

Standard model CP violation is enough

Gilly Elor,^{1,*} Rachel Houtz^{2,3,†}, Seyda Ipek^{4,‡}, and Martha Ulloa^{2,§}

¹Weinberg Institute, Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA

²Department of Physics, University of Florida, Gainesville, Florida 32611, USA

³Theoretical Physics Department, CERN, 1211 Geneva, Switzerland

⁴Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada



(Received 19 September 2024; accepted 16 May 2025; published 2 July 2025)

Is the standard model charge-parity (CP) violation ever enough to generate the observed baryon asymmetry? Yes! We introduce a mechanism of baryogenesis (and dark matter production) that can generate the entire observed baryon asymmetry of the Universe using *only* the CP violation within standard model systems—a feat which no other mechanism currently proposed can achieve. Baryogenesis proceeds through a mesogenesis scenario but with well motivated additional dark sector dynamics: a *morphon* field generates present day mass contributions for the particle mediating the decay responsible for baryogenesis. The effect is an enhancement of baryon production while evading present day collider constraints. The CP violation comes entirely from standard model contributions to neutral meson systems. Meanwhile, the dark dynamics generate gravitational waves that may be searched for with current and upcoming pulsar timing arrays, as we demonstrate with an example potential that is tuned to generate domain walls that annihilate later. This mechanism, *mesogenesis with a morphing mediator*, motivates probing a new parameter space as well as improving the sensitivity of existing mesogenesis searches at hadron and electron colliders.

DOI: 10.1103/glgl-v4v6

Introduction. The quest to discover the theory that creates the baryon asymmetry of the Universe (BAU) has been ongoing since Sakharov laid out the three conditions needed to generate a primordial matter-antimatter asymmetry [1]: the breaking of baryon number, violation of charge (C) and charge-parity (CP) symmetries, and the existence of out-of-equilibrium interactions. While aspects of the Sakharov criteria exist within the standard model (SM), it is widely appreciated that beyond the SM physics is required to successfully generate the observed BAU. Deviating from the traditional approach of all-encompassing new physics, in this Letter we introduce the *only* mechanism, to date, which succeeds in generating the BAU with *just* the SM CP violation (CPV).

CPV arises in the SM as an irreducible phase in the quark mixing matrix. While this CPV phase is not small, the parametrization-independent measure of SM CPV, namely the Jarlskog parameter [2] is $J \sim 10^{-5}$. In electroweak

baryogenesis models, where this CPV *could* be relevant, CPV effects are further suppressed by small Yukawa couplings resulting in an asymmetry that is 10 orders of magnitude smaller than the measured value [3–7]. One approach has been to utilize the Cabbibo-Kobayashi-Maskawa mechanism by making the Yukawa couplings larger in the early Universe, dynamically relaxing to their present-day value [8–11].¹ In such mechanisms, the CPV is different than what is observed in the SM; for example, there is no J suppression.

The SM CPV also arises in neutral meson oscillations. Here, we exploit the CPV in the neutral B -meson system and show that it can be enough to generate the entire BAU. This scenario can be realized through *mesogenesis* [17–19]. In mesogenesis, SM mesons, which are produced out of equilibrium (at a temperature of 5–100 MeV), decay into dark sector states with SM baryon number. Various mesogenesis mechanisms leverage the CPV in charged and neutral meson systems, and the BAU is directly linked to experimental observables [20–24], e.g., the semileptonic asymmetry in neutral meson oscillations—which are computed to be sizable even without new physics concatenations to the SM [25]. However, the SM CPV alone is still not enough [22].

*Contact author: gilly.elor@austin.utexas.edu

†Contact author: rachel.houtz@ufl.edu

‡Contact author: Seyda.Ipek@carleton.ca

§Contact author: m.ulloacalzonzin@ufl.edu

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

¹Dynamical Yukawa couplings can be realized in various models [12,13] and can also lead to a first-order phase electro-weak phase transition [14–16].

Mesogenesis mechanisms, by construction, require a dark sector which shares an equal and opposite baryon asymmetry to that of the SM sector. There must also exist a SM-dark sector mediator $\mathcal{Y}$ which allows SM mesons to decay into the dark sector. Hence, mesogenesis also provides an explanation for the nature and origin of dark matter. In this Letter we consider various dark sector dynamics which allow the SM-dark sector mediator $\mathcal{Y}$ to acquire a temperature dependent contribution to its mass. Using this simple, albeit fine-tuned yet theoretically well motivated, *morphing* of the mediator mass, we show that there does exist a mechanism of baryogenesis where the SM CPV is enough. Furthermore, the dark sector dynamics open up new classes of signals which augment the existing mesogenesis experimental program—with unique signals of mesogenesis with a morphing mediator (3M).

