Spontaneous Leptogenesis in Continuum-Clockwork Axion Models

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[IBS-CTPU]

[arXiv:1809.XXXXX]

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Outstanding Issues

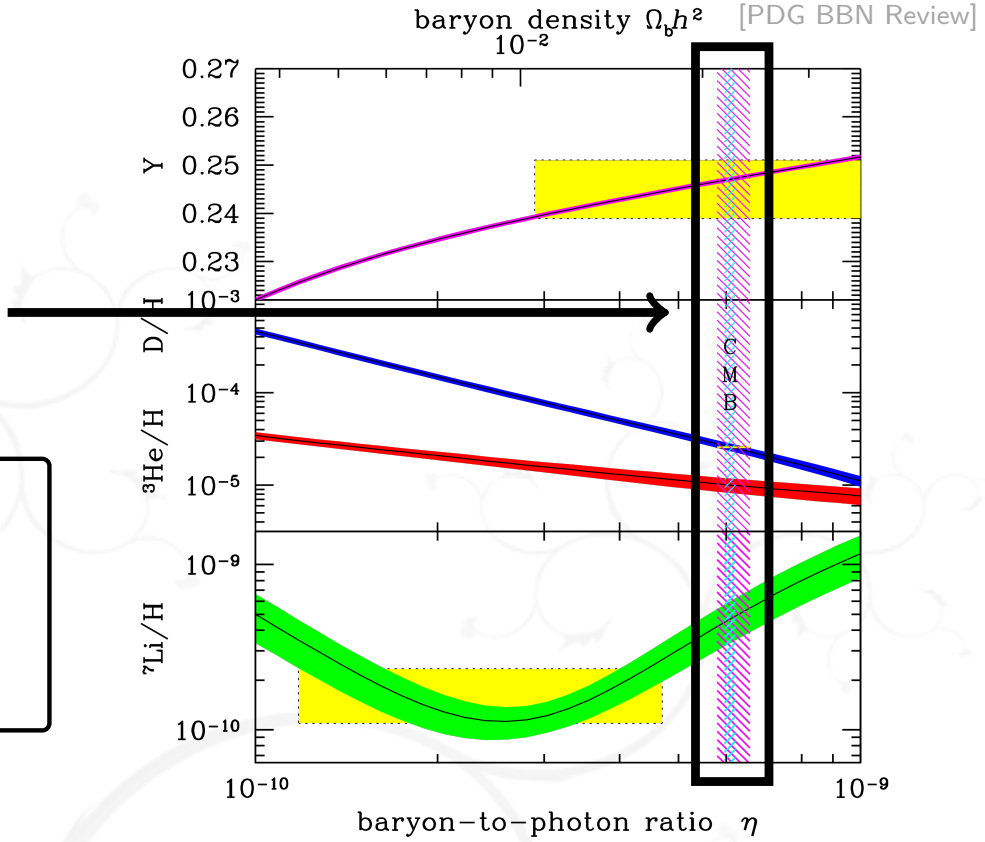
matter-antimatter asymmetry:

need to explain baryon-to-photon ratio:

$$\eta_B^0 \equiv \frac{n_b^0 - n_{\bar{b}}^0}{n_\gamma^0} \approx \frac{n_b^0}{n_\gamma^0} \approx 6 \times 10^{-10}$$

Typically need ***Sakharov conditions***:

- B and/or L violation
- C and CP violation
- departure from thermal equilibrium



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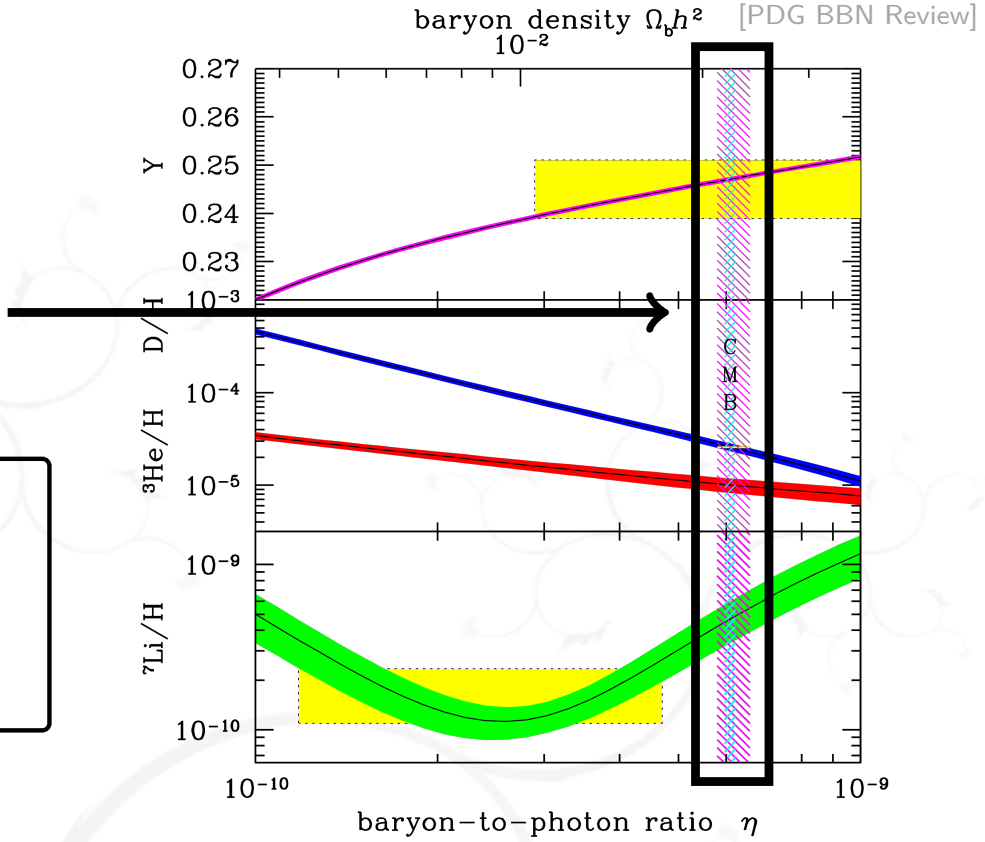

[PDG BBN Review]

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alternatives exist if $\cancel{CPT}$ spontaneously, *e.g.*, with homogeneous scalar field ϕ:

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

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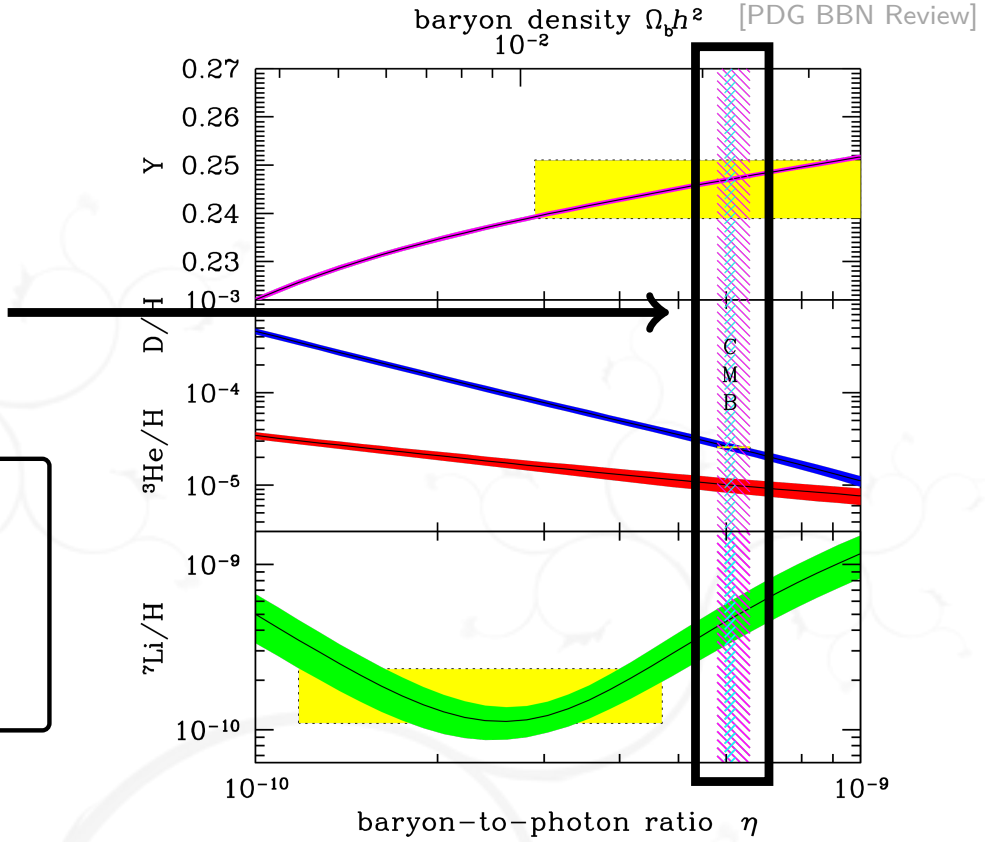

