

Nikhef

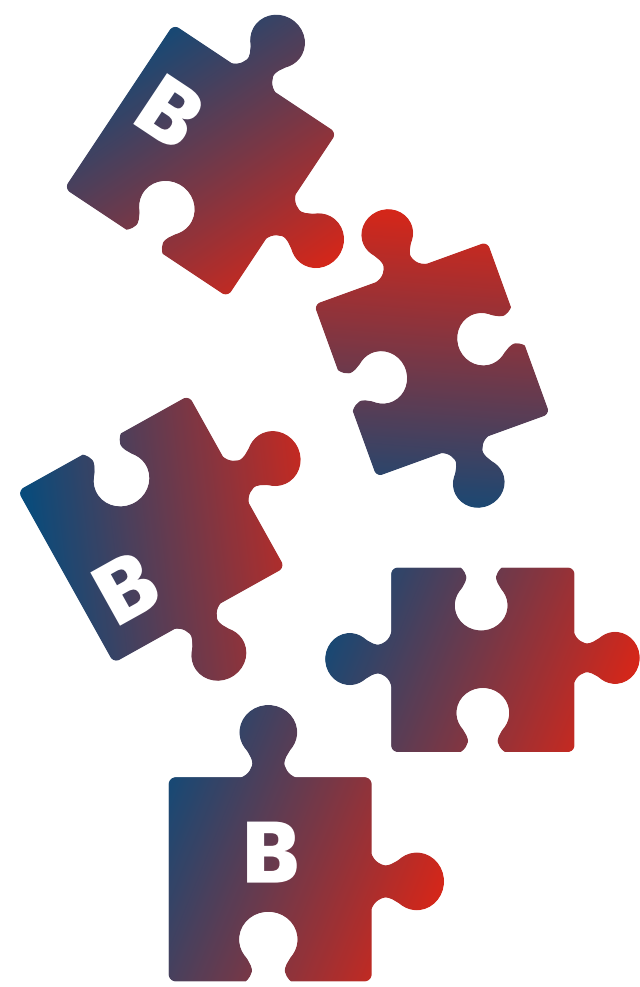


The matter-antimatter

asymmetry

A beautiful puzzle

Topical Lectures
K. Keri Vos



**“The Standard Model of Particle Physics
is a very successful theory,
yet it is incomplete...”**

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[Source: all particle physicists]

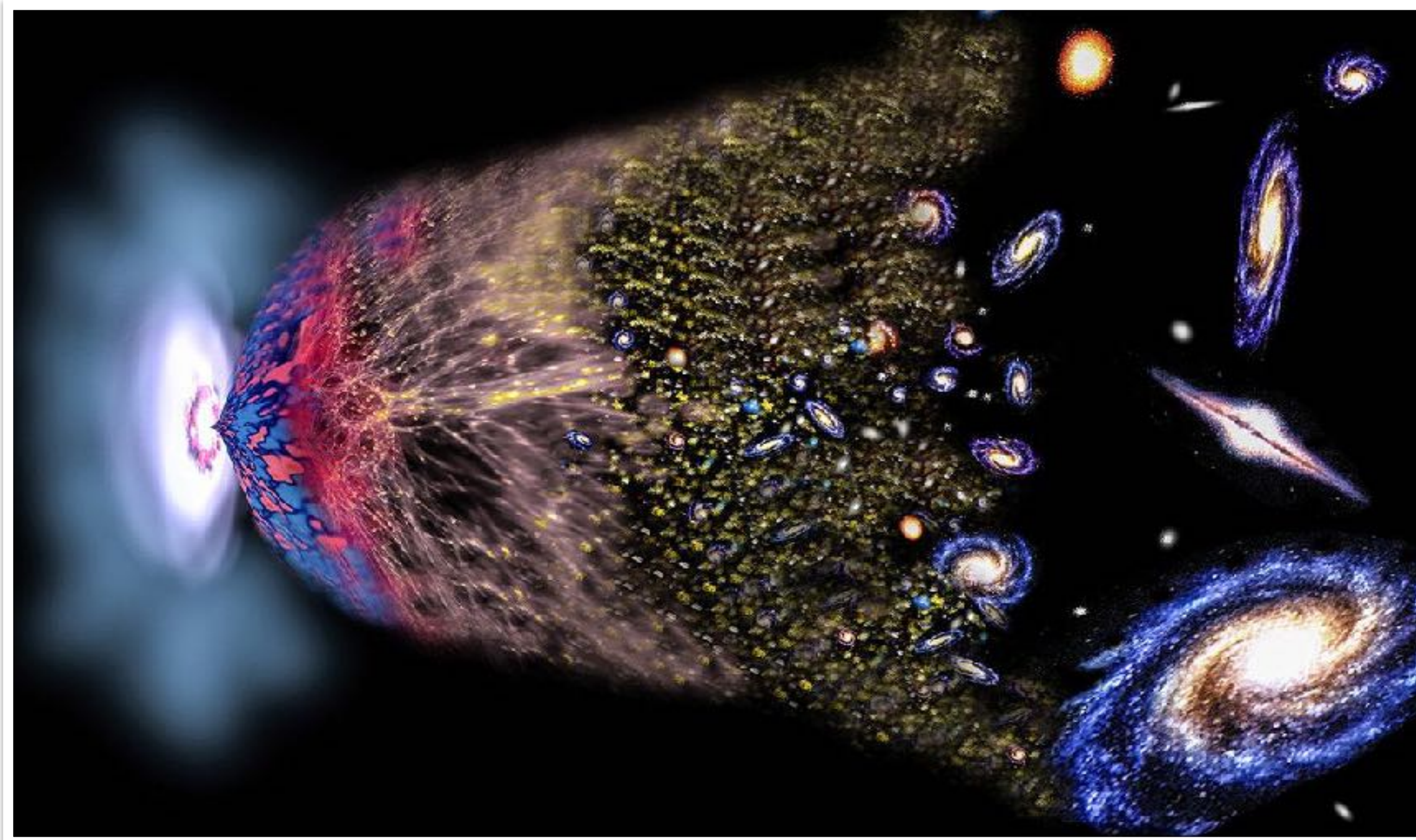
Today's Puzzle: Missing antimatter

s = entropy

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10}$$

Characterises the baryon-antibaryon asymmetry obtained from CMB.