Mesogenesis with a morphing mediator. Mesogenesis requires interactions between SM quarks and a new dark fermion ψ_B carrying antibaryon number, $B = -1$, giving rise to a (B -conserving) effective operator:

$$\mathcal{O}_{d_k, u_i d_j} = \mathcal{C}_{d_k, u_i d_j} \epsilon_{\alpha\beta\gamma} (\bar{\psi}_B d_k^\alpha) (\bar{d}_j^{c\beta} u_i^\gamma), \quad (1)$$

i, j and α, β, γ are flavor and color indices, respectively. Equation (1) can arise in a UV model with a heavy color triplet scalar $\mathcal{Y}$. Assigning $\mathcal{Y}$ an electric charge $-1/3$ and baryon number $-2/3$, symmetry admits the following Lagrangian:

$$\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^* \bar{u}_{iR} d_{jR}^c - \sum_k y_{\psi d_k} \bar{\psi}_B \mathcal{Y} d_{kR}^c + \text{H.c.} \quad (2)$$

In a simple supersymmetric realization [26] $\mathcal{Y}$ can be a squark. LHC searches for squarks constrain the Wilson coefficient of the effective operators: $\mathcal{C}_{d_k, u_i d_j} \equiv y_{\psi d_k} y_{u_i d_j} / M_{\mathcal{Y}}^2$, where the couplings $y_{\psi d_k}, y_{u_i d_j} \lesssim 4\pi$ by perturbativity. Hence, the $\mathcal{Y}$ mass, like squarks, is constrained to be heavier than a few TeV [22]. Proton decay through $\psi_B udd$ is kinematically forbidden by requiring all dark sector baryons to have a mass $\gtrsim 1$ GeV.

In neutral B mesogenesis [19], equal numbers of neutral $B_{s,d}$ mesons and antimesons are produced by the late-time decay of a heavy scalar Φ^2 at a temperature $T_d \lesssim 100$ MeV, and undergo CP violating meson-antimeson oscillations. Next, portal operators in Eq. (1) involving one b -quark mediate the out-of-thermal equilibrium meson decay: $B_{d,s}^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}$, into the dark antibaryon and a SM baryon. The result is an equal and opposite baryon asymmetry between the dark and SM sectors. ψ_B ultimately decays into

the stable dark matter. The nature of the final state SM baryon depends on the flavorful variations³ of Eq. (1).

Mesogenesis occurs when the temperature of the Universe, T_d , was $O(10 \text{ MeV})$; before the era of big bang nucleosynthesis (BBN) but after the quark-hadron phase transition. The measured BAU, defined as the baryon-to-entropy ratio $Y_B^{\text{meas}} \equiv (n_B - n_{\bar{B}})/s = (8.718 \pm 0.004) \times 10^{-11}$ [27–30], is generated as [19,22,26]

$$Y_B \simeq 5 \times 10^{-5} \sum_{i=d,s} [\text{Br}(B_i^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}) A_{sl}^i] \alpha_i(T_d), \quad (3)$$

where the inclusive branching fraction is over all possible final states. $A_{sl}^{i=s,d}$ is the semileptonic asymmetry, an *observable* CP violating parameter in B^0 meson oscillations, $A_{sl}^i \equiv \frac{\Gamma(\bar{B}_i^0 \rightarrow B_i^0 f) - \Gamma(B_i^0 \rightarrow \bar{B}_i^0 \bar{f})}{\Gamma(\bar{B}_i^0 \rightarrow B_i^0 f) + \Gamma(B_i^0 \rightarrow \bar{B}_i^0 \bar{f})}$ for various final states f . The T_d dependent functions $\alpha_i \in [0, 1]$ capture the higher temperature oscillation-spoiling decoherence effects [19]. Generically, B_s^0 mesons dominate production at higher $T_d > 35$ MeV while B_d mesons are relevant at lower T_d . Φ parameter dependence is weak in the regions we consider.

From Eq. (3), it is clear that generating the observed BAU requires $\text{Br} \times A_{sl} \gtrsim 10^{-5}$. The SM CPV in B^0 oscillations have been calculated to be [25]

$$A_{sl}^d|_{\text{SM}} = (-4.7 \pm 0.4) \times 10^{-4}, \quad (4a)$$

$$A_{sl}^s|_{\text{SM}} = (2.1 \pm 0.2) \times 10^{-5}. \quad (4b)$$

Meanwhile, recasting the large electron-positron collider (LEP) constraints on b -quark decays constrains $\mathcal{C}_{d_k, u_i d_j}$, and therefore the branching fraction $\text{Br}(B_i^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}) \lesssim 10^{-4} - 10^{-3}$ [22], as summarized in Tables I and II. Additionally, designated mesogenesis searches by the Belle-II [31] and BABAR [32] collaborations have set limits on B mesogenesis through the $\psi_B \text{bus}$ operator; $\text{Br}(B_d^0 \rightarrow \Lambda + \text{MET}) \lesssim (2-4) \times 10^{-5}$. Clearly, the SM CPV, Eq. (4), is not enough to generate the entire observed BAU.

We now make the observation that, if the branching fraction $\text{Br}(B_i^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}})$ in the early Universe was enhanced compared to its present-day value, the SM CPV could be enough to produce the observed BAU. This can be achieved if the mass of $\mathcal{Y}$ was temperature dependent, $M_{\mathcal{Y}}(T)$, such that $\mathcal{Y}$ was lighter during the epoch of mesogenesis than today. In particular, we evoke the existence of some dark sector dynamics which *morphs* the mediator mass $M_{\mathcal{Y}}^i \rightarrow M_{\mathcal{Y}}^f > M_{\mathcal{Y}}^i$ at a temperature $T_{\text{morph}} < T_d \sim 5-80$ MeV. Thus, present-day collider constraints on $\mathcal{Y}$ are maintained, but $\text{Br}(B^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}})$ is

²This could be a scalar field in a multifield inflation scenario, a moduli field, or even a saxion.

³There is no *a priori* reason to assume a specific flavor structure [22,26].