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effective **chemical potential**

$$\mu_{\rm eff} \equiv \dot{\phi}/f$$

for lepton number density n_L

$\Rightarrow$ opportunity for asymmetry generation **even at equilibrium**

The $\mu_{\rm eff} \neq 0$ **shifts equilibrium** $n_L^{\rm eq}$ value away from zero:

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

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

$$\dot{n}_L + 3Hn_L \;=\; -\,\Gamma_L\,(n_L^{\rm eq} - n_L)$$

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

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

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

then the rate is fixed by experiment:

$$\Gamma_L = 4n_\ell^{\rm eq}\langle\sigma_L v\rangle \sim \mathcal{O}(10^8\,{\rm GeV}) \left(\frac{T}{10^{13}\,{\rm GeV}}\right)^3 \;.$$

Spontaneous Leptogenesis via Axions [Kusenko '18]

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

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

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

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

which can readily arise [*e.g.*, string axion models]

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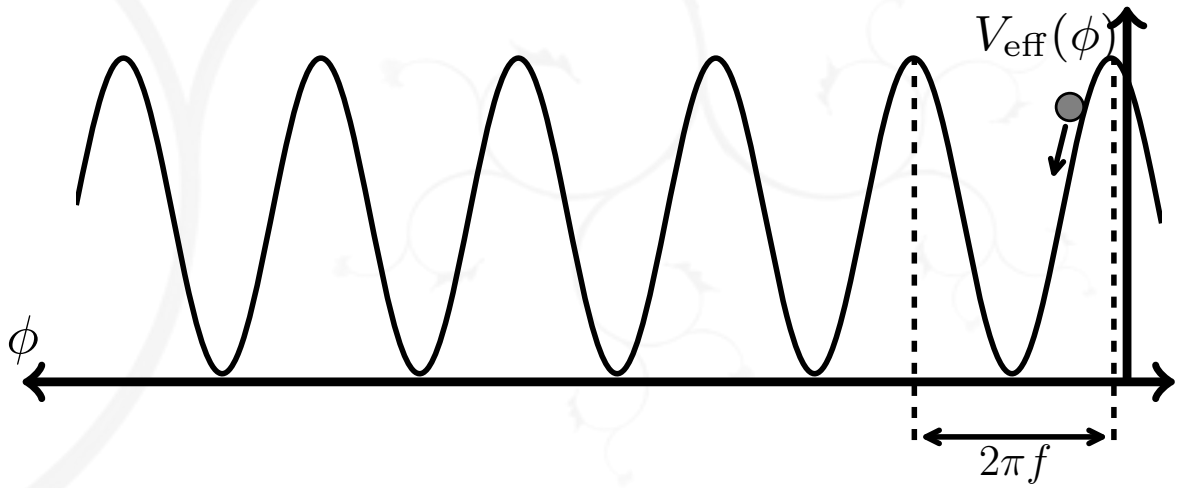

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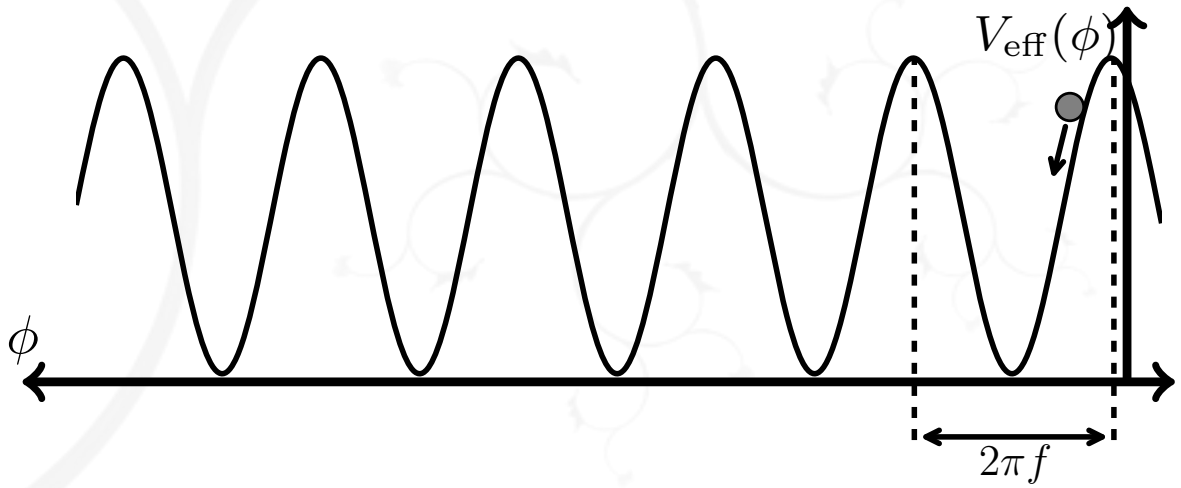

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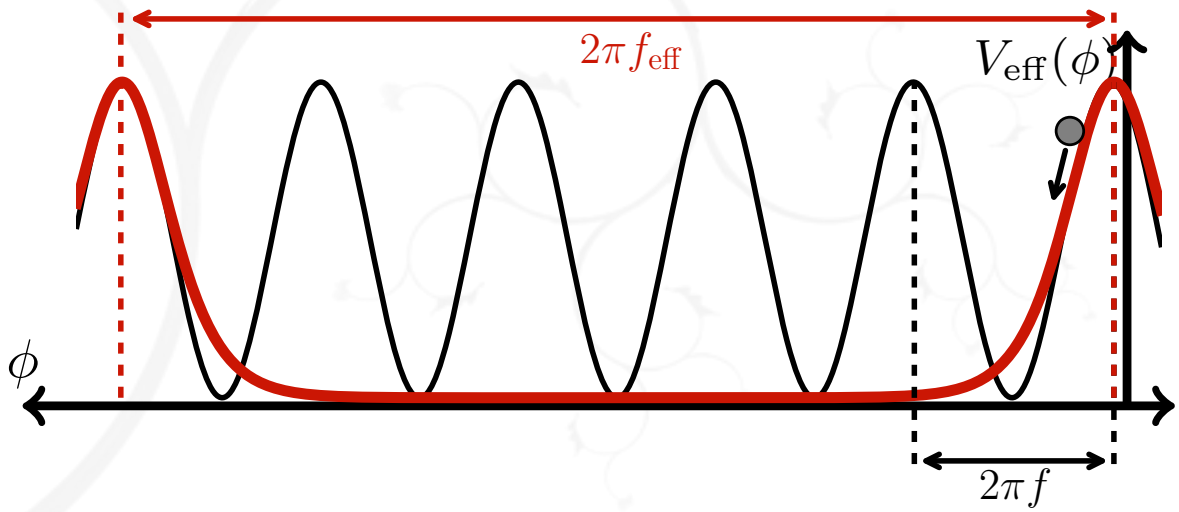