Huge fine tuning!



Today's Puzzle: Missing antimatter

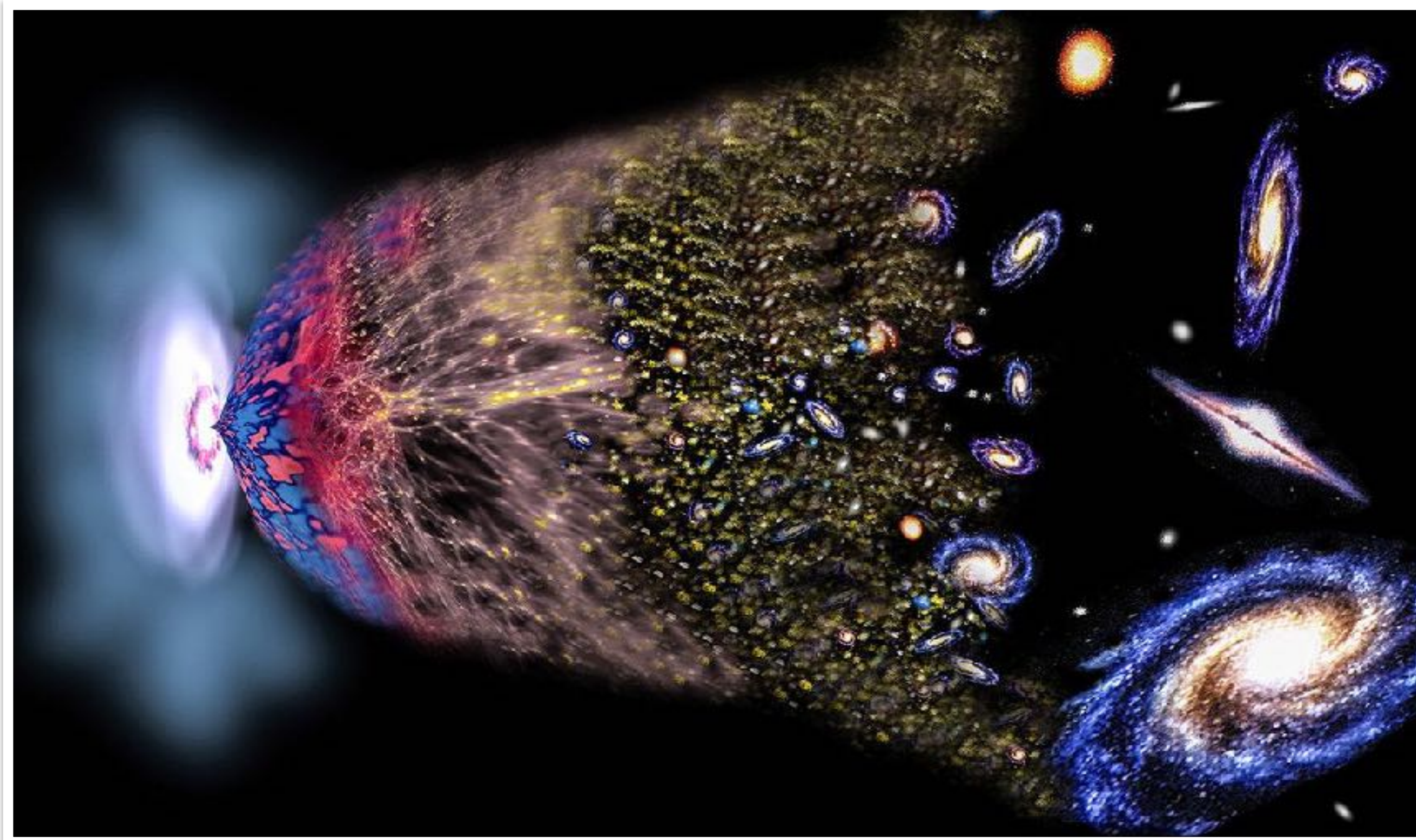
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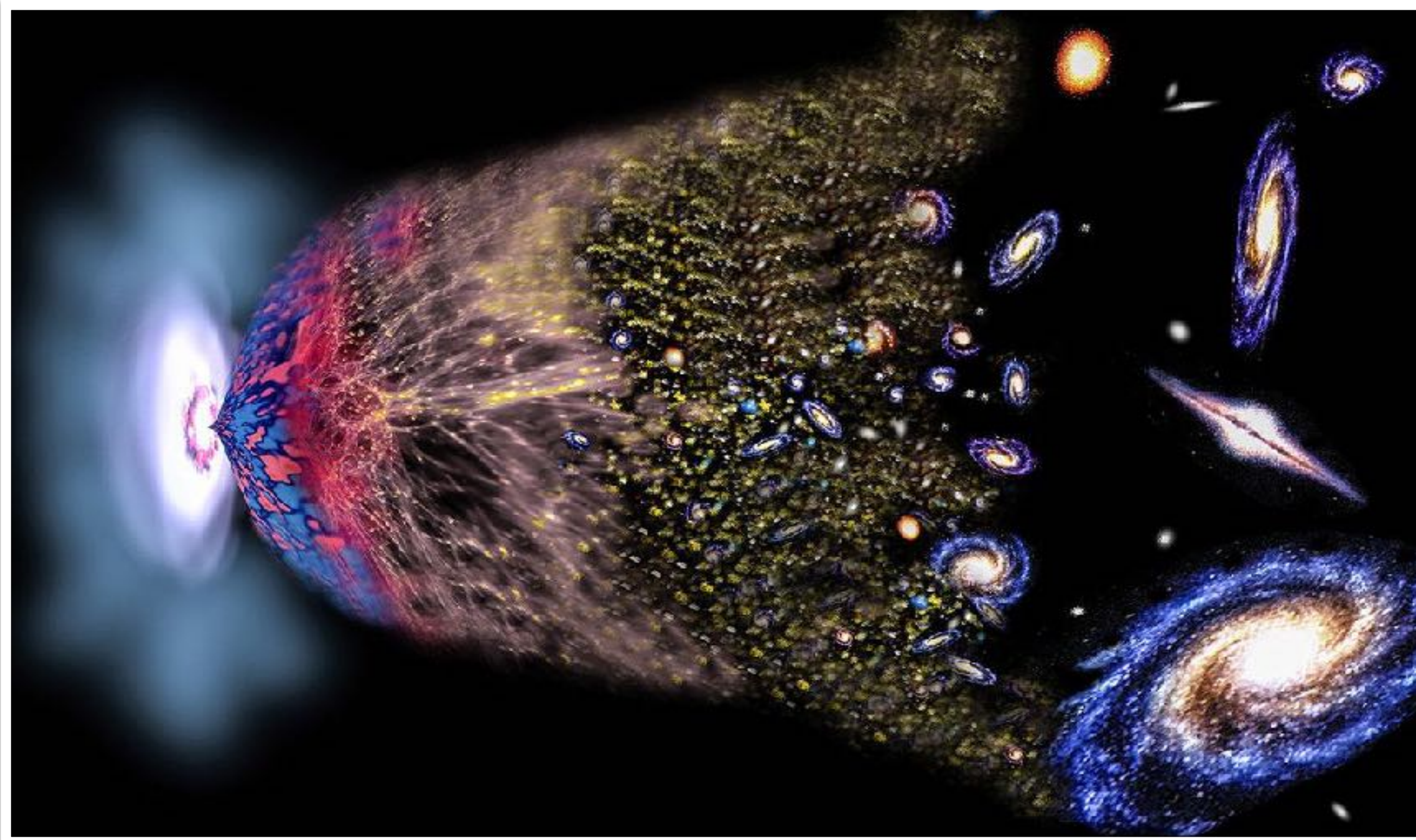