TABLE I. Bounds for operators $\mathcal{O}_{b,u_i d_j} \equiv i\epsilon_{\alpha\beta\gamma} b^\alpha (\bar{d}_j^{c\beta} u_i^\gamma)$ as constrained by present-day collider searches [22]. We quote the maximal value (evaluated at $m_{\psi_B} = 1$ GeV) of this decay rate [21], with coefficients factored out: $\Gamma_0 \equiv \Gamma_B|_{m_{\psi_B}=1 \text{ GeV}} / \mathcal{C}_{b,u_i d_j}^2$.

Operator	$(M_{\mathcal{Y}}^f)_{\min}$ [TeV]	Decay	Γ_0 [GeV ⁵]
$\mathcal{O}_{b,ud}$	$\sim 1.7\sqrt{y_{\psi b} y_{ud}}$	$B_d \rightarrow \bar{\psi}_B n$	$3.5_{\pm 0.4} \times 10^{-5}$
		$B_s \rightarrow \bar{\psi}_B \Lambda$	$\dots$
$\mathcal{O}_{b,us}$	$\sim 1.7\sqrt{y_{\psi b} y_{us}}$	$B_d \rightarrow \bar{\psi}_B \Lambda$	$1.4_{\pm 0.1} \times 10^{-4}$
		$B_s \rightarrow \bar{\psi}_B \Xi^0$	$3.2_{\pm 0.1} \times 10^{-5}$
$\mathcal{O}_{b,cd}$	$\sim 0.9\sqrt{y_{\psi b} y_{cd}}$	$B_d \rightarrow \bar{\psi}_B \Sigma_c^0$	$0.7_{\pm 0.4} \times 10^{-6}$
		$B_s \rightarrow \bar{\psi}_B \Xi_c^0$	$6.6_{\pm 3.3} \times 10^{-7}$
$\mathcal{O}_{b,cs}$	$\sim 0.9\sqrt{y_{\psi b} y_{cs}}$	$B_d \rightarrow \bar{\psi}_B \Xi_c^0$	$4.7_{\pm 2.0} \times 10^{-6}$
		$B_s \rightarrow \bar{\psi}_B \Omega_c$	$5.0_{\pm 3.0} \times 10^{-6}$

TABLE II. Analogous to Table I, for operators with structure: $\mathcal{O}_{d_j, u_i b} \equiv i\epsilon_{\alpha\beta\gamma} d_j^\alpha (\bar{b}^{c\beta} u_i^\gamma)$.

Operator	$(M_{\mathcal{Y}}^f)_{\min}$ [TeV]	Decay	Γ_0 [GeV ⁵]
$\mathcal{O}_{d,ub}$	$\sim 3.8\sqrt{y_{\psi d} y_{ub}}$	$B_d \rightarrow \bar{\psi}_B n$	$3.6_{\pm 0.4} \times 10^{-5}$
		$B_s \rightarrow \bar{\psi}_B \Lambda$	$\dots$
$\mathcal{O}_{s,ub}$	$\sim 2.3\sqrt{y_{\psi s} y_{ub}}$	$B_d \rightarrow \bar{\psi}_B \Lambda$	$1.3_{\pm 0.4} \times 10^{-4}$
		$B_s \rightarrow \bar{\psi}_B \Xi^0$	$2.0_{\pm 0.1} \times 10^{-5}$
$\mathcal{O}_{d,cb}$	$\sim 1.1\sqrt{y_{\psi d} y_{cb}}$	$B_d \rightarrow \bar{\psi}_B \Sigma_c^0$	$8.2_{\pm 0.4} \times 10^{-5}$
		$B_s \rightarrow \bar{\psi}_B \Xi_c^0$	$7.0_{\pm 0.4} \times 10^{-5}$
$\mathcal{O}_{s,cb}$	$\sim 1.1\sqrt{y_{\psi s} y_{cb}}$	$B_d \rightarrow \bar{\psi}_B \Xi_c^0$	$9.7_{\pm 5.0} \times 10^{-5}$
		$B_s \rightarrow \bar{\psi}_B \Omega_c$	$1.3_{\pm 0.6} \times 10^{-4}$

enhanced in the early Universe relative to present day by a factor of $(M_{\mathcal{Y}}^f/M_{\mathcal{Y}}^i)^4$, lowering the requisite CPV to generate the BAU. Given the SM CPV in B^0 -meson oscillations, it is clear from Eq. (3) that $\text{Br}(B^0 \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}) \gtrsim 3\%$ for the SM CPV alone is sufficient to generate the entire BAU. Therefore, a mass shift of no more than $\Delta(M_{\mathcal{Y}}) \sim \mathcal{O}(\text{TeV})$ can generate the BAU with only the SM CPV, while maintaining present-day collider constraints.

Detailed theoretical calculations of decay rates for $B_i \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}$ were performed in [21]. The decay rate goes as $\Gamma(B \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}}) = (y_{u_i d_j} y_{\psi d_k} / M_{\mathcal{Y}})^4 \Gamma_0$, where Γ_0 is a function of particle masses, $\Delta m \equiv m_B - (m_{\psi_B} + m_{\mathcal{B}_{\text{SM}}}) \in [0, 3 \text{ GeV}]$. Maximal values of Γ_0 , when $m_{\psi_B} = 1 \text{ GeV}$, are quoted in Tables I and II. Fixing A_{sl}^i to their SM values and expressing the branching fraction as

$$\text{Br}_{B_i} = \frac{\sum_{\mathcal{B}_{\text{SM}}} \mathcal{C}_i^2 \Gamma_0(B_i \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}})}{(\tau_{B_{d,s}}^{\text{SM}})^{-1} + \sum_{\mathcal{B}_{\text{SM}}} \mathcal{C}_i^2 \Gamma_0(B_i \rightarrow \bar{\psi}_B \mathcal{B}_{\text{SM}})}, \quad (5)$$