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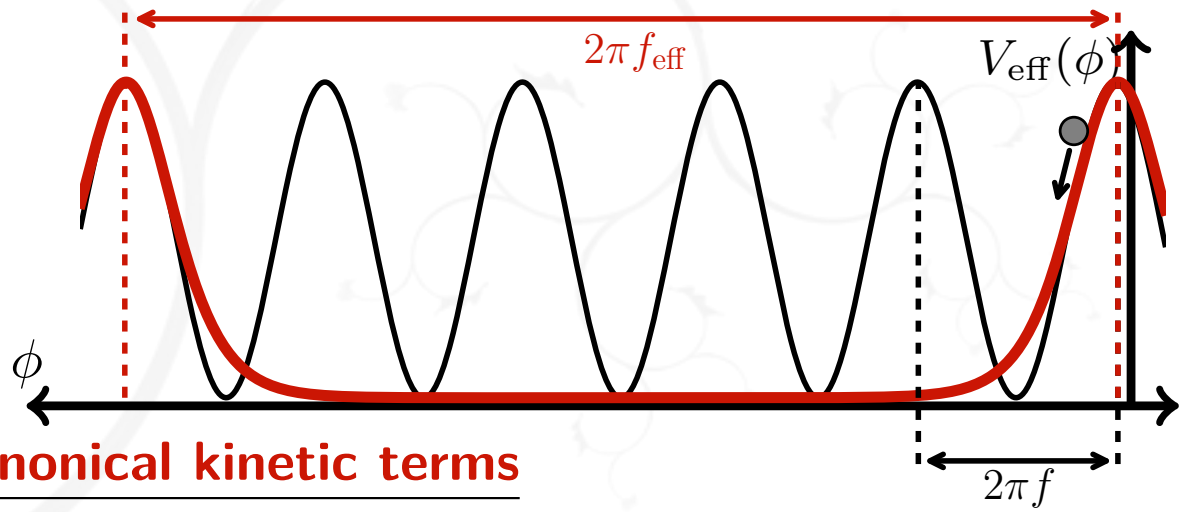


how? $\Rightarrow$ can appear via **non-canonical kinetic terms**

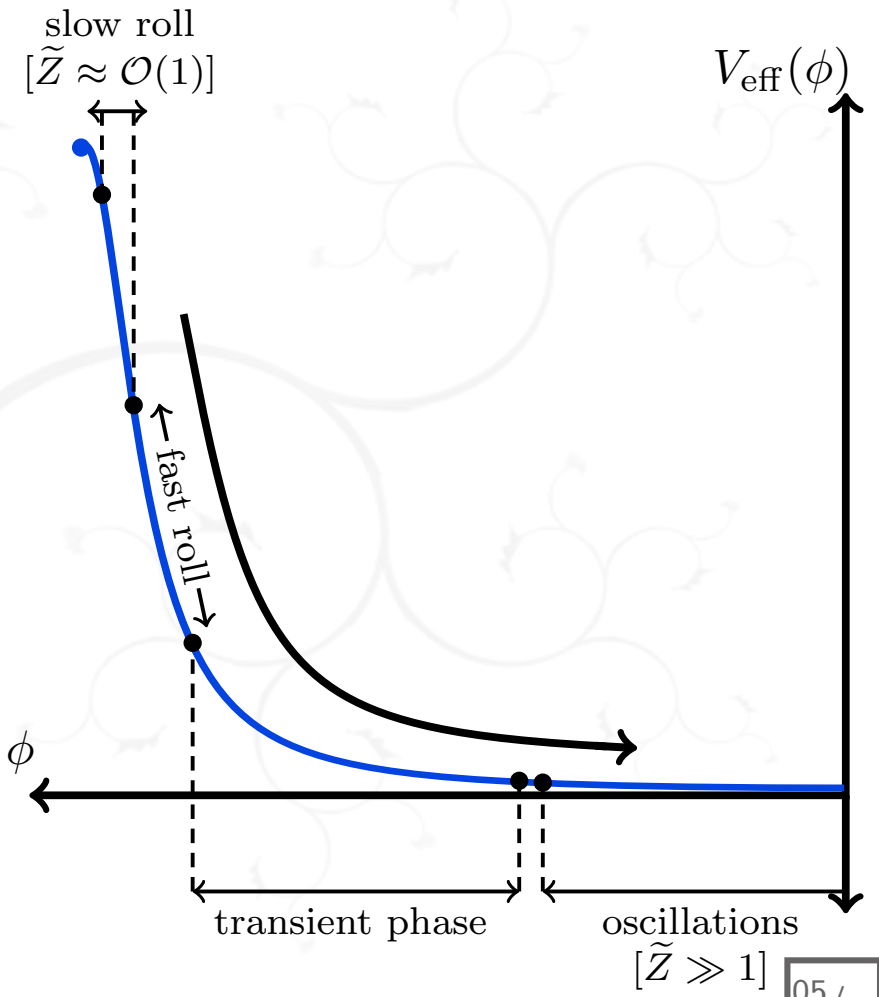
Non-Canonical Kinetic Term

- As a toy model, consider periodic scalar $\theta(x)$ with non-trivial wavefunction renormalization $Z(\theta)$:

$$\begin{aligned}\mathcal{L} &= -\frac{Z(\theta)}{2} f^2 \left(\partial_\mu \theta\right)^2 - \Lambda^4 \left(1 - \cos\theta\right) + \frac{\theta}{8\pi^2} \left[F\widetilde{F}\right]_{\rm SM} \\ &\equiv -\underbrace{\frac{1}{2}\left(\partial_\mu \phi\right)^2 - V_{\rm eff}(\phi)}_{\text{canonically-normalized}}\end{aligned}$$

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

- The properties in $V_{\rm eff}(\phi)$ can arise from:
  - $Z(\theta) \gg 1$ near minimum
    [suppression of mass, couplings, *etc.*]
  - $Z(\theta) \approx \mathcal{O}(1)$ toward edges
    [maintain sizeable $\mu_{\rm eff}$ during leptogenesis]



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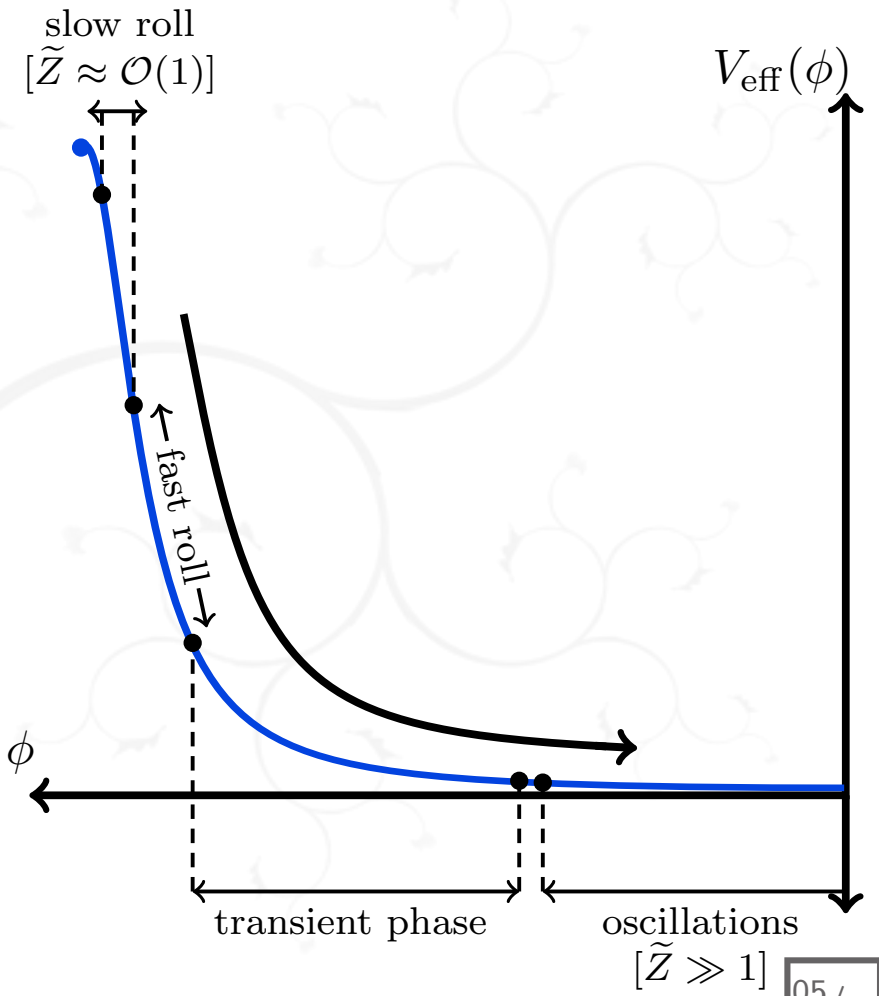
Models *already exist* that furnish such $Z(\theta)$
example: continuum-clockwork models