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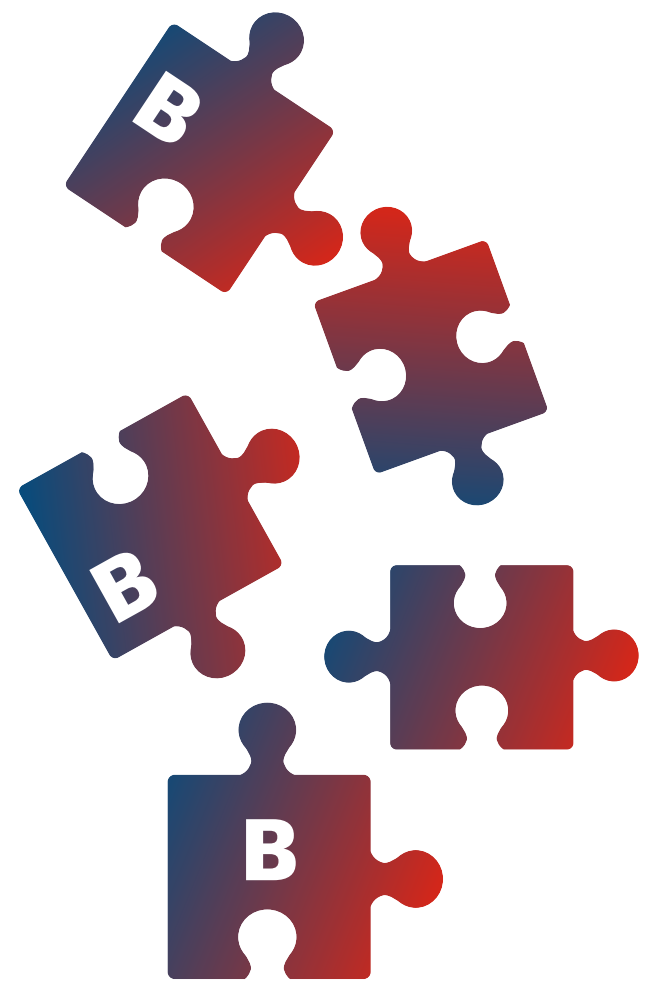
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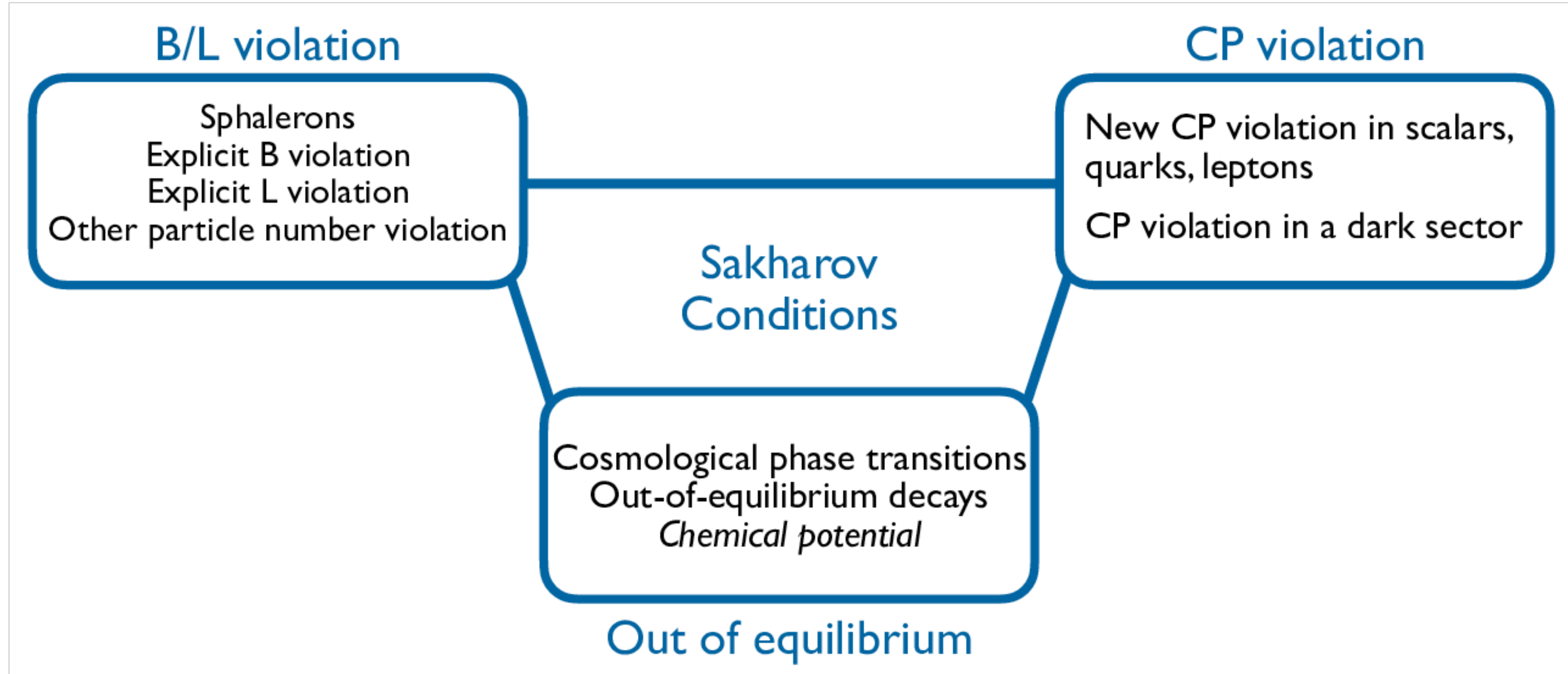
Could this be an initial asymmetry?