Eq. (3) is used to solve for $\mathcal{C}_{d_k, u_i d_j}$ such that the entire BAU is generated for a given operator in Tables I and II. (The SM B meson lifetime is $\tau_{B_{d,s}}^{\text{SM}} \simeq 1.5 \times 10^{-12} \text{ s.}$) Results are shown in Fig. 1 where each colored band represents the needed $M_{\mathcal{Y}}^i$, with fixed Yukawas, such that the SM CPV alone generates the entire BAU. To obtain the requisite mass shift, Fig. 1 can be compared to the bounds on the Wilson coefficients in Tables I and II. In much of the parameter space, a modest mass shift of 500 GeV–1 TeV can lead to successful baryogenesis.

Given that the SM value of A_{sl}^d is negative, B_d^0 decays will decrease the generated asymmetry, as such $3M$ baryogenesis cannot proceed solely from B_d^0 mesons. The relative amounts of B_s and B_d produced in the early Universe depend on the model dependent fragmentation function of Φ . To this end, we consider two cases in Fig. 1: in the left panel we assume only B_s mesons are produced, $\text{Br}(\Phi \rightarrow B_s) = 1$. Since B_d 's are not produced and do not deplete the asymmetry, this case represents the maximal possible enhancement to the early Universe branching fraction. The right panel displays the case where Φ decays produce 50% B_d and B_s mesons; in this case the observed BAU can only be generated for higher values of T_d , roughly above 15–20 MeV depending on the operator—reflecting the effect of coherent B_d oscillations (which peak at temperatures lower than for the B_s system) depleting the asymmetry. In either case, for $T_d \gtrsim 70 \text{ MeV}$, coherent oscillations are significantly suppressed due to electron scattering of the B^0 charge radius, and the baryon production ceases. Solid lines in Fig. 1 represent central values, while shaded regions correspond to a combination of uncertainties from the SM CPV values in Eq. (4), the charge radius of the neutral B mesons (which translates into uncertainties in $\alpha_{s,d}$ [22,26]), and the QCD uncertainties in the branching fraction for each operator [21]. The entire area below each upper curve is allowed for larger values of m_{ψ_B} .

Morphing with dark dynamics. To generate the BAU with only the SM CPV in neutral $B_{s,d}$ meson oscillations, we must facilitate the *morphing* of $\mathcal{Y}$'s mass such that it was light enough during the era of baryon production, but heavy enough ($\sim \text{TeV}$) today to evade collider constraints. As an example, consider a scenario in which $M_{\mathcal{Y}}$ depends on the vacuum expectation value (VEV) of a scalar *morphon* field ϕ . The ϕ VEV changes at a temperature $T_{\text{morph}} \simeq 6\text{--}80 \text{ MeV}$, e.g., due to a delayed phase transition. For this scenario, we use the following morphon scalar potential:

$$V_{\text{scalar}} = m_{\mathcal{Y}_0}^2 |\mathcal{Y}|^2 + y_{\phi \mathcal{Y}} |\mathcal{Y}|^2 \phi + \frac{1}{2} \lambda_{\phi \mathcal{Y}} |\mathcal{Y}|^2 \phi^2 + \frac{1}{4} \lambda (\phi^2 - \phi_0^2)^2 + \epsilon \phi_0 \phi^3. \quad (6)$$

