Is the SM CP Violation ever enough to produce the BAU?

Mesogenesis: A baryogenesis mechanism

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Arxiv:2408.12647

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Baryogenesis → Mesogenesis

Baryogenesis is the general framework used to explain the BAU.

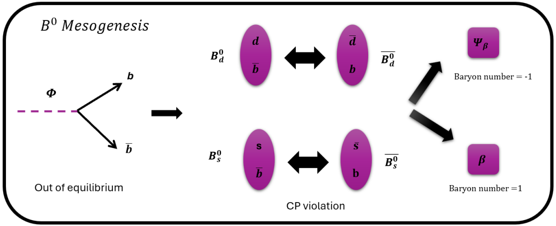
- **Baryonic density - Entropy ratio:** $Y_{\mathcal{B}} \approx \frac{(n_B - n_{\bar{B}})}{s} = 8.7 \times 10^{-11}$

Sakharov established the three building blocks for it.

1. **Baryon number violation:** Anomalously violated in the SM during weak interactions, producing an excess of baryons over antibaryons.
2. **C and CP violation:** Exists in the CKM matrix, but insufficient to explain the BAU.
3. **Departure from thermal equilibrium:** No SM process can achieve 1 and 2 in equilibrium ⇒ requires BSM physics.

Mesogenesis

- **Satisfies Sakharov conditions.**
- **Explains Dark Matter relic abundance:** $\Omega_c h^2 = 0.120 \pm 0.001$
- **Advantage:** Operates at the MeV scale, accessible to colliders and experiments.
- **Baryon number conservation:** Conserves globally, but breaks it in the visible sector.



Baryon Asymmetry of the Universe

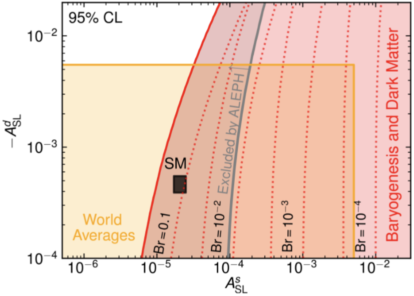
$$\boxed{Y_{\mathcal{B}} \approx \frac{(n_B - n_{\bar{B}})}{n_\gamma} = 8.7 \times 10^{-11} \rightarrow Y_{\mathcal{B}} \approx 10^{-5} \sum_{i=d,s} Br(B_i^0 \rightarrow \bar{\psi}_{\mathcal{B}} \mathcal{B}_{SM}) A_{sl}^i \alpha_i(T_d)}$$

Semileptonic Asymmetry:

$$A_{sl}^i \equiv \frac{\Gamma(\bar{B}_i^0 \rightarrow B_i^0 \rightarrow f) - \Gamma(B_i^0 \rightarrow \bar{B}_i^0 \rightarrow \bar{f})}{\Gamma(\bar{B}_i^0 \rightarrow B_i^0 \rightarrow f) + \Gamma(B_i^0 \rightarrow \bar{B}_i^0 \rightarrow \bar{f})}$$

Standard Model prediction Values:

$A_{sl}^{d,SM} = (-4.7 \pm 0.4) \times 10^{-4}$, $A_{sl}^{s,SM} = (2.1 \pm 0.2) \times 10^{-5}$



Plot taken from: Gonzalo Alonso, Gilly Elor, and Miguel Escudero. Arxiv: 2101.02706

The **thermal correction** functions arise from decoherence due to scattering off the plasma such as the severe suppression of the Y_B at high temperatures.

Mesogenesis Mechanism

$$\boxed{\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j}\, \mathcal{Y}^* \, \bar{u}_{iR} d_{jR}^c - \sum_k y_{\psi d_k}\, \bar{\psi}_{\mathcal{B}} \mathcal{Y} d_{kR}^c + h.c.}$$

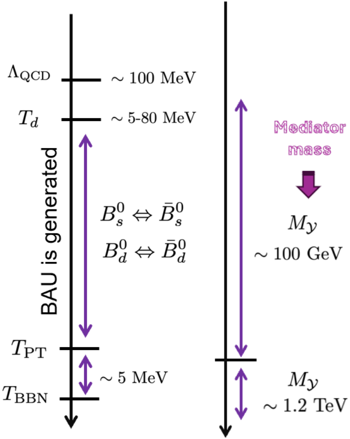
4-Fermi operator: $\mathcal{O}_{d_k, u_i d_j} = \mathcal{C}_{d_k, u_i d_j}\, \epsilon_{\alpha\beta\gamma} (\bar{\psi}_{\mathcal{B}} d_k^\alpha)(\bar{d}_j^{c\beta} u_i^\gamma)$