No, would be washed out by inflation





What do we need to explain the matter- antimatter asymmetry?



Why are these needed?

- Baryon number violation: obvious... need an asymmetry in baryons
- Without C and CP:
 - rate of left-chiral particle creation = rate of right-chiral antiparticle creation
- Exercise: show that Baryon number is indeed odd under C and CP

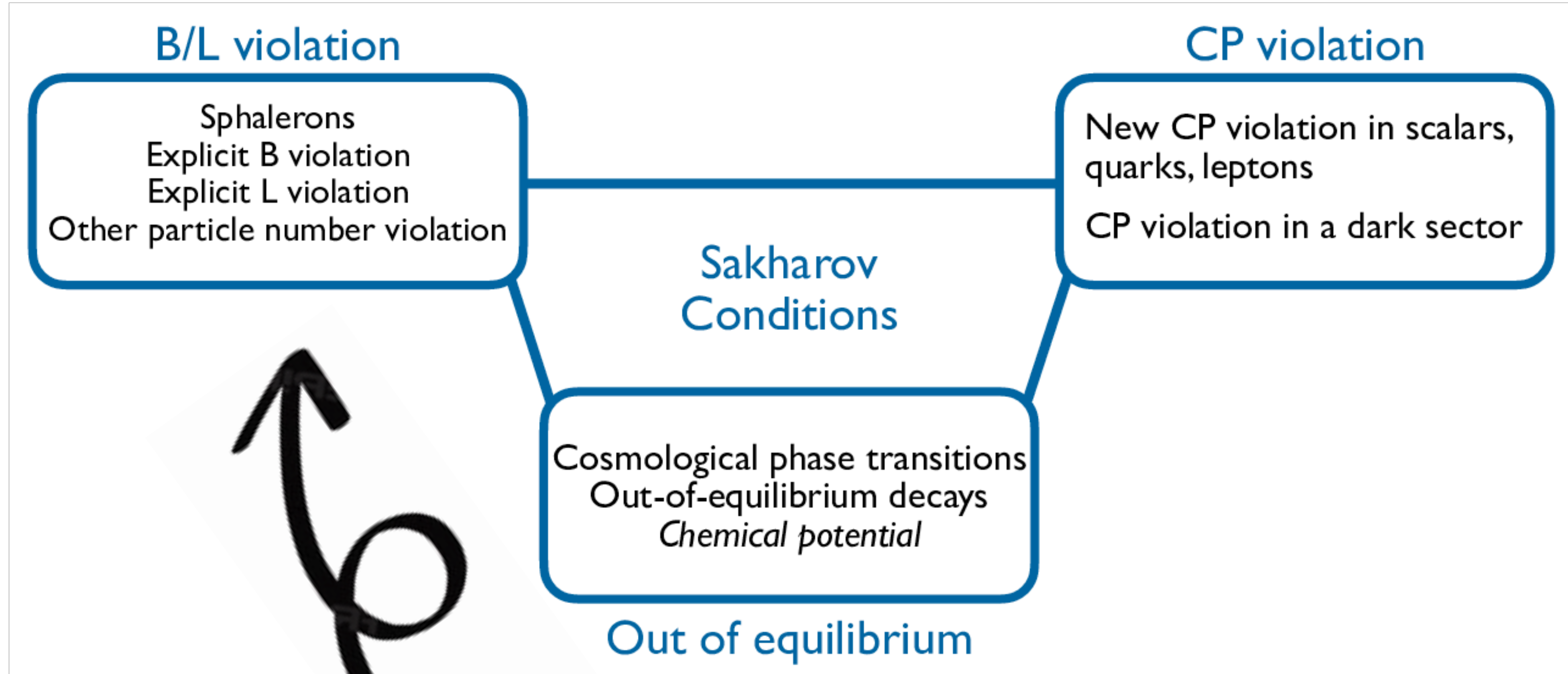
- In Thermal equilibrium there is no direction of time
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What about the SM?