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

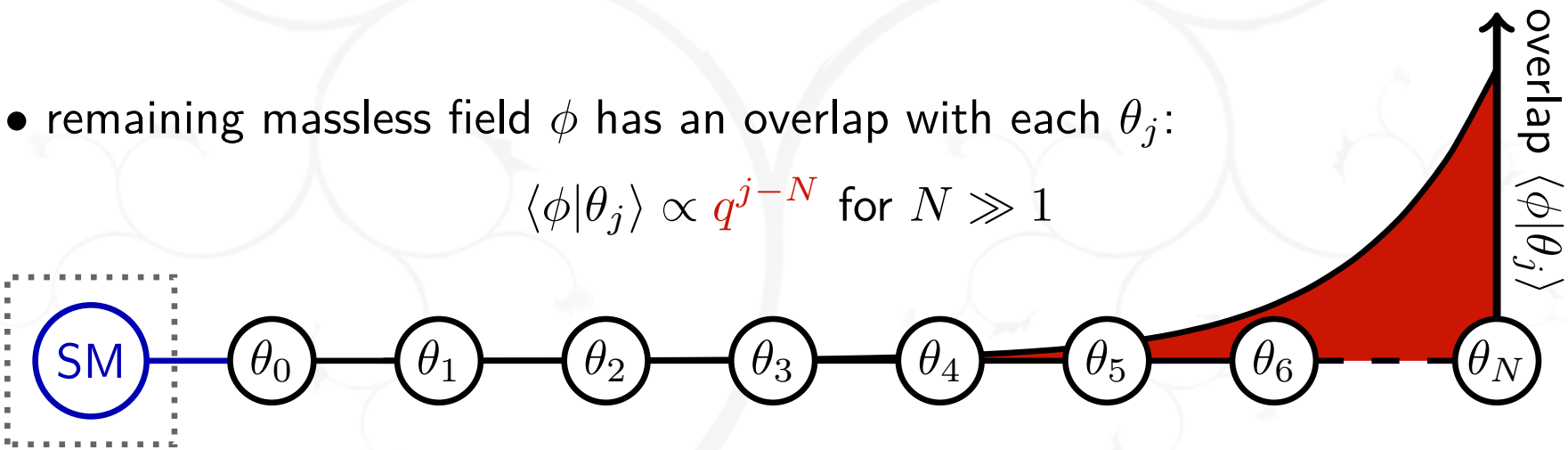
• Consider $N+1$ Nambu-Goldstone bosons θ_j and introduce some "nearest-neighbor" interactions ($q \in \mathbb{Z}$):

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

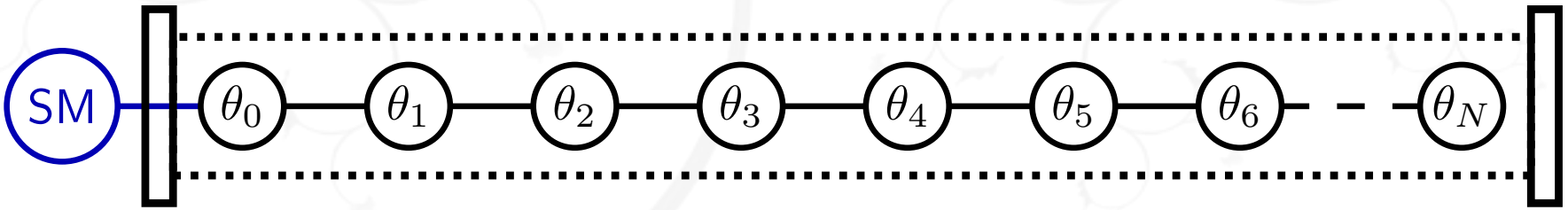
$\Rightarrow U(1)^{N+1}$ broken down to $U(1)_{\rm CW} : \theta_j \to \theta_j + \alpha q^j$

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

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

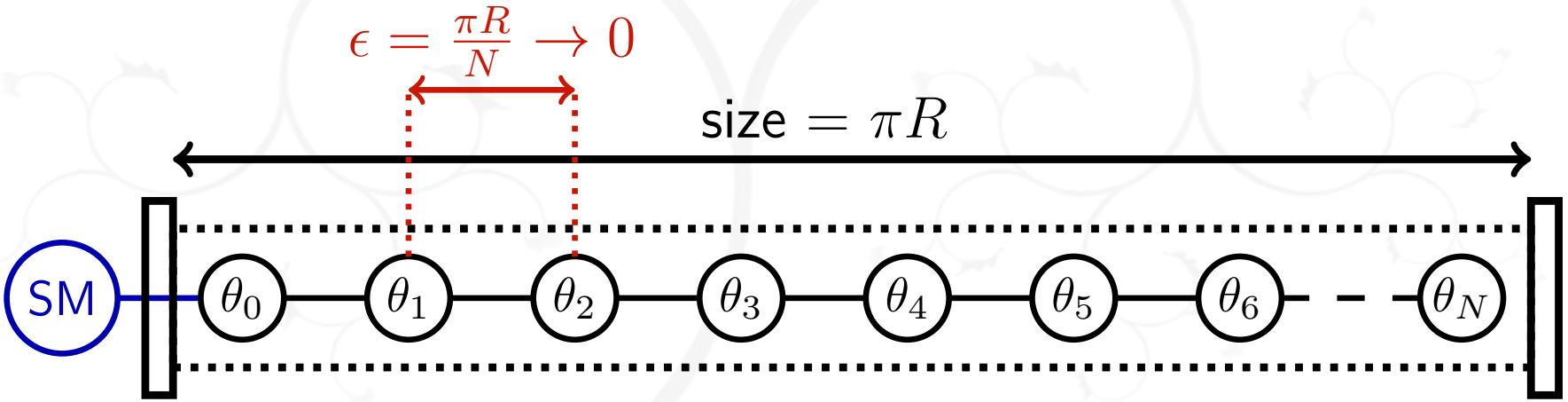


any couplings $q^{-N}\phi\mathcal{O}_{\rm SM}$ **exponentially suppressed**


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

[Giudice *et al.* '16] [Craig *et al.* '17] [Choi *et al.* '17]

In continuum limit, find action for resulting bulk field $\theta(x, y)$:

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

- massless 4D mode $\phi(x)$ realized as:

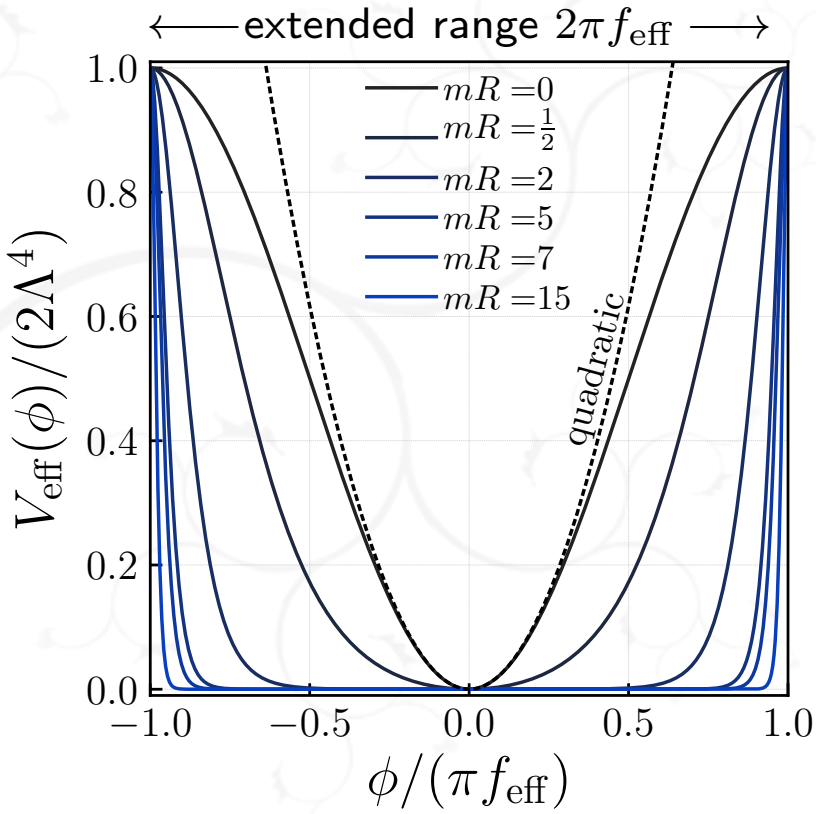
$$\tan\left[\frac{\theta(x,y)}{2}\right] = e^{my}\underbrace{u\left[\phi(x)\right]}_{ie^{-\pi mR}\mathrm{sn}\left[\frac{\phi(x)}{2if}\middle| e^{-2\pi mR}\right]}$$

- any small deviation in boundary masses generates a potential:

$$V_{\rm eff}(\phi) = \Lambda^4\left\{1-\cos\left[\theta(x,0)\right]\right\}$$
$$= \frac{2\Lambda^4\left[u(\phi)\right]^2}{1+\left[u(\phi)\right]^2}$$

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

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



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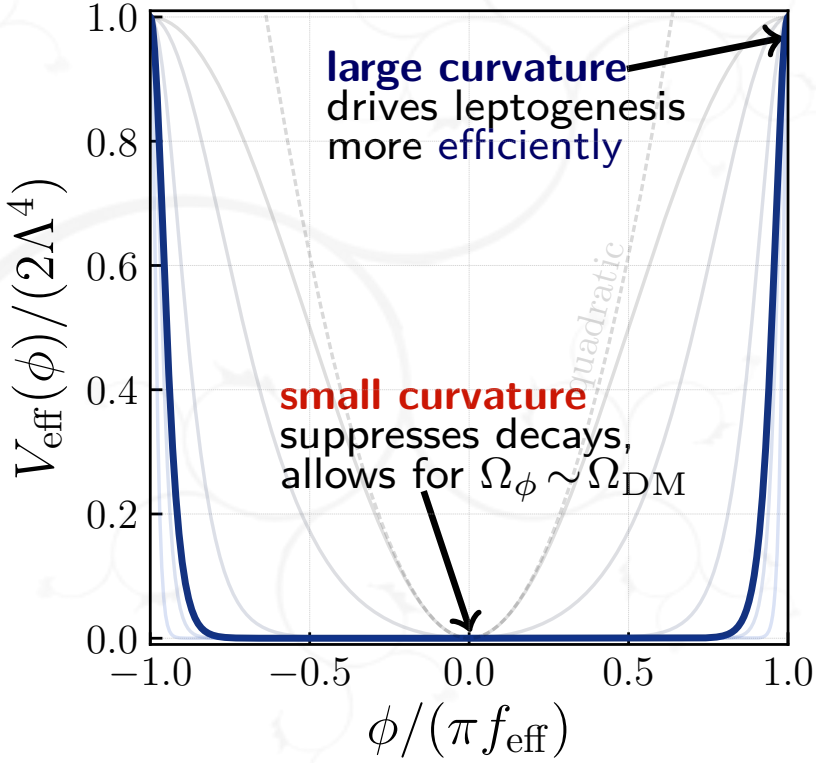
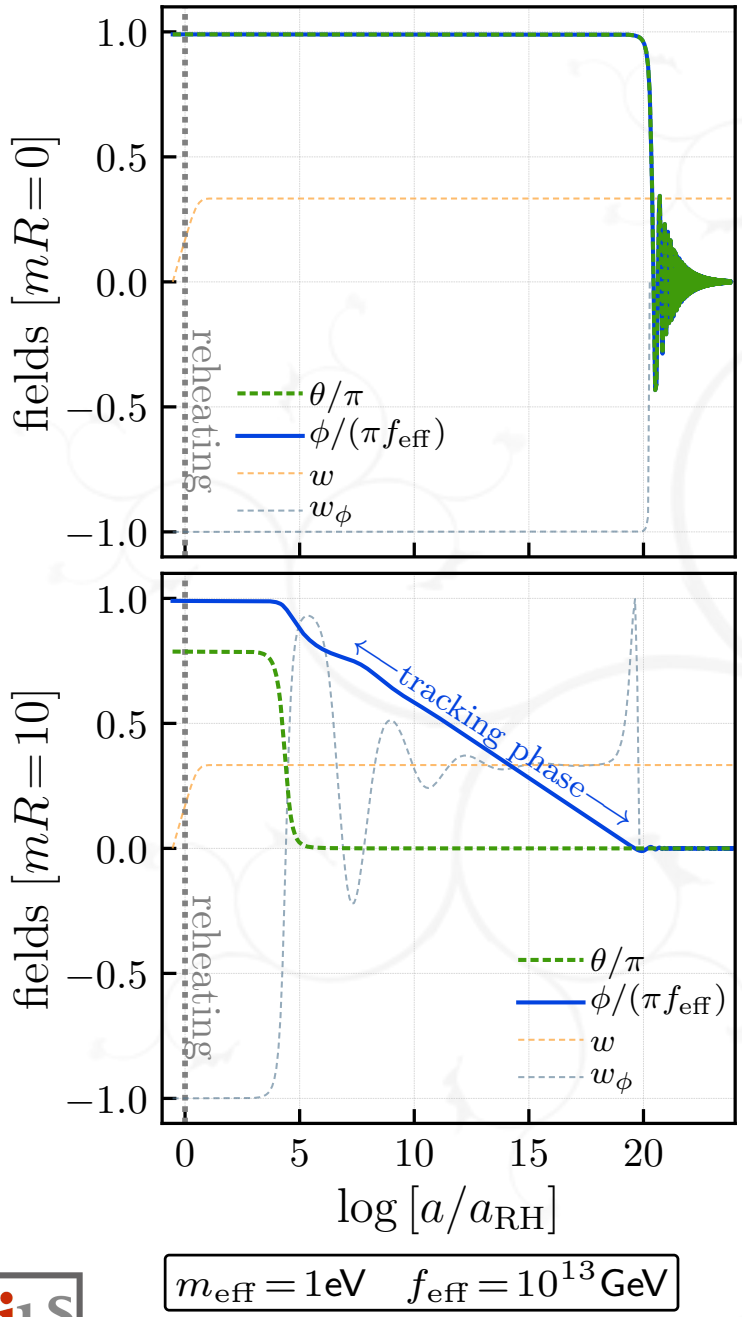