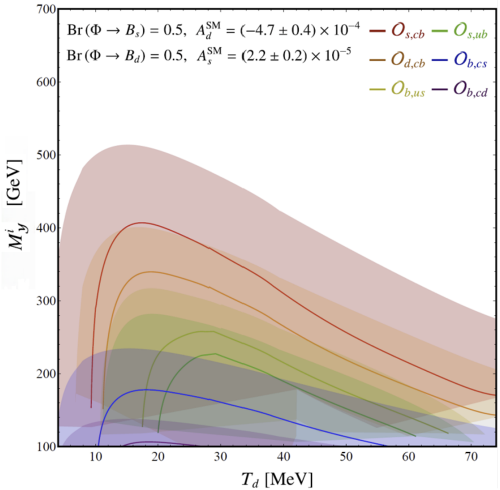
Wilson Coefficient: $\mathcal{C}_{d_k, u_i d_j} = \dfrac{y_{\psi d_k} y_{u_i d_j}}{M_{\mathcal{Y}}^2}$

3M mechanism → Successful Baryogenesis

Mesogenesis with a Morphing Mediator

Enhancing the $Br(B \to \psi_B B_{SM}) \approx \frac{1}{(\mathcal{M}_{\mathcal{Y}})^4}$ produces the required $Y_B = 8.7 \times 10^{-11}$.





Decay rate split equally: 50% to B_s and B_d channels.

Domain Walls and Gravitational Wave Signature

The volume pressure due to the energy difference between the two vacua $p_V = V_{bias} = \epsilon_b \phi_0^4$ accelerates the walls towards the false vacuum, converting false vacuum into true vacuum.

$$V = m_{Y_0}^2 |\mathcal{Y}|^2 + y_{\phi\mathcal{Y}} |\mathcal{Y}|^2 \phi + \frac{1}{2} \lambda_{\phi\mathcal{Y}} |\mathcal{Y}|^2 \phi^2 + V(\phi_0)$$

$$V(\phi_0) = \tfrac{1}{4}\lambda(\phi^2 - \phi_0^2)^2 + \epsilon \phi_0 \phi^3$$

$$M_{\mathcal{Y}}^2(\phi) = m_{Y_0}^2 + y_{\phi\mathcal{Y}}\phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}}\phi^2,$$

ϕ is the morphon field, responsible for changing $M_{\mathcal{Y}}$

$$M_{\mathcal{Y}}^i(v_{\text{false}}) = \mathcal{O}(100\,\text{GeV}) \to M_{\mathcal{Y}}^f(v_{\text{true}}) = \mathcal{O}(\text{TeV})$$

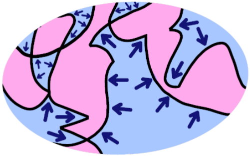
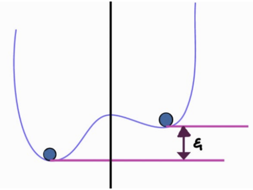
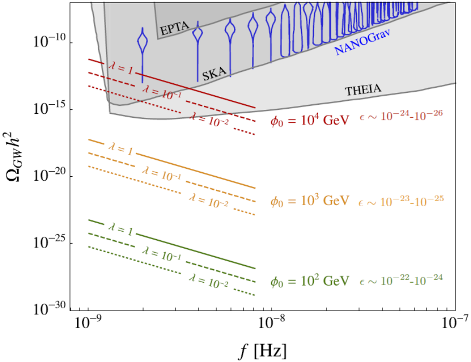


Figure kindly provided by Rachel Houtz.