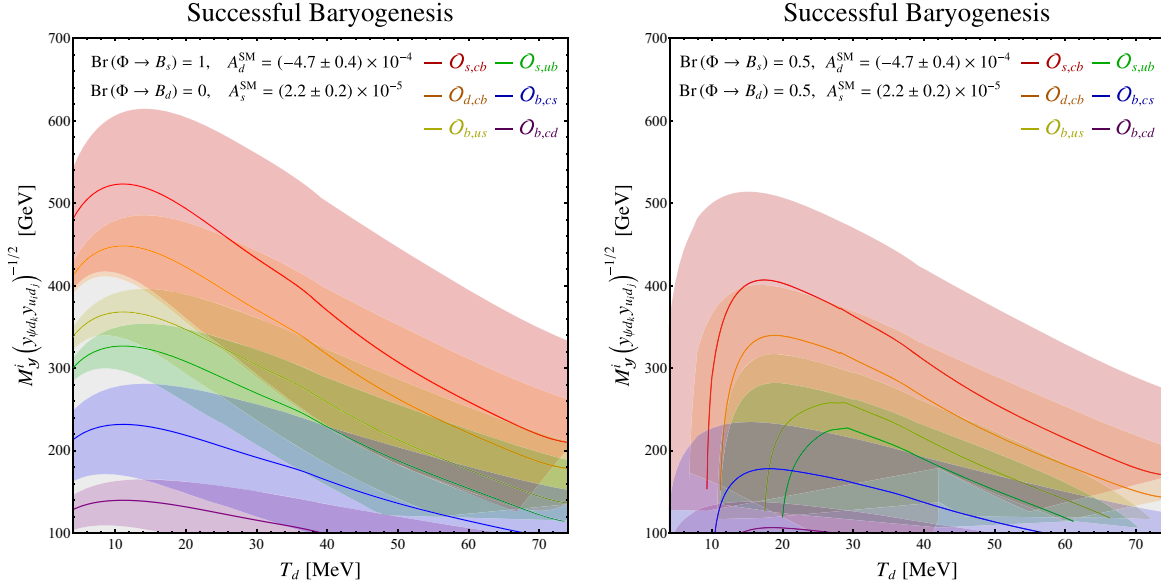


FIG. 1. Requisite initial $\mathcal{Y}$ mass and dark Yukawa couplings, such that the BAU is generated with only the SM CPV. Solid lines correspond to the central value for each operator in Tables I and II. Shaded bands account for uncertainties. The entire parameter space below the upper line for each operator is allowed. We require $M_{\mathcal{Y}}^i > 100$ GeV to ensure that the operator Eq. (1) is well defined. Left: only B_s mesons are produced in the early Universe, i.e., the branching fraction of $\Phi \rightarrow B_s$ is 100%. This corresponds to the maximal possible BAU generation (and smallest requisite $\Delta M_{\mathcal{Y}}$) with only the SM CPV. Right: scenario where $\text{Br}(\Phi \rightarrow B_s) = 0.5 = \text{Br}(\Phi \rightarrow B_d)$.

The field-dependent mass of $\mathcal{Y}$ is

$$M_{\mathcal{Y}}^2(\phi) = m_{\mathcal{Y}_0}^2 + y_{\phi\mathcal{Y}}\phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}}\phi^2. \quad (7)$$

Note that $y_{\phi\mathcal{Y}}$ carries mass dimension one. Following the results displayed in Fig. 1 and the constraints summarized in Tables I and II, we require that $M_{\mathcal{Y}}$ shifts between the false and true ϕ vacua such that

$$M_{\mathcal{Y}}^i = M_{\mathcal{Y}}(v_{\text{false}}) = \mathcal{O}(100 \text{ GeV}), \quad (8a)$$

$$M_{\mathcal{Y}}^f = M_{\mathcal{Y}}(v_{\text{true}}) = \mathcal{O}(\text{TeV}). \quad (8b)$$

For a successful $3M$ baryogenesis, the following general conditions are required of the morphon model: (i) *Nucleation*: The $\mathcal{Y}$ mass shift must occur after the BAU generation, i.e., $T_d > T_{\text{morph}} > T_{\text{BBN}} \sim 5$ MeV. Generically, in order to delay the VEV change significantly below $T \sim \phi_0$, the effective potential for ϕ must have a high barrier between the minima and a small ρ_{vac} , the energy difference between the true and false minimum. (ii) *Percolation*: The Universe must efficiently and completely transit from the false to the true morphon vacuum. (iii) *Avoiding inflation*: The morphon, which remains trapped in a false vacuum until late times, must not dominate the energy density of the Universe triggering a period of inflation during or after the BAU is generated. Avoiding inflation selects morphon potentials with small ρ_{vac} .

In summary, $3M$ baryogenesis favors a fast percolating MeV scale phase transition, with a small ρ_{vac} . While we leave open the possible models for generating such a potential, we present a specific example below.

Example: Domain walls. Consider the benchmark values: $m_{\mathcal{Y}_0} = 624.5$ GeV, $y_{\phi\mathcal{Y}} = -70$ GeV, $\lambda_{\phi\mathcal{Y}} = 0.007$, $\lambda = 1$, $\epsilon = 3 \times 10^{-26}$, and $\phi_0 = 10$ TeV.⁴ The resulting potential and the $M_{\mathcal{Y}}$ shift is shown in Fig. 2. This potential has nearly degenerate minima at $T \simeq 20$ TeV.⁵ If the bias between the true and false vacuum is small enough, see Eq. (A1), the morphon field will fall into patches of true and false minima, forming a network of domain walls (DWs) that eventually annihilate [34–42]. DWs can grow to horizon size if Eq. (A2) is satisfied, separating large patches of the Universe where ϕ has fallen into the false vacuum from large patches in the true vacuum $v_{\text{false/true}} = \pm\phi_0 + \mathcal{O}(\epsilon)$. The mass of $\mathcal{Y}$ is smaller in the false vacuum and larger in the true vacuum, see Fig. 2. Since the BAU is mainly produced in patches where $\mathcal{Y}$ is light, i.e. the false vacuum, we need to overproduce the asymmetry initially. Therefore, for our example, we pick a false vacuum where $M_{\mathcal{Y}} \simeq 200$ GeV (well below the $M_{\mathcal{Y}}$ upper bounds shown in Fig. 1).

⁴It would be interesting to explore UV models in which ϵ can be made technically natural [33].

⁵We take ϵ to be tuned at $T = 0$. This tuning is not spoiled at finite temperature since the counterterms will scale the same way as the $|\mathcal{Y}|^2\phi$ term.

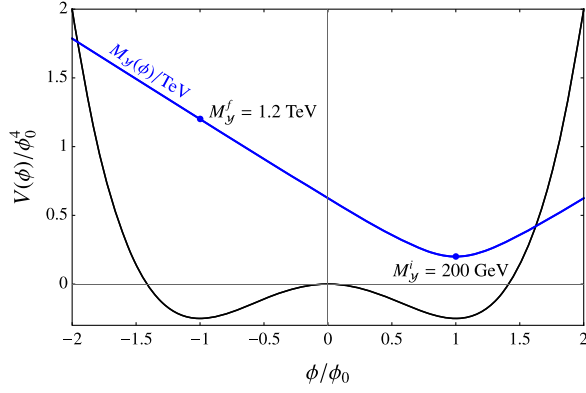


FIG. 2. The morphon potential $V(\phi)$ (black) that shifts the $\mathcal{Y}$ mass from 200 GeV in the false vacuum to 1.2 TeV in the true vacuum. In blue, we plot $M_{\mathcal{Y}}(\phi)$ to demonstrate the mass shift in $\mathcal{Y}$ from the false minimum $v_{\text{false}} = \phi_0 + \mathcal{O}(\epsilon)$ to the (final) true minimum $v_{\text{true}} = -\phi_0 + \mathcal{O}(\epsilon)$.