Some Interesting Early Dynamics



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

- *prior* to undergoing coherent oscillations, axion field enters **"tracking phase"** (similar to that found in models of quintessence):

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

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

- these are attractor solutions that largely erase dependence on misalignment angle

- $mR > 0$ deformation of potential triggers leptogenesis at **higher temperatures**

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

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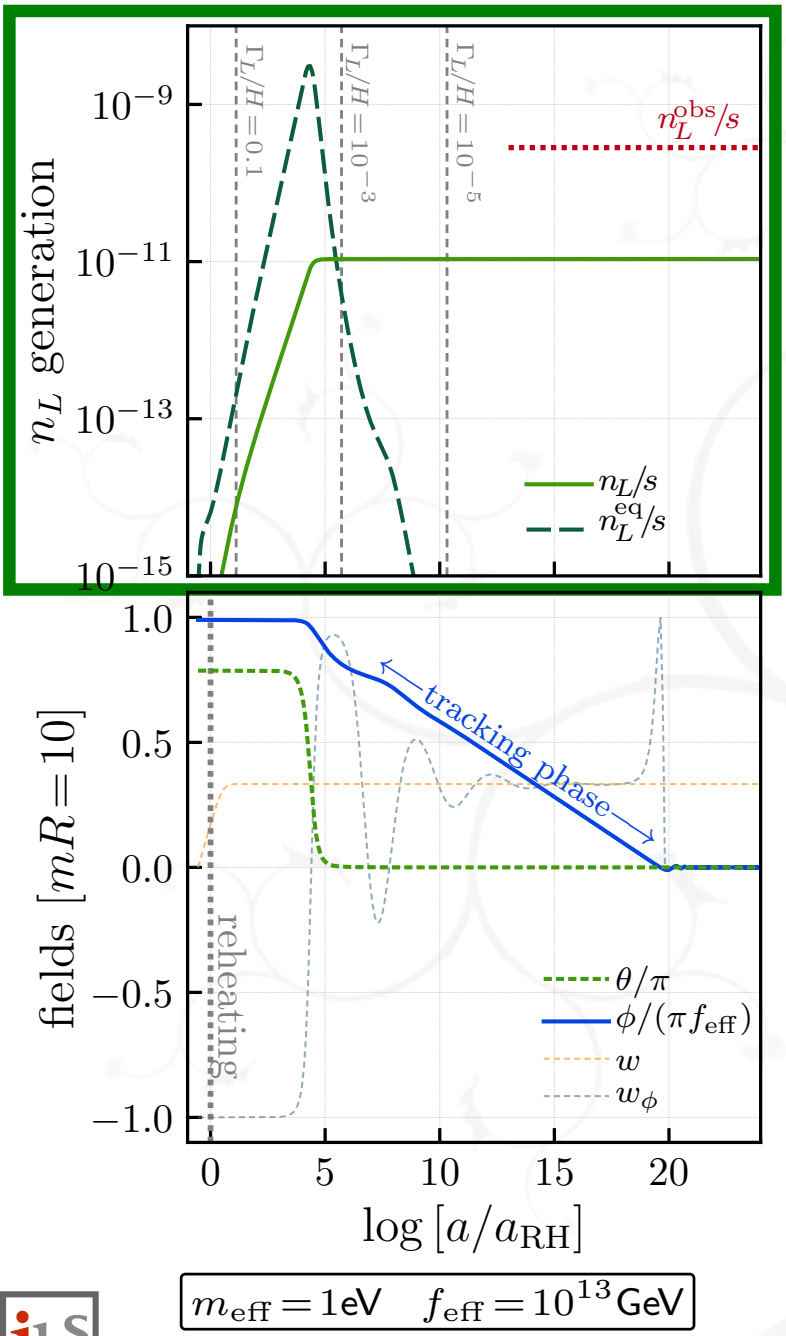

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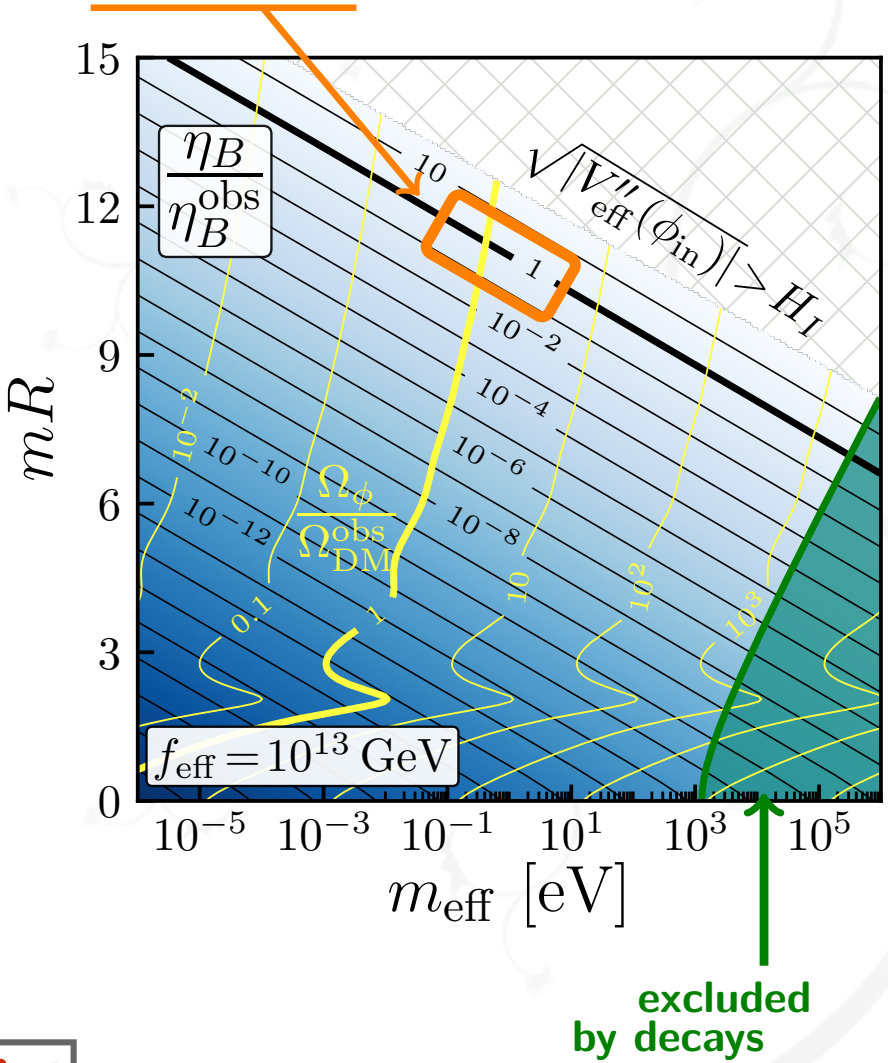
Viable Regions from Numerical Simulations