$x-axis$: ϕ field values,
$y-axis$: $V(\phi)$ potential



Conclusions

Achieving the BAU with only the SM CPV remains an open problem in physics

Mesogenesis with a Morphing Mediator achieves:

  - Generating CP violation solely within the SM framework at the MeV scale.
  - Dark Matter production consistent with the relic density.
  - 3M mechanism achieves BAU via SM CPV

- **Example Scenario:** Domain Walls
- **Signature:** Gravitational Waves

Next Steps:

- Address initial assumptions on the mechanism
  - Sufficient B^0–$\bar{B}^0$ oscillations before decoherence to allow CP violation to generate baryon asymmetry
  - Scattering of B mesons with the thermal plasma
- Explore the broad parameter space in the potential:
  - For DWs and tunneling scenario. **Goal:** Achieve a more natural phase transition.

Thank you!

Backup slides

Composition and History of the Universe

Standard cosmology describes a born universe with equal parts of matter and antimatter. **Observations** inferred from the **CMB** indicate an asymmetry:

- **Baryonic density - Entropy ratio:** $Y_{\mathcal{B}} \approx \frac{(n_B - n_{\bar{B}})}{s} = 8.7 \times 10^{-11}$

A hot **Big Bang** governed only by SM physics leads to a Universe with equal parts of matter and antimatter. Requiring new physics to **explain** the observed **asymmetry**.

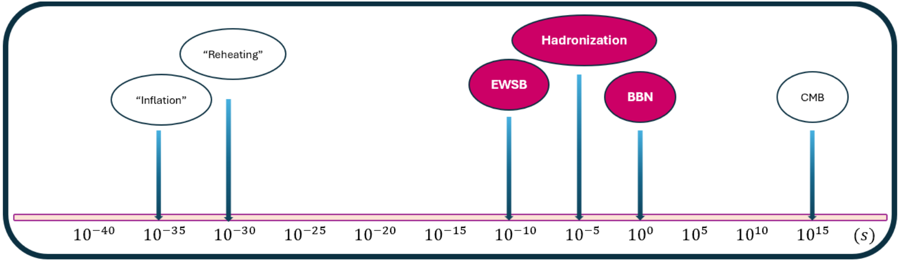


Figure: Cosmic timeline illustrating the major eras in the universe's history.

The model

The BAU is generated using only the CP Violation present in the Standard Model by enhancing the branching fraction $Br(B_i^0 \to \bar{\psi}_{\mathcal{B}} \mathcal{B}_{SM})$ of the decay rates of neutral B mesons in the early Universe.

The model is described by the following Lagrangian:

$$\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^* \bar{u}_{iR} d^c_{jR} - \sum_{k} y_{\psi d_k} \bar{\psi}_{\mathcal{B}} \mathcal{Y} d^c_{kR} + h.c.$$

4-fermi effective operator
$\mathcal{O}_{d_k,u_i d_j} = \mathcal{C}_{d_k,u_i d_j} \epsilon_{\alpha\beta\gamma} (\bar{\psi}_{\mathcal{B}} d_k^{\alpha})(\bar{d}_j^{c\beta} u_i^{\gamma})$
Wilson Coefficient and Branching Ratio
$\mathcal{C}_{d_k,u_i d_j} \equiv \frac{y_{\psi d_k} y_{u_i d_j}}{M^2_{\mathcal{Y}}}, \quad Br \approx \left(\frac{1}{M_{\mathcal{Y}}}\right)^4$

Field	Spin	Q_{EM}	Baryon #	Mass
Φ	0	0	0	11–100 GeV
$\mathcal{Y}$	0	$-\frac{1}{3}$	$-\frac{2}{3}$	$\mathcal{O}(\mathrm{TeV})$
ψ	$\frac{1}{2}$	0	-1	$\mathcal{O}(\mathrm{GeV})$

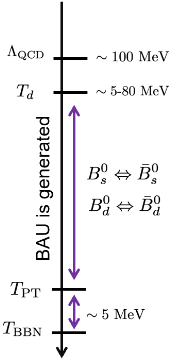
Mesogenesis with a Morphing Mediator (3M)

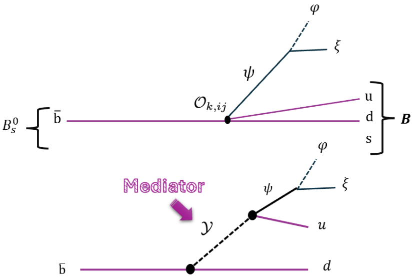
$$\boxed{\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j}\,\mathcal{Y}^*\,\bar{u}_{iR} d^c_{jR} - \sum_{k} y_{\psi d_k}\,\bar{\psi}_{\mathcal{B}}\mathcal{Y} d^c_{kR} + h.c.}$$

