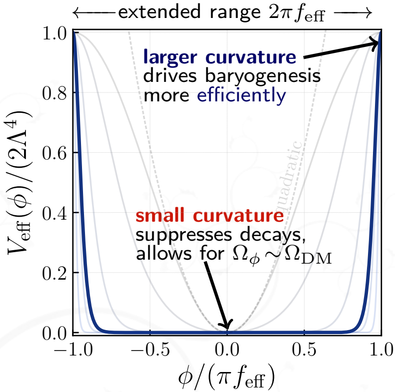

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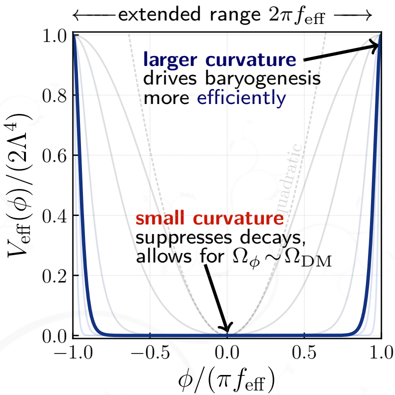
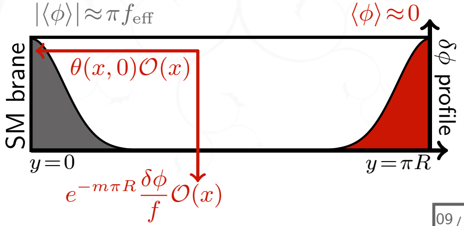
- The interactions $\sim \theta[F_{\mu\nu}\widetilde{F}^{\mu\nu}]_{\rm SM}$ also get modified such that axion decay widths are **also suppressed** by

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





The canonically-normalized four-dimensional model then appears as

$$\mathcal{S}_{\rm eff} \simeq \int d^4x\sqrt{-g}\Big[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_{\rm eff}(\phi) - \mu_{\rm eff}n_L + \cdots\Big]$$

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- The equilibrium asymmetry:

$$Y_L^{\text{eq}} \equiv \frac{n_L^{\text{eq}}}{s} \propto \dot{\theta} = \frac{\frac{1}{2\Lambda^4}\left|\frac{\partial V_{\text{eff}}}{\partial\phi}\right|}{\sqrt{\left(1-\frac{V_{\text{eff}}}{2\Lambda^4}\right)\frac{V_{\text{eff}}}{2\Lambda^4}}}\dot{\phi}$$

is now a more complicated function of ϕ and $\dot{\phi}$ which can alter dynamics:

$$\frac{dY_L}{d\log T} = \underbrace{\frac{T}{T_{\text{dec}}}}_{T_{\text{dec}}\sim 10^{13}\ \text{GeV}}\left(Y_L - Y_L^{\text{eq}}\right)$$

The canonically-normalized four-dimensional model then appears as

$$\mathcal{S}_{\text{eff}} \simeq \int d^4x \sqrt{-g}\Big[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_{\text{eff}}(\phi) - \mu_{\text{eff}} n_L + \cdots\Big]$$

- The equilibrium asymmetry:

$$Y_L^{\text{eq}} \equiv \frac{n_L^{\text{eq}}}{s} \propto \dot{\theta} = \frac{\frac{1}{2\Lambda^4}\left|\frac{\partial V_{\text{eff}}}{\partial\phi}\right|}{\sqrt{\left(1-\frac{V_{\text{eff}}}{2\Lambda^4}\right)\frac{V_{\text{eff}}}{2\Lambda^4}}}\dot{\phi}$$

is now a more complicated function of ϕ and $\dot{\phi}$ which can alter dynamics:

$$\frac{dY_L}{d\log T} = \underbrace{\frac{T}{T_{\text{dec}}}}_{T_{\text{dec}}\sim 10^{13}\text{ GeV}}\left(Y_L - Y_L^{\text{eq}}\right)$$

- In order to model the **reheating epoch** we include inflaton ρ_φ and radiation ρ_R energy densities:

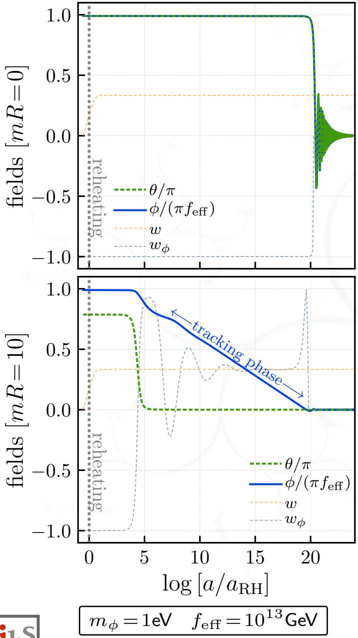
$$\overbrace{\dot{\rho}_\varphi + 3H\rho_\varphi = -\Gamma_\varphi\rho_\varphi}^{\text{inflaton}}$$

$$\underbrace{\dot{\rho}_R + 4H\rho_R}_{\text{radiation}} = +\Gamma_\varphi\rho_\varphi + \Gamma_\phi\rho_\phi$$

and the axion evolution goes as

$$\ddot{\phi} + (3H+\Gamma_\phi)\dot{\phi} + \frac{\partial V_{\text{eff}}}{\partial\phi} = \underbrace{\frac{\partial\mu_{\text{eff}}}{\partial\dot{\phi}}\Gamma_L(n_L - n_L^{\text{eq}})}_{\text{backreaction usually negligible}}$$

Some Interesting Early Dynamics



taking $mR \neq 0$ shows **substantial** differences:

- *prior* to undergoing coherent oscillations, axion field enters **tracking period**:

$$|\phi(t)| \approx -2f \log\left[\frac{m_\phi t}{\sqrt{2}} + \text{constant}\right]$$

for many e-foldings that drives $w_\phi \to w = \frac{1}{3}$

- these attractor-like solutions largely erase dependence on misalignment angle

- $mR > 0$ deformation of potential will trigger baryogenesis at **higher temperatures**

- Y_L never matches equilibrium value Y_L^{eq} $\Rightarrow$ asymmetry generated through **"freeze-in"** type process, in contrast to other models

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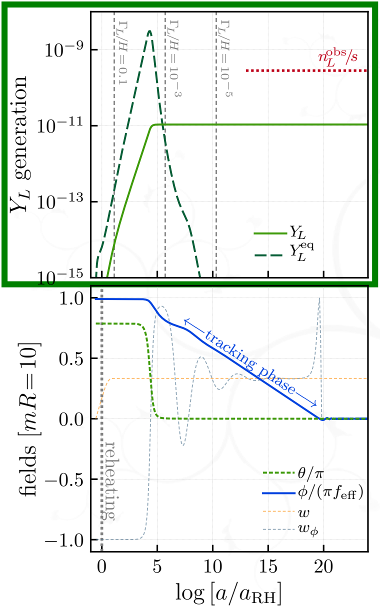

$m_\phi = 1$eV $\quad f_{\rm eff} = 10^{13}$GeV

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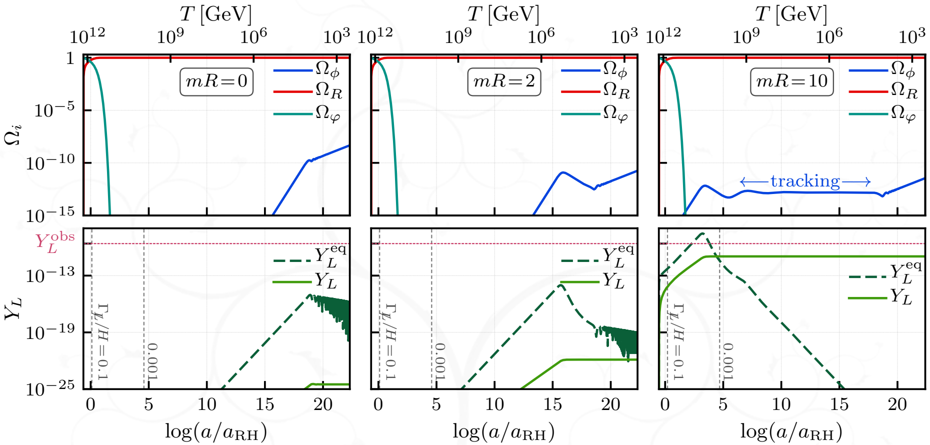
Some Interesting Early Dynamics

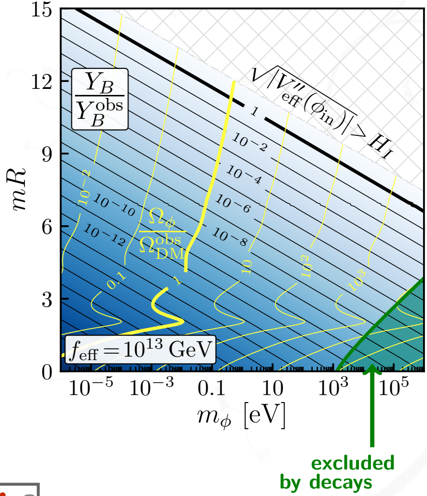
The axion Ω_ϕ, radiation Ω_R, inflaton Ω_φ, and lepton Y_L abundances:



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

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

Viable Regions from Numerical Simulations



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

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

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

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

and rendered **insensitive** to initial misalignment angle

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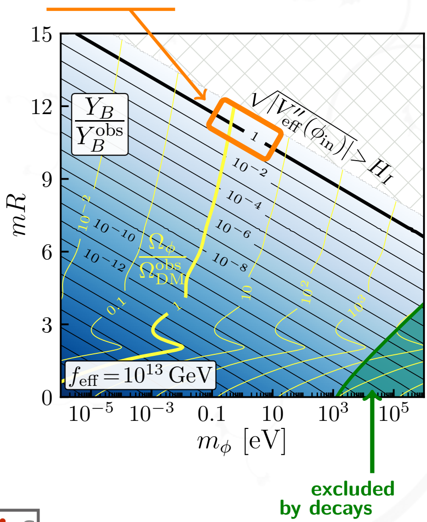
the **baryon asymmetry** η_B and **axion abundance** Ω_ϕ can be achieved simultaneously in observed amounts:



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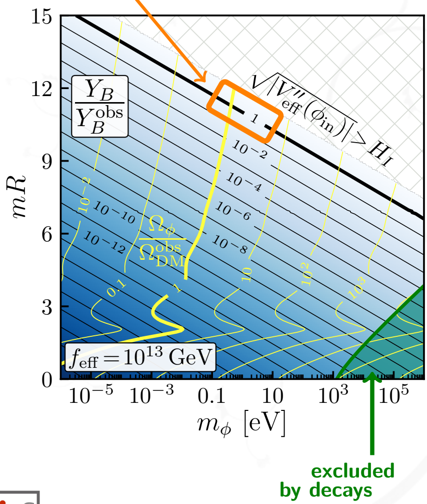

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constraints from **isocurvature**?
at first glance, presents a major concern for this type of scenario

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

Isocurvature Perturbations

- In general we analyze a scalar perturbation on the metric

$$ds^2 \;=\; (1+2\Phi)dt^2 - a(t)^2(1-2\Phi)d\vec{x}^2$$

and solve for the evolution of the corresponding perturbations

$\frac{k^2}{a^2}\Phi + 3H\left(H\Phi + \dot{\Phi}\right) \;=\; -\frac{\delta\rho_{\rm tot}}{2M_p^2}$	gravitational potential
$\delta\ddot{\phi} + 3H\delta\dot{\phi}\left[\frac{k^2}{a^2} + V''_{\rm eff}(\phi)\right]\delta\phi \;=\; 4\phi\dot{\phi}\dot{\Phi} - 2V'_{\rm eff}(\phi)\Phi$	axion field
$\dot{\delta}_B - \frac{k^2}{a^2}v_{B\gamma} = -\Gamma_L\left(\delta_B - \frac{\delta\mu_{\rm eff}}{\mu_{\rm eff}}\right)\frac{n_L^{\rm eq}}{n_L} + 3\dot{\Phi}$	baryons
$\dot{\delta}_\gamma - \frac{4}{3}\frac{k^2}{a^2}v_{B\gamma} \;=\; 4\dot{\Phi}$	photons
$\dot{v}_{B\gamma} + \frac{1}{4}\delta_\gamma \;=\; 0$	velocity potential

$\Rightarrow$ can solve numerically, but let us consider some useful **analytical limits**

Isocurvature Perturbations

Baryon Component

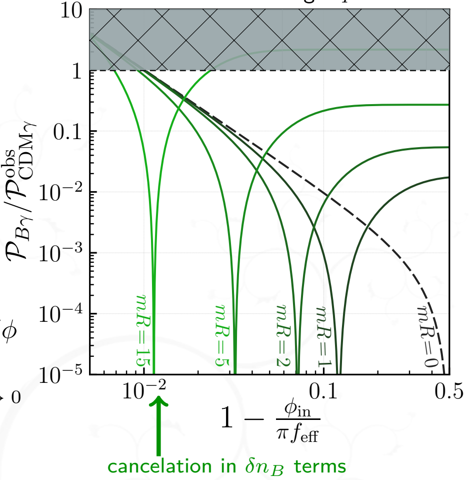
- If asymmetry were generated at equilibrium, then

$$n_B \;\propto\; \dot{\theta} T^2 \;\propto\; \frac{\left[V'_{\rm eff}(\phi)\right]^2}{\sqrt{\left[1 - \frac{V_{\rm eff}}{2\Lambda^4}\right] \frac{V_{\rm eff}}{2\Lambda^4}}}$$