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



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

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

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

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

and rendered **insensitive** to initial misalignment angle

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

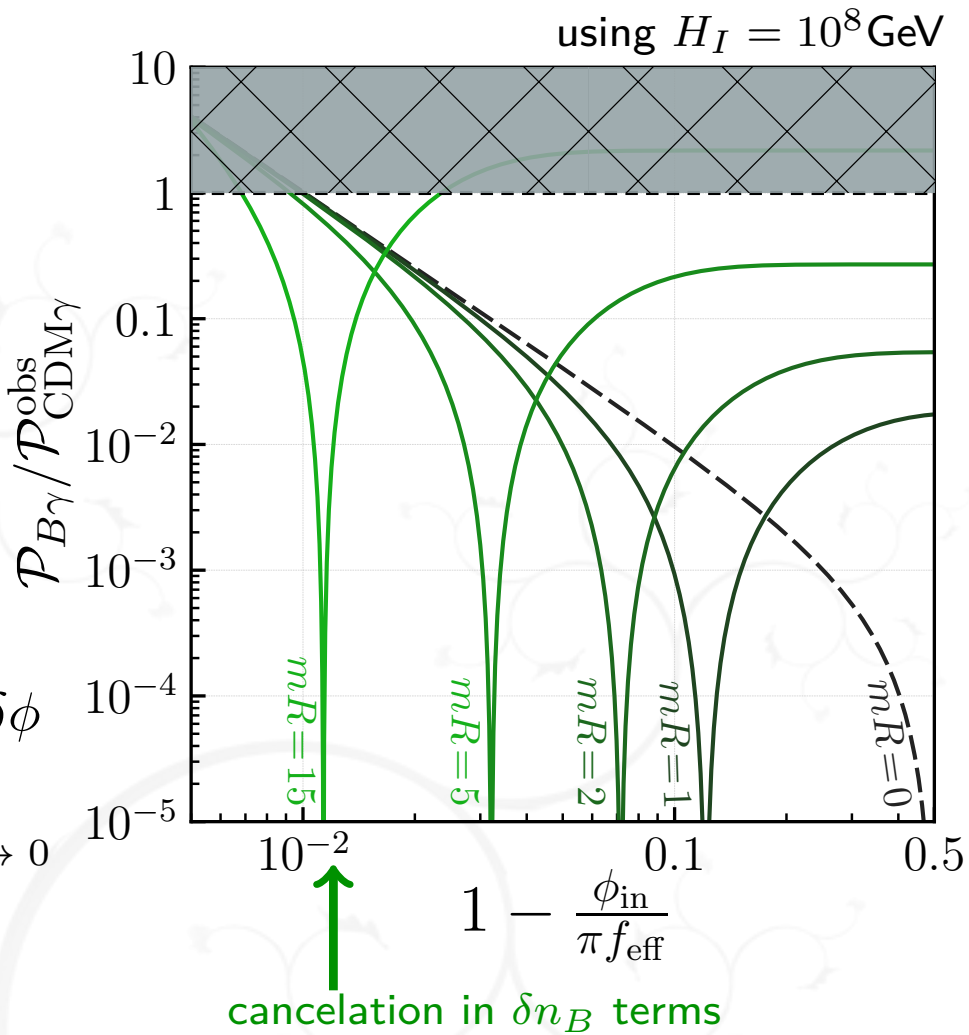
Baryon Component

- If lepton 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:

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



- 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 $S_{\phi\gamma}$

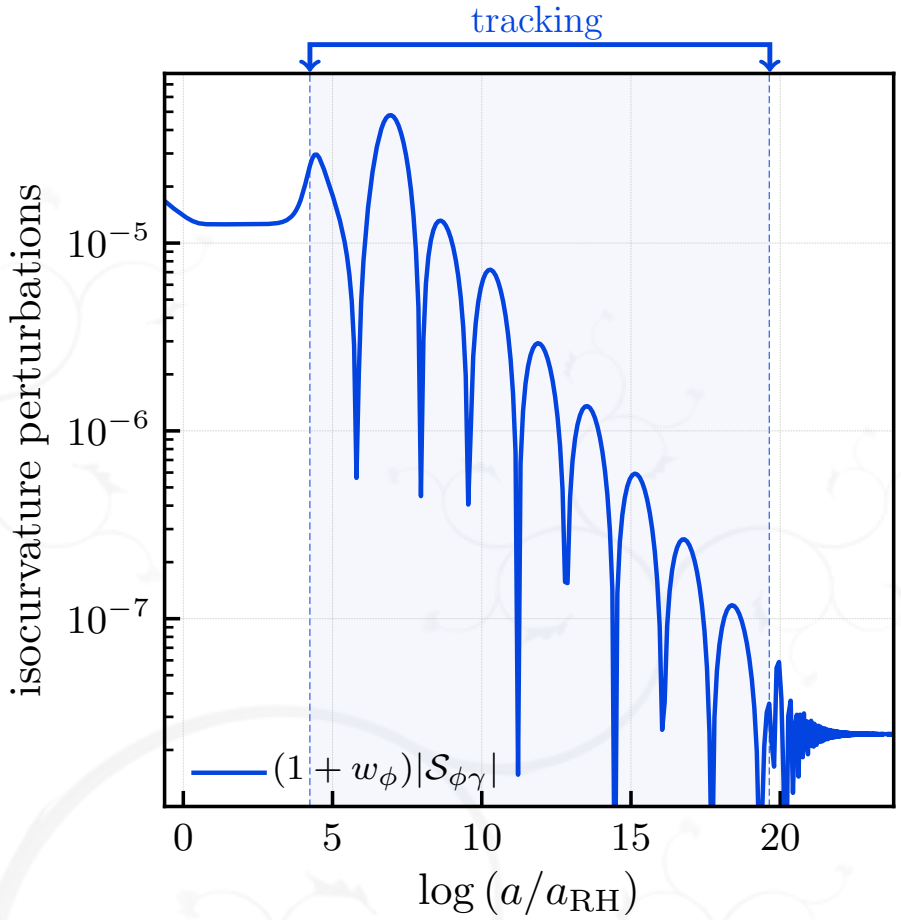
$$\frac{1}{2}\frac{d\left[(1+w_\phi)S_{\phi\gamma}\right]}{d\log a} = \Gamma$$

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

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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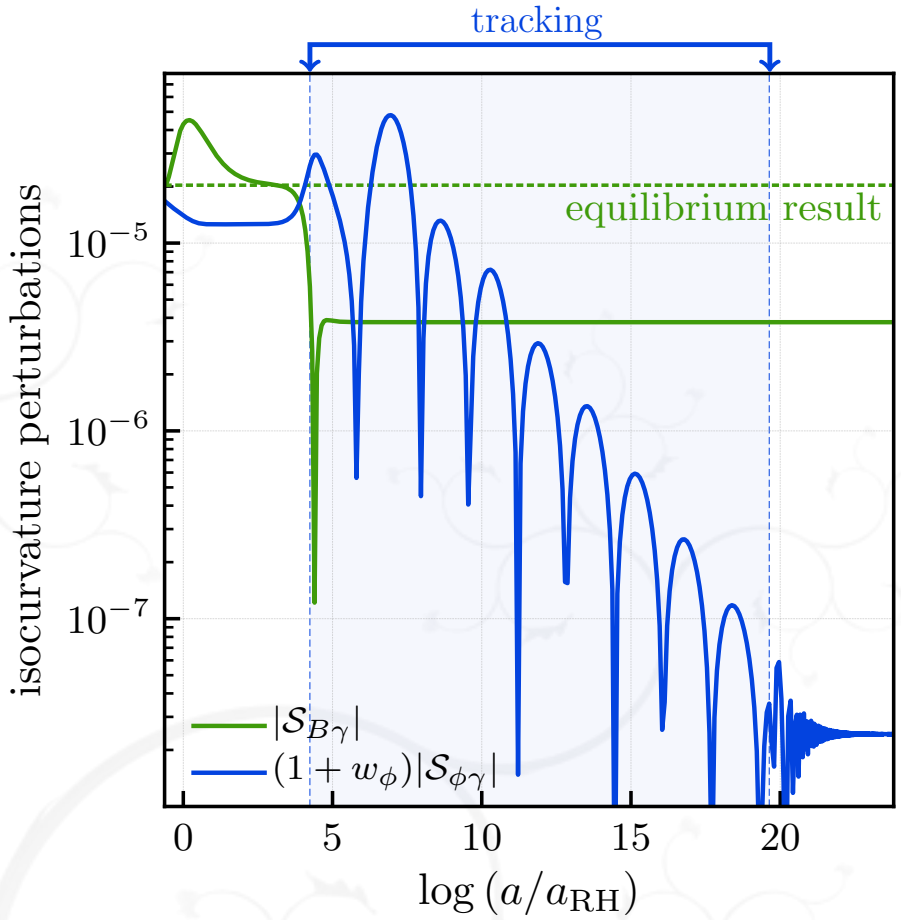