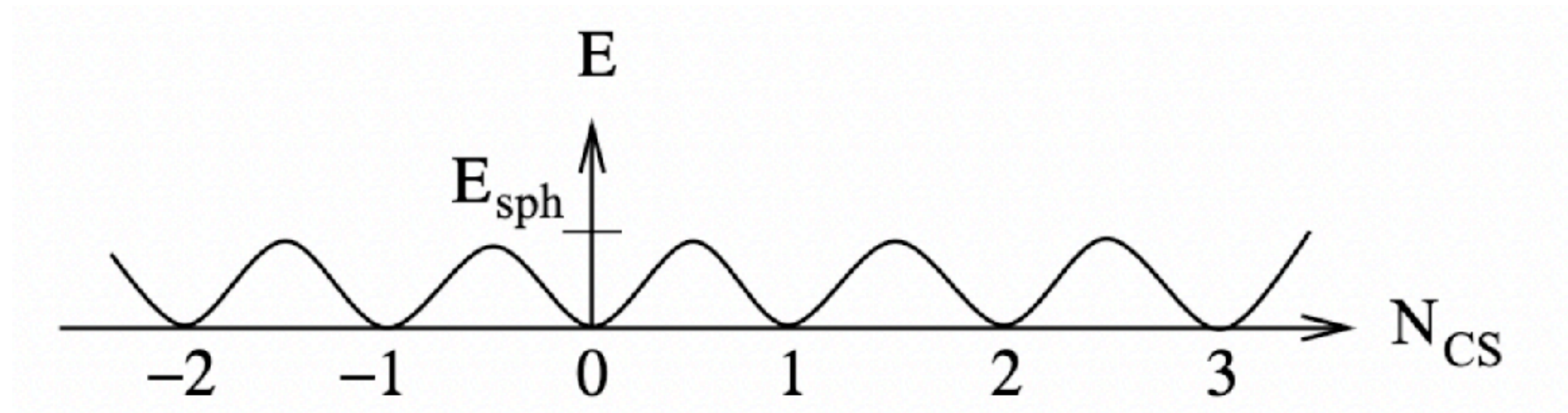
Baryon Number Violation

- SM Lagrangian is invariant under global U(1)_B and U(1)_L
- Lepton number and Baryon number are “good enough” quantum numbers in the lab.
- Perturbative corrections break this global U(1) symmetry

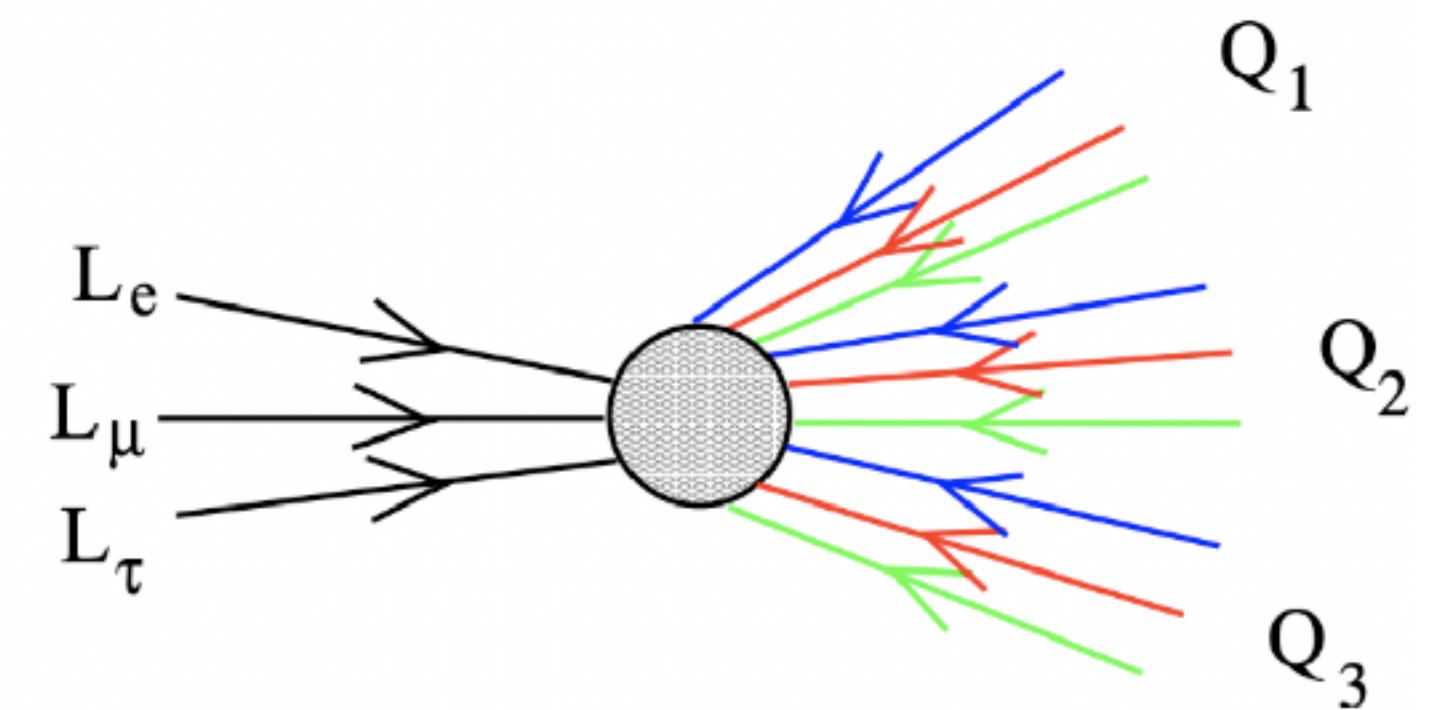
$$\partial^\mu J_\mu^B = \partial^\mu J_\mu^L = \frac{n_F}{32\pi^2} (g^2 W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - g'^2 B_{\mu\nu} \tilde{B}^{\mu\nu}),$$