$\Rightarrow$ perturbation after decoupling:

$$\frac{\delta n_B}{n_B} \approx \underbrace{\left\{ 2\frac{V''_{\rm eff}(\phi)}{V'_{\rm eff}(\phi)} - \frac{1}{2}\frac{V'_{\rm eff}(\phi)}{V_{\rm eff}(\phi)}\left[\frac{1-\frac{V_{\rm eff}}{\Lambda^4}}{1-\frac{V_{\rm eff}}{2\Lambda^4}}\right]\right\}}_{\text{inflection points/cancelations in terms can drive} \rightarrow 0} \delta\phi$$

using $H_I = 10^8\,$GeV



- Serves as a good benchmark for our **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 $S_{\phi\gamma}$

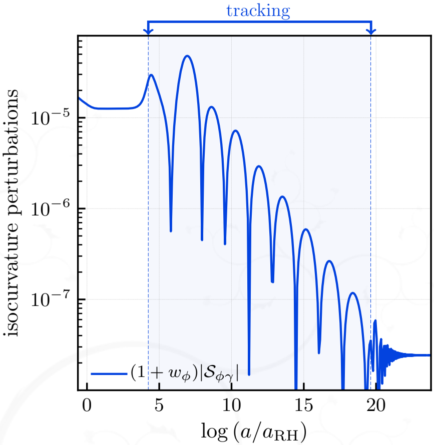
$$\frac{1}{2}\frac{d\left[(1+w_\phi)S_{\phi\gamma}\right]}{d\log a} = \Gamma$$

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

where it is coupled to the intrinstic entropy perturbation:

$$\Gamma \equiv \frac{\overbrace{\delta P_\phi}^{\text{pressure perturbation}}/\rho_\phi - c_\phi^2\delta_\phi}{1-\underbrace{c_\phi^2}_{\text{adiabatic sound speed}}}$$

$\Rightarrow$ can be solved analytically to show amplitude of $S_{\phi\gamma} \propto 1/\sqrt{a}$ **falls** while axion follows **tracking trjaectory**



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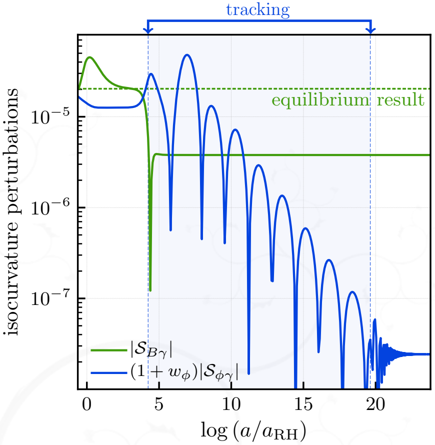


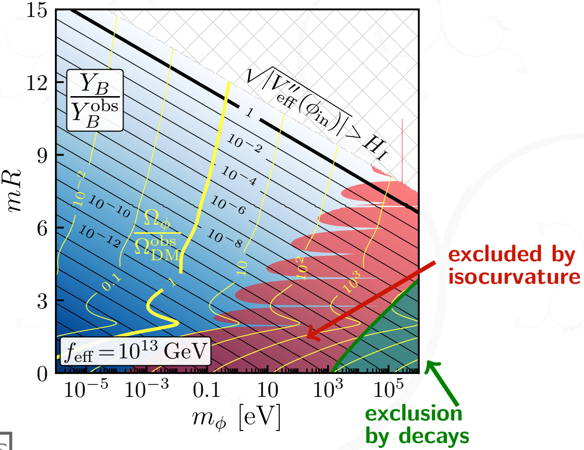
axion dynamics lead generically to a ***suppression*** of the axion $S_{\phi\gamma}$ and baryon $S_{B\gamma}$ isocurvature modes

Revisiting the Viable Regions

Including Isocurvature Constraints

The baryonic and axionic contributions to the isocurvature mode are exactly correlated and **CMB observations place a bound** on

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



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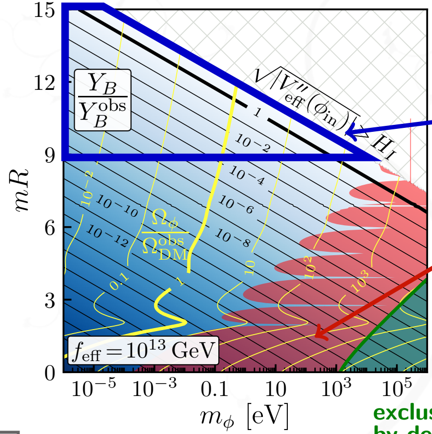

isocurvature **suppressed** by tracking dynamics and cancelations in $S_{B\gamma}$: **interesting regions remain viable**

excluded by isocurvature

exclusion by decays

THANK YOU FOR YOUR ATTENTION!