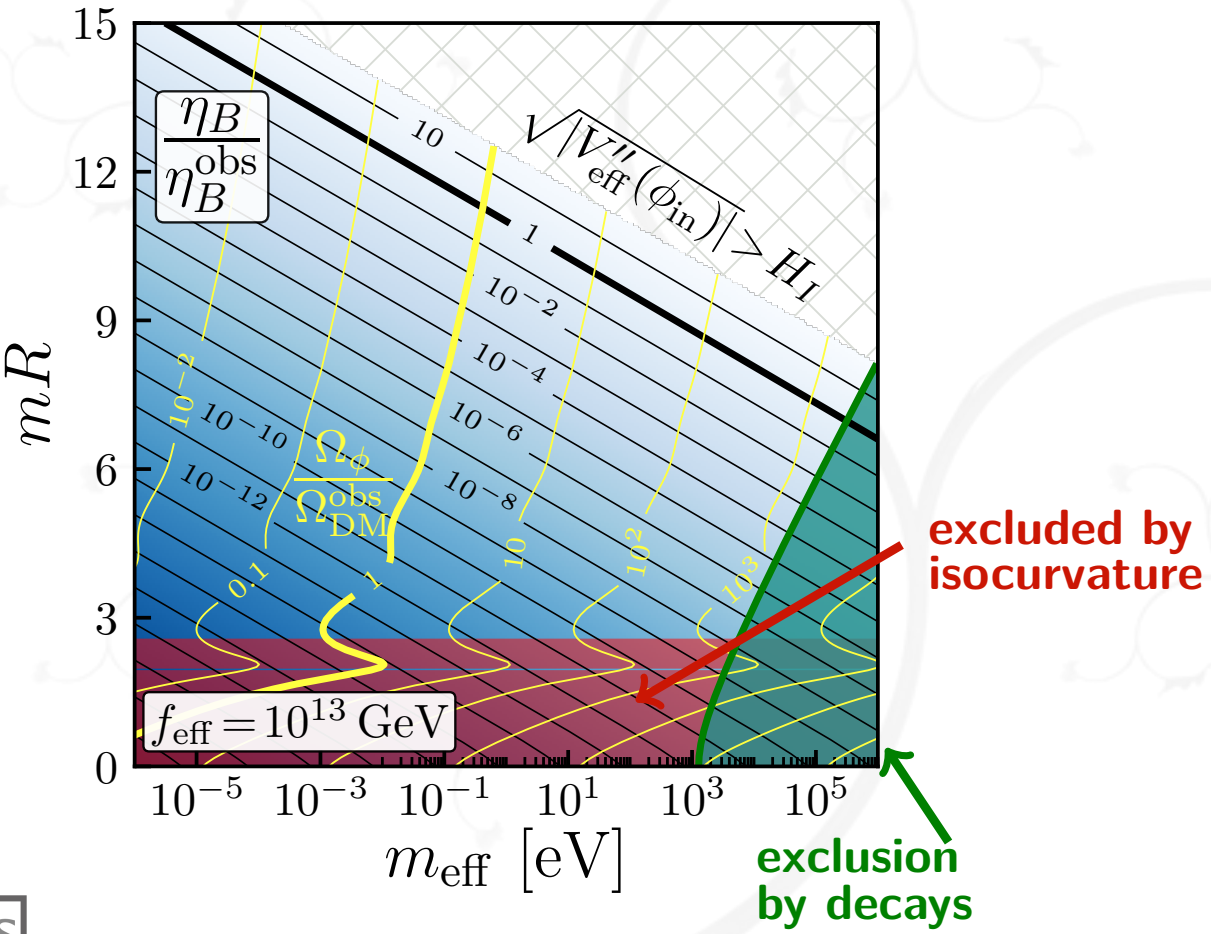
axion dynamics lead generically to a ***suppression*** of the axion $S_{\phi\gamma}$ and baryon $S_{B\gamma}$ isocurvature modes

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

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



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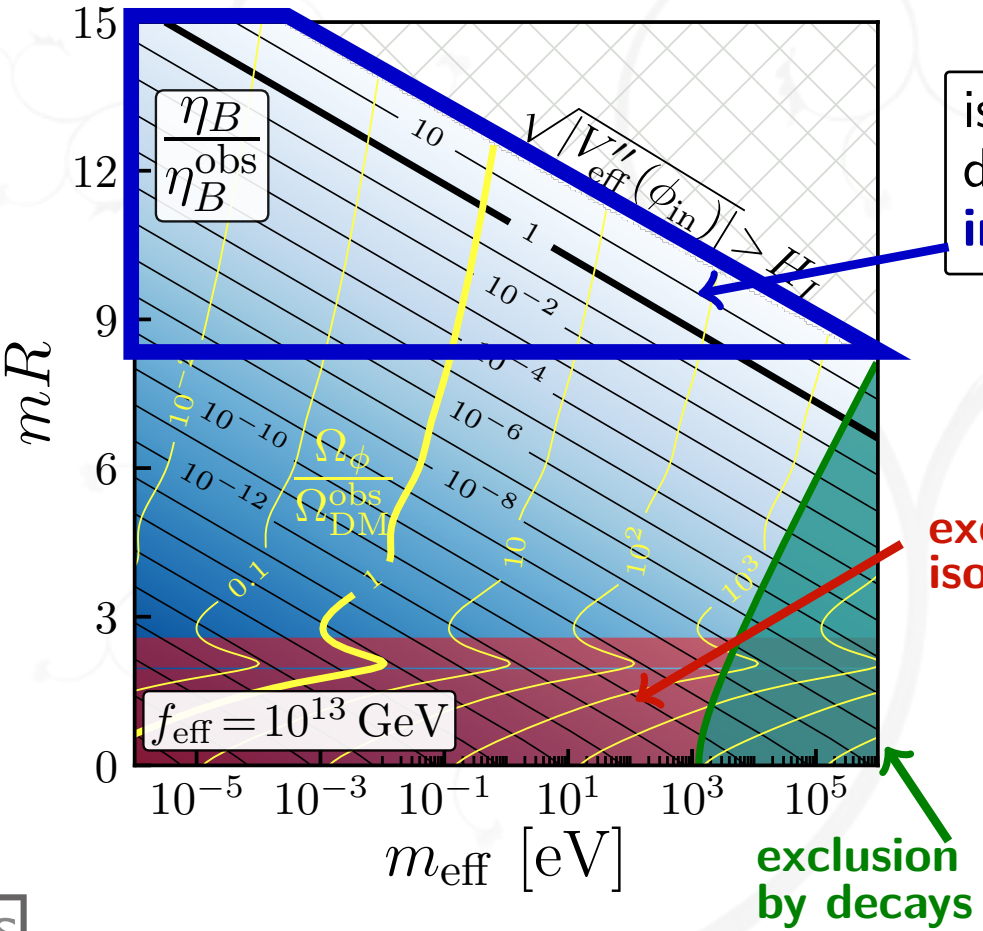

isocurvature **suppressed** by tracking dynamics and cancelations in $S_{B\gamma}$: **interesting regions remain viable**

excluded by isocurvature

exclusion by decays

TAKE-AWAY MESSAGE:

Taking advantage of deformations in effective potential of **continuum-clockwork axion**, we can generate appropriate **matter-antimatter asymmetry** via spontaneous leptogenesis, with axion serving as **dark matter**

- axion exhibits **"tracking behavior"**: driven towards $w_\phi \approx \frac{1}{3}$, delaying coherent oscillations and washing out dependence on misalignment angle

- **suppression of isocurvature** and more efficient asymmetry production due to these deformations

- this talk serves as an example, but ***in general*** *this can arise from models with non-canonical kinetic terms*

THANK YOU FOR YOUR ATTENTION!