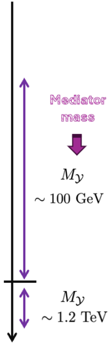
4-Fermi Operator: $\mathcal{O}_{d_k,u_i d_j} = \mathcal{C}_{d_k,u_i d_j}\,\epsilon_{\alpha\beta\gamma}(\bar{\psi}_{\mathcal{B}} d_k^{\alpha})(\bar{d}_j^{c\beta} u_i^{\gamma})$

Wilson Coefficient: $\mathcal{C}_{d_k,u_i d_j} = \dfrac{y_{\psi d_k} y_{u_i d_j}}{M^2_{\mathcal{Y}}}$

Enhancing $Br(B \to \psi_B B_{SM}) \approx \dfrac{1}{(\mathcal{M}_{\mathcal{Y}})^4}$





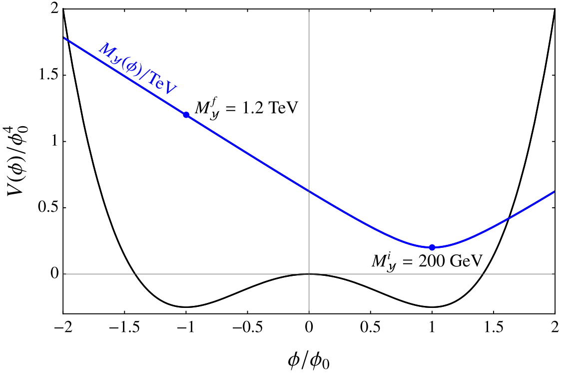


Domain Walls

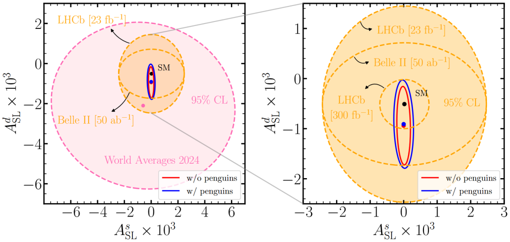
The scalar potential is given by:

$$V(\phi) = \frac{1}{4}\lambda(\phi^2 - \phi_0^2)^2 + \epsilon\phi_0\phi^3$$

- The real **morphon field** undergoes approximate Z_2 **symmetry breaking.**
- Results in nearly degenerate minima.
- Regions of the universe may settle into different minima, forming **Domain Walls**.
- **Domain wall** network expands and eventually **collapses** before Big Bang Nucleosynthesis (BBN).



B-Mesogenesis in Tension



(a) Considering SM penguin contributions.
Plot lifted from: Carlos Miro, Miguel Escudero, and Miguel Nebot. Arxiv: 2410.13936.

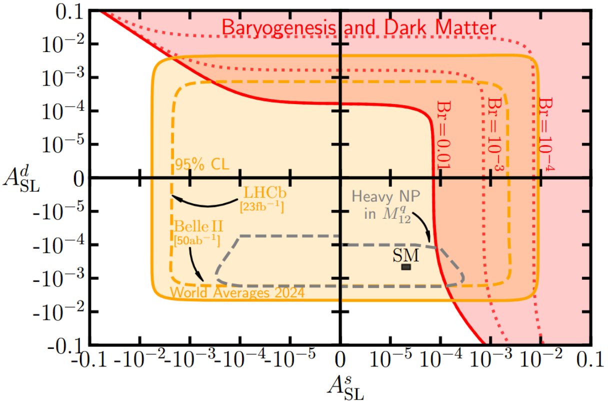
$$
\begin{aligned}
\delta A_{\rm SL}^s &= 10\times 10^{-4} && [\text{LHCb}\,(23\,\text{fb}^{-1})-2025]\,,\\
\delta A_{\rm SL}^s &= 3\times 10^{-4} && [\text{LHCb}\,(300\,\text{fb}^{-1})-2040]\,,\\
\delta A_{\rm SL}^d &= 8\times 10^{-4} && [\text{LHCb}\,(23\,\text{fb}^{-1})-2025]\,,\\
\delta A_{\rm SL}^d &= 2\times 10^{-4} && [\text{LHCb}\,(300\,\text{fb}^{-1})-2040]\,,\\
\delta A_{\rm SL}^d &= 5\times 10^{-4} && [\text{Belle II}\,(50\,\text{ab}^{-1})-2035]\,,
\end{aligned}
$$

(b) Expected sensitivities.
Projected sensitivities for the semileptonic asymmetries from LHCb and Belle *II*.