Finally, we require that the DW network safely disappears. The DWs must annihilate by $T \sim 10$ MeV, sufficiently before BBN, and the DWs must avoid dominating the energy density of the Universe and triggering inflation. Relevant conditions on the evolution of the DW network are summarized in the Appendix. The example shown in Fig. 2 and the parameter space presented in Fig. 3 satisfy all four of the conditions (A1)–(A4) in the Appendix. The DW's form at ϕ_0 (A1) and grow to horizon size (A2); the false vacuum persists until DW annihilation before 10 MeV (A3), and they do not trigger inflation (A4).

The annihilation of the DW network can leave behind a stochastic gravitational wave (GW) background [35,48,49]. We used expressions in Ref. [35] to calculate the GW peak frequency f_{peak} and power spectrum Ω_{GW} evaluated at f_{peak} . The temperature of the DW annihilation, T_{ann} , sets the peak frequency of the signal. This mechanism requires the annihilation temperature for the DWs to be in the small window 10–80 MeV, which translates to a prediction for the peak frequency of the GW signal power spectrum $f_{\text{peak}} \in [1 - 8] \times 10^{-9}$ Hz. Such frequencies are probed by pulsar timing array (PTA) experiments [43,44,46,47]. We show the GW signal for a set of DW models in Fig. 3. The discussed mass shift of $\mathcal{Y}$ can be achieved by taking $y_{\phi\mathcal{Y}} = -70$ GeV, -700 GeV, and -7 TeV for decreasing ϕ_0 values in Fig. 3.

Signals. Violent processes in the early Universe can source GWs. For the morphon scenario, if it happens through a first-order phase transition, the transition of interest will occur at late times and be relatively fast corresponding to small values of the β/H parameter. Such phase transitions are generically expected to yield low frequency GW signals that can be probed with current and future PTAs [43–47,50]. This is expected to be a generic feature of dark dynamics that lead to the requisite morphing.

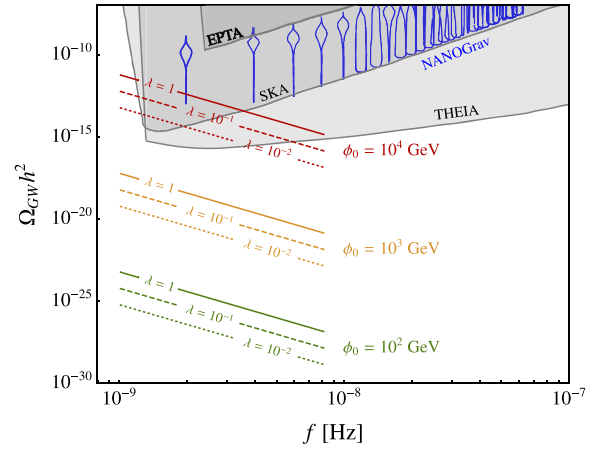


FIG. 3. Each line corresponds to the peak of the gravitational wave power spectrum while scanning over the DW annihilation temperature, T_{ann} , from 10 to 80 MeV (corresponding to f_{peak} from ~ 1 to 8 nHz, respectively) at fixed ϕ_0 and λ . Current and future sensitivity curves are shown for the European Pulsar Timing Array (EPTA) [43], the Square Kilometre Array (SKA) [44], GAIA/THEIA [45] and NanoGrav [46,47].

In the $3M$ baryogenesis, the branching fraction of the rare B meson decays measured at colliders today can be much smaller than the values predicted by B mesogenesis. Accordingly, a measurement $\text{Br} < 10^{-5}$ could be an indication that $3M$ is the mechanism responsible for generating the BAU and dark matter. This will be especially evident if PTAs see a GW peak consistent with morphing dark dynamics. Importantly, signals of the dark dynamics only complement the existing mesogenesis search program. For instance, the dark dynamics do not alter the expected signal of induced proton decay [20].

Future directions. $3M$ baryogenesis generates both the BAU and the dark matter abundance using SM CPV within B meson systems. This demonstrated that *the standard model CPV is, indeed, enough*. $3M$ can be tested through GW signals in conjunction with collider searches already targeting mesogenesis (but with better sensitivity), paving the way to various experimental searches.

While an explicit morphing model (in which DW annihilations lead to GW signals) was presented here, many possibilities remain to be explored. For instance, morphing can be achieved through a first-order dark sector phase transition (delayed through supercooling or through the presence of a trigger field, e.g., [51]). Another possibility is a dark sector with multiple morphon fields, each obtaining a VEV. Alternatively, multiple dark sector fields could lead to finite density effects morphing the dark Yukawas similar to [52]. Care would need to be taken to ensure the number density of morphons does not trigger inflation. Another option would be a dark confining phase transition with a large number of dark quark condensates

contributing to $M_{\mathcal{Y}}$. The possible morphon models and signals will be explored in [33].