- Chiral anomaly
- B-L conserved in SM, but B+L broken
- Working this out: B and L violated by three units

Sphalerons

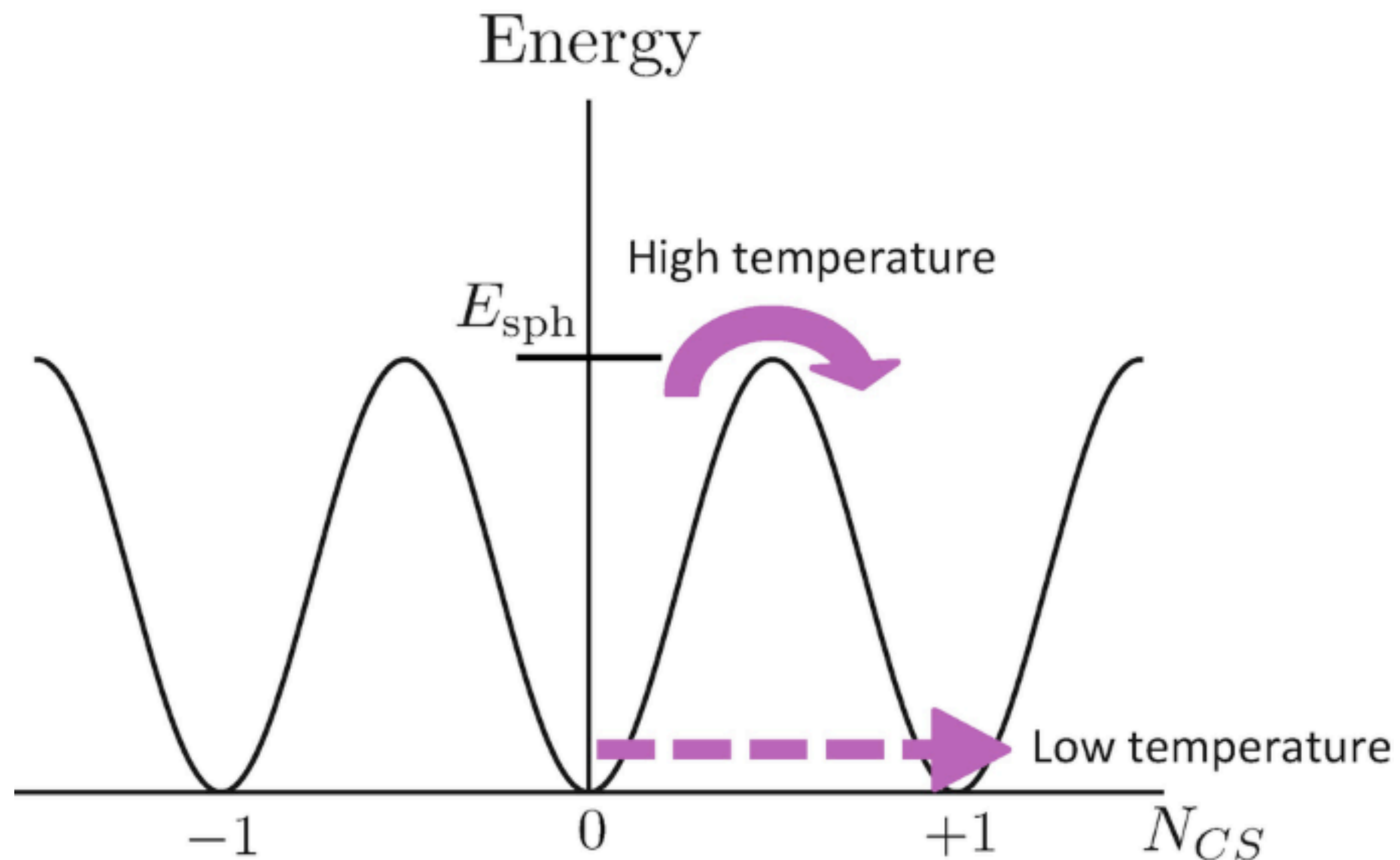


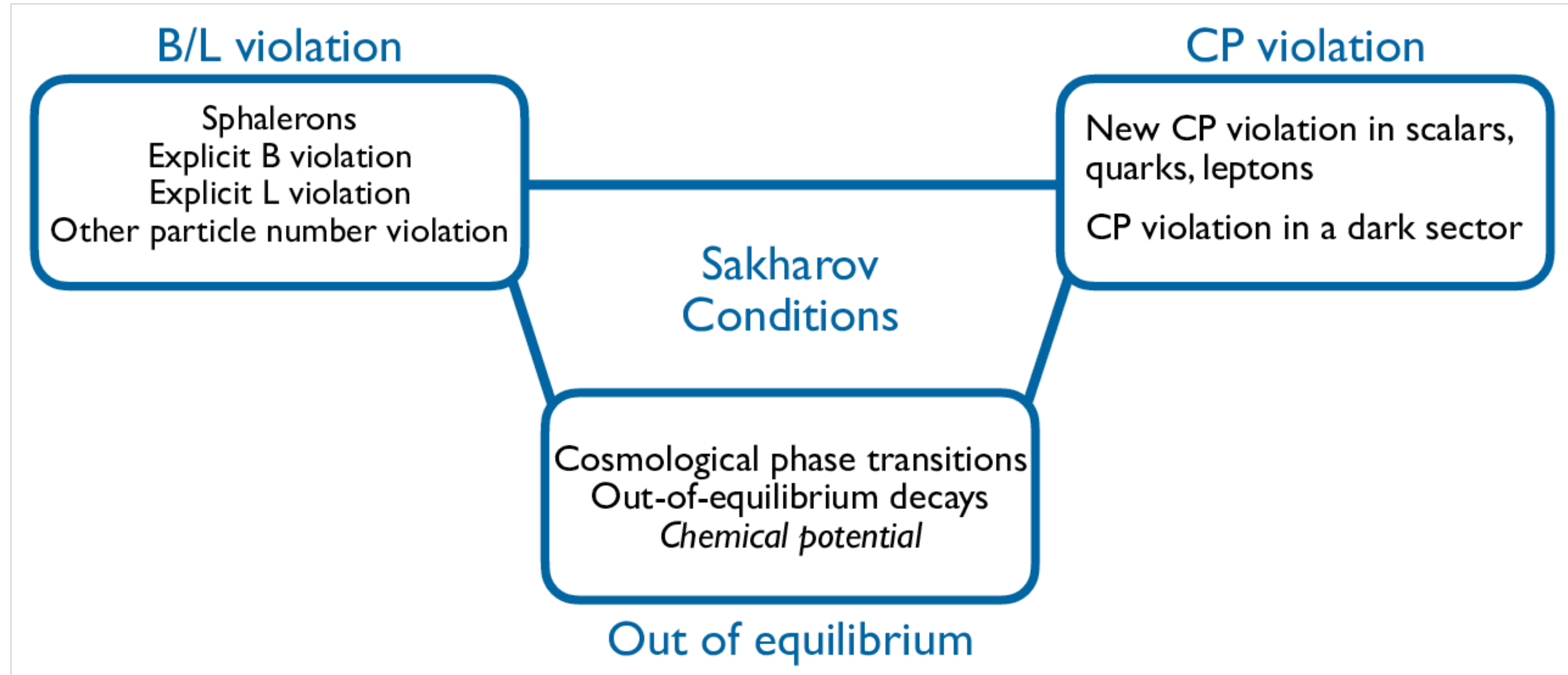
- SU(2) has a non-trivial vacuum structure characterised by Chern-Simons number N_{CS}
- Height between different vacuum are "Sphaleron" solutions