B-Mesogenesis in Tension

Adding BSM physics to B meson neutral mixing via:

- Heavy new physics contributions to M_{12}
- Up-type and down-type vector-like quarks ⇒ non-unitary CKM matrix
- Decay width mixings in Γ_q

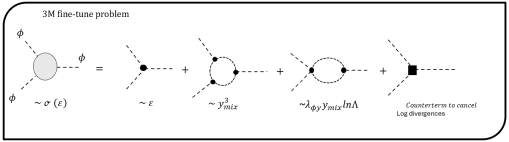


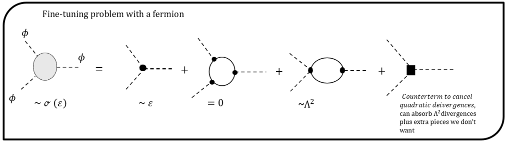
Plot lifted from: Carlos Miro, Miguel Escudero, and Miguel Nebot. Arxiv: 2410.13936

Future Directions: Fine-Tuning in 3M

- Arises when introducing ϕ_0, the morphon field.
- The tuning occurs due to the comparison between the size of the $\epsilon\phi_0\phi^3$ term and the $y_{\phi y}$, $\lambda_{\phi y}$ couplings.
- Using counterterms to ensure the bias ϵ remains at 10^{-15} to 10^{-26}.

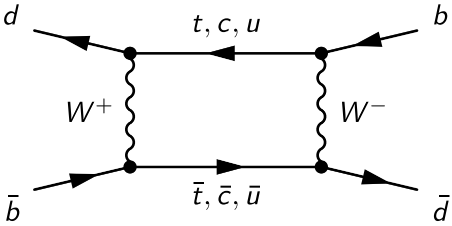
This way we achieve to maintain a cubic interaction (ϕ^3) at the loop level. **The fine tuning is as severe as the SM Higgs mass.**

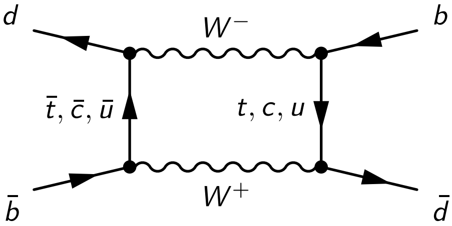




Box diagrams

SM box diagrams mediating neutral meson oscillations $B_d - \bar{B}_d$ mixing:





Scalar, Radiation, Hubble:

$$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +\Gamma_\Phi m_\Phi n_\Phi$$

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

Dark Matter:

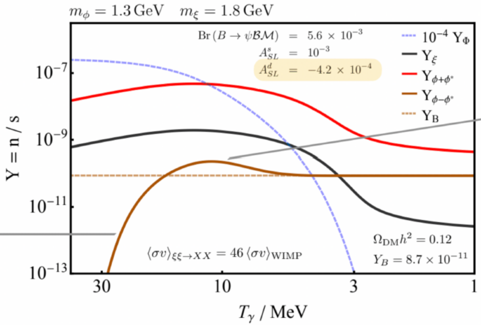
$$\frac{dn_{\phi+\phi^*}}{dt} + 3\,H\,n_{\phi+\phi^*} = 2\,\Gamma_\Phi^B\,n_\Phi - 2\,\langle\sigma v\rangle_\phi\left(n_{\phi+\phi^*}^2 - n_{{\rm eq},\,\phi+\phi^*}^2\right)$$

Baryon Asymmetry:

$$\frac{dn_{\phi-\phi^*}}{dt} + 3Hn_{\phi-\phi^*} = 2\Gamma_\Phi^B \sum_q {\rm Br}\left(\bar b \to B_q^0\right) A_{\rm SL}^q f_{\rm deco}^q n_\Phi$$