Acknowledgments. The research of G. E. is supported by the National Science Foundation (NSF) Grant No. PHY-2210562, by a grant from University of Texas at Austin. S. I. is supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada. R. H. was supported by the Institute for Fundamental Theory at the University of Florida. M. U. is supported by a scholarship from Consejo Nacional de Ciencia Humanidades y Tecnología (CONAHCYT) of Mexico. M. U. also acknowledges the CERN TH Department for hospitality while this research was being carried out.

Appendix: Domain wall evolution and constraints. We require a phase transition to enhance the four-fermion operator that translates the CPV in B -meson oscillations to visible baryon asymmetry. The example presented here proceeds via rolling from a symmetry-preserving minimum into two sets of nearly degenerate minima. One minimum is the false vacuum (small $\mathcal{Y}$ mass) and the other is the true vacuum (large $\mathcal{Y}$ mass). A domain wall network forms between patches of the Universe with different ϕ VEVs.

To ensure our DW-forming potential accomplishes baryogenesis while evading constraints, we impose requirements on the potential parameters, following the analysis of [35]. First, the two minima must be degenerate enough to reach a percolation threshold and form a DW network initially. Second, we require large regions of the Universe to be in the false vacuum during baryogenesis, meaning the walls must reach horizon size. Third, the DW network must disappear at $T \geq 10$ MeV to avoid spoiling BBN observations. Finally, the energy stored in the domain walls must not dominate the energy density of the Universe and trigger inflation.

Two competing parameters determine the evolution of the DW network: the vacuum pressure and the surface pressure of the walls. The vacuum pressure $p_{\text{vac}} = \epsilon \phi_0^4$ encodes the preference for the true vacuum over the false vacuum, pushing regions of true vacuum to expand and

accelerating the walls until they annihilate. The surface pressure is $p_T = \sigma/R$, where $\sigma = (2\sqrt{2}/3)\sqrt{\lambda}\phi_0^3$ is the surface tension and R is the average radius of the curvature of the wall. Roughly, the surface pressure decreases when the walls grow and flatten out. The walls annihilate when $p_{\text{vac}} > p_T$. Requiring the percolation and growth of DWs will put an upper bound on ϵ , and requiring the disappearance of DWs will put a lower bound.

We summarize these constraints as follows:

- (1) DWs percolate [34,41]:

$$\epsilon \lesssim 0.2\lambda. \quad (\text{A1})$$

- (2) DWs grow to horizon size, $p_{\text{vac}} < p_T$, when $R(T) \sim 1/2H(T)$:

$$\epsilon < \frac{2\sqrt{2}}{3} \sqrt{\frac{8\pi^3 g_{\text{eff}}}{90}} \frac{T^2}{M_{\text{Pl}} \phi_0} \sqrt{\lambda} \Big|_{T=T_c=2\phi_0}. \quad (\text{A2})$$

- (3) DWs annihilate, $p_{\text{vac}} > p_T$, at 10 MeV:

$$\epsilon > \frac{2\sqrt{2}}{3} \sqrt{\frac{8\pi^3 g_{\text{eff}}}{90}} \frac{T^2}{M_{\text{Pl}} \phi_0} \sqrt{\lambda} \Big|_{T=10 \text{ MeV}}. \quad (\text{A3})$$

- (4) DWs annihilate before they trigger inflation:

$$\epsilon > \left(\frac{4}{3}\right)^3 \frac{4\pi\lambda\phi_0^2}{M_{\text{Pl}}^2}, \quad (\text{A4})$$

where g_{eff} is the effective active number of degrees of freedom, M_{Pl} is the Planck mass, and T_c is the critical temperature or domain wall formation, estimated to be $T_c \sim 2\phi_0$. Equations (A2) and (A3) have the same form because once the walls reach horizon size, they enter a scaling regime and follow $R \sim 1/2H$. To arrive at Eq. (A4), we again follow Ref. [35]. The walls trigger inflation when the energy density stored in the walls, $\rho_w \sim \sigma/R$, exceeds the critical density $\rho_c = 3M_{\text{Pl}}^2/32\pi t^2$. The time when inflation would begin must be larger than the time when the walls annihilate, $t_{\text{ann}} \sim \sigma/\epsilon\phi_0^4$, yielding Eq. (A4).

[1] A. D. Sakharov, *Pis'ma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967).
[2] C. Jarlskog, *Phys. Rev. Lett.* **55**, 1039 (1985).
[3] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pene, *Mod. Phys. Lett. A* **9**, 795 (1994).
[4] M. B. Gavela, M. Lozano, J. Orloff, and O. Pene, *Nucl. Phys. B* **430**, 345 (1994).
[5] M. B. Gavela, P. Hernandez, J. Orloff, O. Pene, and C. Quimbay, *Nucl. Phys. B* **430**, 382 (1994).

[6] P. Huet, in *1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94)* (World Scientific Pub Co Inc., Singapore, 1994), pp. 1377–1380, <https://inspirehep.net/conferences/968643?ui-citation-summary=true>.
[7] P. Huet and E. Sather, *Phys. Rev. D* **51**, 379 (1995).
[8] M. Berkooz, Y. Nir, and T. Volansky, *Phys. Rev. Lett.* **93**, 051301 (2004).