- "Sphaleron" = ready to fall
- Static saddle point solution of field equations



Sphalerons

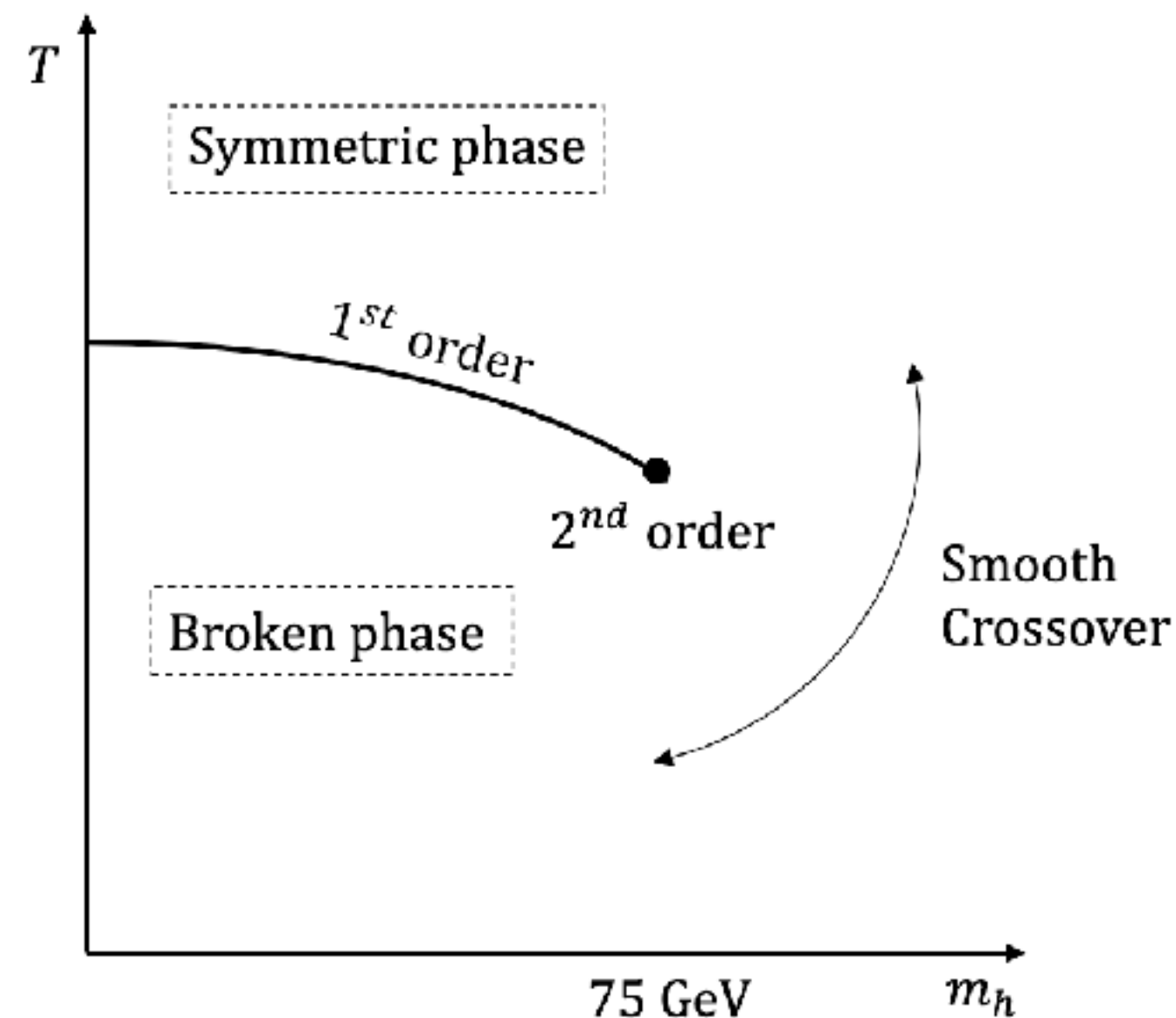
- Today **sphaleron** processes suppressed needs to happen through tunnelling
- Early universe, enough energy to hop over the barrier, instead of tunnelling, around $T=100$ GeV.