$T_{B_s} \lesssim 20\,{\rm MeV}$

Coherent Bs oscillations start to produce an asymmetry


$m_\phi = 1.3\,{\rm GeV}$ $m_\xi = 1.8\,{\rm GeV}$

$T_{B_d} \lesssim 10\,{\rm MeV}$

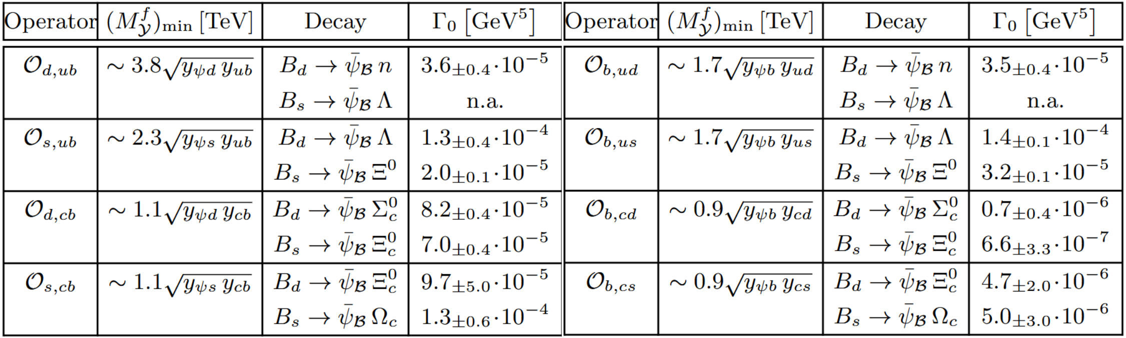
Coherent Bd oscillations start to deplete the asymmetry

Need a net positive charge asymmetry

G. Elor

Slide belongs to G. Elor

Constraints on Branching fraction channels



Operator	$(M^f_{\mathcal{Y}})_{\rm min}$ [TeV]	Decay	Γ_0 [GeV^5]	Operator	$(M^f_{\mathcal{Y}})_{\rm min}$ [TeV]	Decay	Γ_0 [GeV^5]
$\mathcal{O}_{d,ub}$	$\sim 3.8\sqrt{y_{\psi d}\, y_{ub}}$	$B_d \to \bar\psi_{\mathcal{B}}\, n$	$3.6_{\pm 0.4}\cdot 10^{-5}$	$\mathcal{O}_{b,ud}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{ud}}$	$B_d \to \bar\psi_{\mathcal{B}}\, n$	$3.5_{\pm 0.4}\cdot 10^{-5}$
		$B_s \to \bar\psi_{\mathcal{B}}\, \Lambda$	n.a.			$B_s \to \bar\psi_{\mathcal{B}}\, \Lambda$	n.a.
$\mathcal{O}_{s,ub}$	$\sim 2.3\sqrt{y_{\psi s}\, y_{ub}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Lambda$	$1.3_{\pm 0.4}\cdot 10^{-4}$	$\mathcal{O}_{b,us}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{us}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Lambda$	$1.4_{\pm 0.1}\cdot 10^{-4}$
		$B_s \to \bar\psi_{\mathcal{B}}\, \Xi^0$	$2.0_{\pm 0.1}\cdot 10^{-5}$			$B_s \to \bar\psi_{\mathcal{B}}\, \Xi^0$	$3.2_{\pm 0.1}\cdot 10^{-5}$
$\mathcal{O}_{d,cb}$	$\sim 1.1\sqrt{y_{\psi d}\, y_{cb}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Sigma_c^0$	$8.2_{\pm 0.4}\cdot 10^{-5}$	$\mathcal{O}_{b,cd}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cd}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Sigma_c^0$	$0.7_{\pm 0.4}\cdot 10^{-6}$
		$B_s \to \bar\psi_{\mathcal{B}}\, \Xi_c^0$	$7.0_{\pm 0.4}\cdot 10^{-5}$			$B_s \to \bar\psi_{\mathcal{B}}\, \Xi_c^0$	$6.6_{\pm 3.3}\cdot 10^{-7}$
$\mathcal{O}_{s,cb}$	$\sim 1.1\sqrt{y_{\psi s}\, y_{cb}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Xi_c^0$	$9.7_{\pm 5.0}\cdot 10^{-5}$	$\mathcal{O}_{b,cs}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cs}}$	$B_d \to \bar\psi_{\mathcal{B}}\, \Xi_c^0$	$4.7_{\pm 2.0}\cdot 10^{-6}$
		$B_s \to \bar\psi_{\mathcal{B}}\, \Omega_c$	$1.3_{\pm 0.6}\cdot 10^{-4}$			$B_s \to \bar\psi_{\mathcal{B}}\, \Omega_c$	$5.0_{\pm 3.0}\cdot 10^{-6}$