- [9] G. Perez and T. Volansky, *Phys. Rev. D* **72**, 103522 (2005).
- [10] S. Bruggisser, T. Konstandin, and G. Servant, *J. Cosmol. Astropart. Phys.* **11** (2017) 034.
- [11] I. Baldes, T. Konstandin, and G. Servant, *J. High Energy Phys.* **12** (2016) 073.
- [12] B. von Harling and G. Servant, *J. High Energy Phys.* **05** (2017) 077.
- [13] S. Bruggisser, B. von Harling, O. Matsedonskyi, and G. Servant, *Phys. Rev. Lett.* **121**, 131801 (2018).
- [14] I. Baldes, T. Konstandin, and G. Servant, *Phys. Lett. B* **786**, 373 (2018).
- [15] S. Bruggisser, B. von Harling, O. Matsedonskyi, and G. Servant, *J. High Energy Phys.* **12** (2018) 099.
- [16] K. Fuyuto, W.-S. Hou, and E. Senaha, *Phys. Lett. B* **776**, 402 (2018).
- [17] F. Elahi, G. Elor, and R. McGehee, *Phys. Rev. D* **105**, 055024 (2022).
- [18] G. Elor and R. McGehee, *Phys. Rev. D* **103**, 035005 (2021).
- [19] G. Elor, M. Escudero, and A. Nelson, *Phys. Rev. D* **99**, 035031 (2019).
- [20] J. Berger and G. Elor, *Phys. Rev. Lett.* **132**, 081002 (2024).
- [21] G. Elor and A. W. M. Guerrero, *J. High Energy Phys.* **02** (2023) 100.
- [22] G. Alonso-Álvarez, G. Elor, and M. Escudero, *Phys. Rev. D* **104**, 035028 (2021).
- [23] M. Borsato *et al.*, *Rep. Prog. Phys.* **85**, 024201 (2022).
- [24] G. Alonso-Álvarez, G. Elor, M. Escudero, B. Fornal, B. Grinstein, and J. Martin Camalich, *Phys. Rev. D* **105**, 115005 (2022).
- [25] A. Lenz and G. Tetlalmatzi-Xolocotzi, *J. High Energy Phys.* **07** (2020) 177.
- [26] G. Alonso-Álvarez, G. Elor, A. E. Nelson, and H. Xiao, *J. High Energy Phys.* **03** (2020) 046.
- [27] P. A. R. Ade *et al.* (Planck Collaboration), *Astron. Astrophys.* **594**, A13 (2016).
- [28] N. Aghanim *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A6 (2020).
- [29] R. H. Cyburt, B. D. Fields, K. A. Olive, and T.-H. Yeh, *Rev. Mod. Phys.* **88**, 015004 (2016).
- [30] M. Tanabashi *et al.* (Particle Data Group), *Phys. Rev. D* **98**, 030001 (2018).
- [31] C. Hadjivasiliou *et al.* (Belle Collaboration), *Phys. Rev. D* **105**, L051101 (2022).
- [32] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **107**, 092001 (2023).
- [33] G. Elor, R. Houtz, S. Ipek, and M. Ulloa (to be published).
- [34] G. B. Gelmini, M. Gleiser, and E. W. Kolb, *Phys. Rev. D* **39**, 1558 (1989).
- [35] G. B. Gelmini, S. Pascoli, E. Vitagliano, and Y.-L. Zhou, *J. Cosmol. Astropart. Phys.* **02** (2021) 032.
- [36] J. Preskill, S. P. Trivedi, F. Wilczek, and M. B. Wise, *Nucl. Phys. B* **363**, 207 (1991).
- [37] A. Vilenkin, *Phys. Rev. D* **23**, 852 (1981).
- [38] M. Gleiser and R. Roberts, *Phys. Rev. Lett.* **81**, 5497 (1998).
- [39] T. Hiramatsu, M. Kawasaki, and K. Saikawa, *J. Cosmol. Astropart. Phys.* **05** (2010) 032.
- [40] M. Kawasaki and K. Saikawa, *J. Cosmol. Astropart. Phys.* **09** (2011) 008.
- [41] D. Stauffer, *Phys. Rep.* **54**, 1 (1979).
- [42] T. Hiramatsu, M. Kawasaki, and K. Saikawa, *J. Cosmol. Astropart. Phys.* **02** (2014) 031.
- [43] L. Lentati *et al.* (EPTA Collaboration), *Mon. Not. R. Astron. Soc.* **453**, 2576 (2015).
- [44] G. Janssen *et al.*, *Proc. Sci. AASKA14* (2015) 037 [arXiv:1501.00127].
- [45] J. Garcia-Bellido, H. Murayama, and G. White, *J. Cosmol. Astropart. Phys.* **12** (2021) 023.
- [46] G. Agazie *et al.* (NANOGrav Collaboration), *Astrophys. J. Lett.* **951**, L8 (2023).
- [47] A. Afzal *et al.* (NANOGrav Collaboration), *Astrophys. J. Lett.* **951**, L11 (2023); **971**, L27(E) (2024).
- [48] F. Riva, *Phys. Lett. B* **690**, 443 (2010).
- [49] S. Antusch and D. Nolde, *J. Cosmol. Astropart. Phys.* **10** (2013) 028.
- [50] P. Schwaller, *Phys. Rev. Lett.* **115**, 181101 (2015).
- [51] F. Niedermann and M. S. Sloth, *The Hubble Constant Tension* (Springer, Singapore, 2024).
- [52] R. Fardon, A. E. Nelson, and N. Weiner, *J. Cosmol. Astropart. Phys.* **10** (2004) 005.