Conditions for Successful Transition

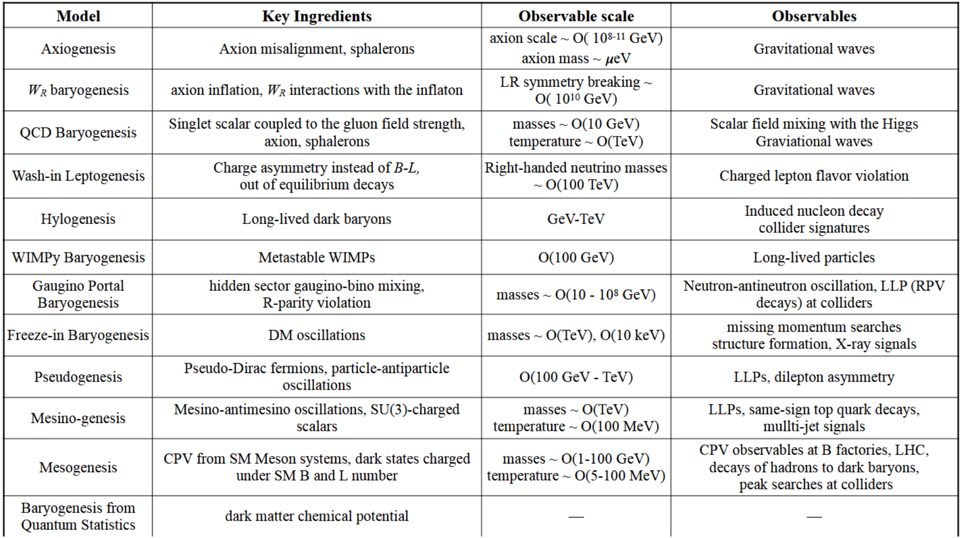
- **Nucleation:** - The mass change of $\mathcal{Y}$ must occur after the BAU is generated, requiring: $T_d > T_{PT} > T_{\mathrm{BBN}} \approx 5\,\mathrm{MeV}$. - To delay the mass shift, the effective potential of ϕ must: - Have a high barrier between minima. - Exhibit a small vacuum energy difference, ρ_{vacuum}, between the true and false vacua.
- **Percolation:** - The Universe must fully transition from the false vacuum to the true morphon vacuum within the available time before the false vacuum dominates.
- **Avoiding Inflation:** - The false vacuum's energy must not dominate the Universe's energy density. - This requires a morphon potential with minimal ρ_{vacuum} to prevent inflation-like behavior.

Domain wall constraints

To ensure this scenario aligns with the physics described, we must constrain the parameter space of the potential. The constraints applied to the potential are:

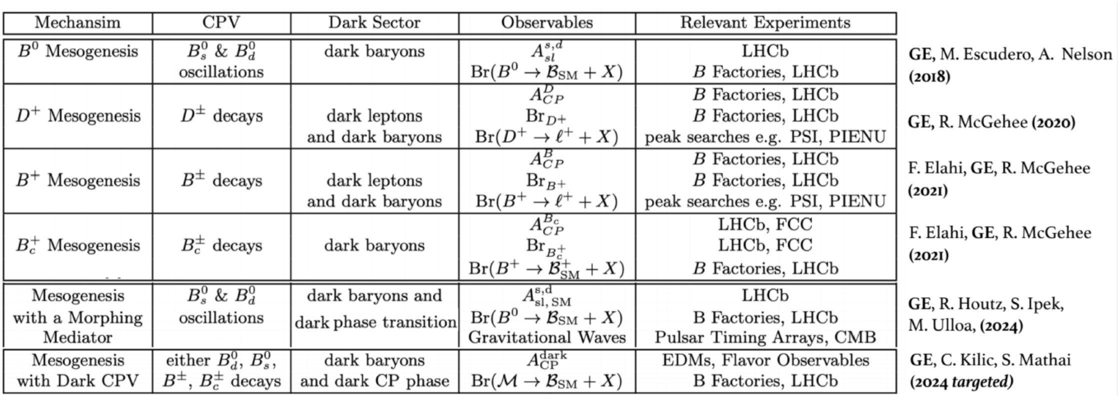
$\epsilon \lesssim 0.2\lambda$	DWs percolate
$\epsilon < \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{eff}}{90}}\frac{T^2}{M_{pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\vert_{T=T_c=2\phi_0}$	DWs grow to horizon size
$\epsilon > \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{eff}}{90}}\frac{T^2}{M_{pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\vert_{T=10\,\mathrm{MeV}}$	DWs annihilate, $p_{\mathrm{vac}} > p_T$ at 10 MeV
$\epsilon > \left(\frac{4}{3}\right)^3 \frac{4\pi\lambda\phi_0^2}{M_{pl}^2}$	DWs annihilate before they trigger inflation ,

Some mechanisms of Baryogenesis



Model	Key Ingredients	Observable scale	Observables
Axiogenesis	Axion misalignment, sphalerons	axion scale ~ O($10^{8\text{-}11}$ GeV) axion mass ~ μeV	Gravitational waves
W_R baryogenesis	axion inflation, W_R interactions with the inflaton	LR symmetry breaking ~ O(10^{10} GeV)	Gravitational waves
QCD Baryogenesis	Singlet scalar coupled to the gluon field strength, axion, sphalerons	masses ~ O(10 GeV) temperature ~ O(TeV)	Scalar field mixing with the Higgs Graviational waves
Wash-in Leptogenesis	Charge asymmetry instead of *B-L*, out of equilibrium decays	Right-handed neutrino masses ~ O(100 TeV)	Charged lepton flavor violation
Hylogenesis	Long-lived dark baryons	GeV-TeV	Induced nucleon decay collider signatures
WIMPy Baryogenesis	Metastable WIMPs	O(100 GeV)	Long-lived particles
Gaugino Portal Baryogenesis	hidden sector gaugino-bino mixing, R-parity violation	masses ~ O(10 - 10^8 GeV)	Neutron-antineutron oscillation, LLP (RPV decays) at colliders
Freeze-in Baryogenesis	DM oscillations	masses ~ O(TeV), O(10 keV)	missing momentum searches structure formation, X-ray signals
Pseudogenesis	Pseudo-Dirac fermions, particle-antiparticle oscillations	O(100 GeV - TeV)	LLPs, dilepton asymmetry
Mesino-genesis	Mesino-antimesino oscillations, SU(3)-charged scalars	masses ~ O(TeV) temperature ~ O(100 MeV)	LLPs, same-sign top quark decays, mullti-jet signals
Mesogenesis	CPV from SM Meson systems, dark states charged under SM B and L number	masses ~ O(1-100 GeV) temperature ~ O(5-100 MeV)	CPV observables at B factories, LHC, decays of hadrons to dark baryons, peak searches at colliders
Baryogenesis from Quantum Statistics	dark matter chemical potential	—	—

Mesogenesis mechanisms proposed to date



Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\mathrm{Br}(B^0 \to \mathcal{B}_{\mathrm{SM}} + X)$	LHCb B Factories, LHCb	**GE**, M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^{D} Br_{D+} $\mathrm{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE**, R. McGehee **(2020)**
B^+ Mesogenesis	$B^\pm$ decays	dark leptons and dark baryons	A_{CP}^{B} Br_{B+} $\mathrm{Br}(B^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	F. Elahi, **GE**, R. McGehee **(2021)**
B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\mathrm{Br}_{B_c^+}$ $\mathrm{Br}(B^+ \to \mathcal{B}_{\mathrm{SM}}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE**, R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\mathrm{sl,\,SM}}^{\mathrm{s,d}}$ $\mathrm{Br}(B^0 \to \mathcal{B}_{\mathrm{SM}} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE**, R. Houtz, S. Ipek, M. Ulloa, **(2024)**
Mesogenesis with Dark CPV	either B_d^0, B_s^0, $B^\pm$, $B_c^\pm$ decays	dark baryons and dark CP phase	$A_{\mathrm{CP}}^{\mathrm{dark}}$ $\mathrm{Br}(\mathcal{M} \to \mathcal{B}_{\mathrm{SM}} + X)$	EDMs, Flavor Observables B Factories, LHCb	**GE**, C. Kilic, S. Mathai ***(2024 targeted)***