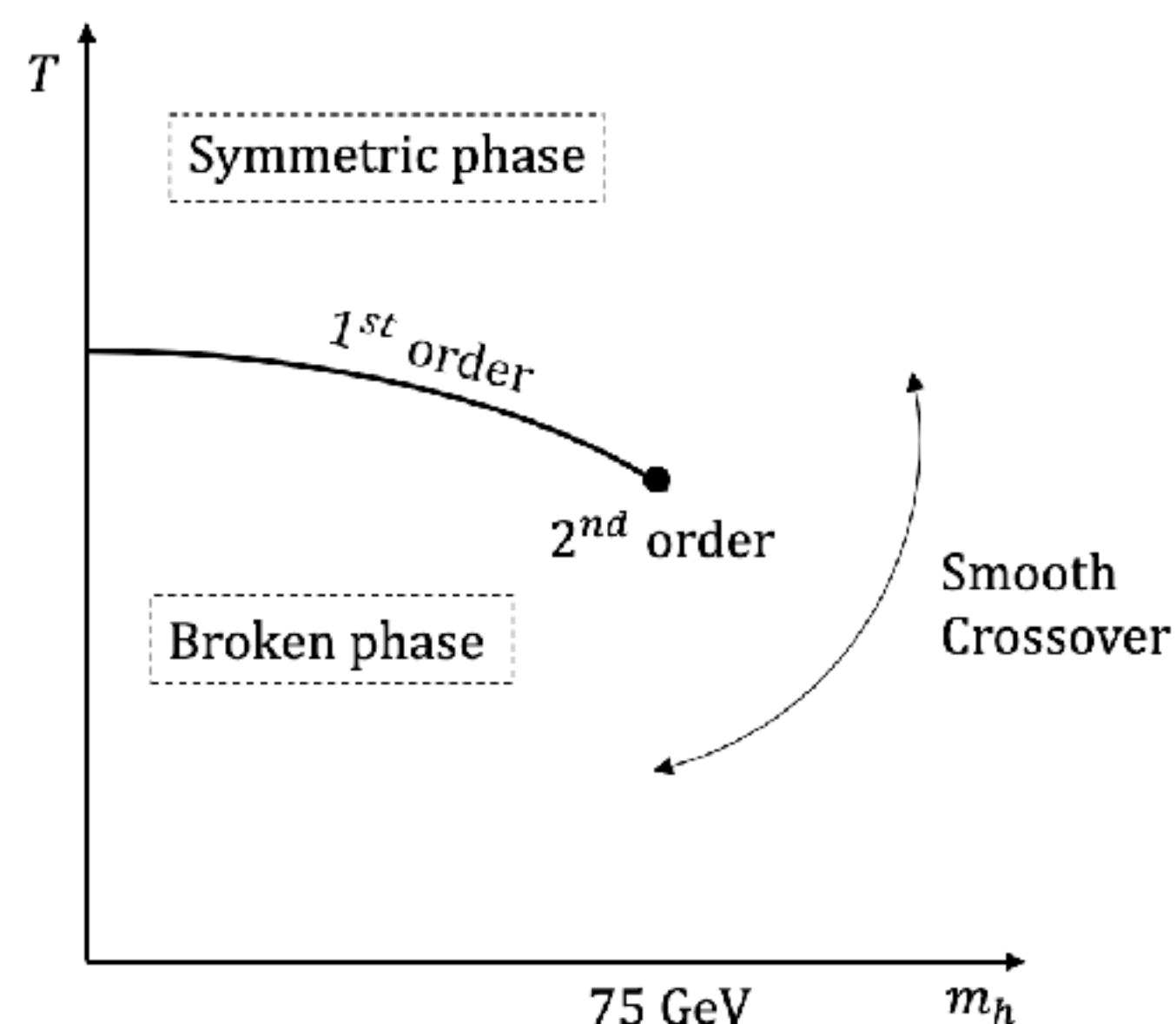
Out of Equilibrium

- In standard hot big bang cosmology, there are no out-of-equilibrium dynamics in the SM!
- With the Higgs mass as it is*, the EW phase transition is a smooth cross over!



Out of Equilibrium

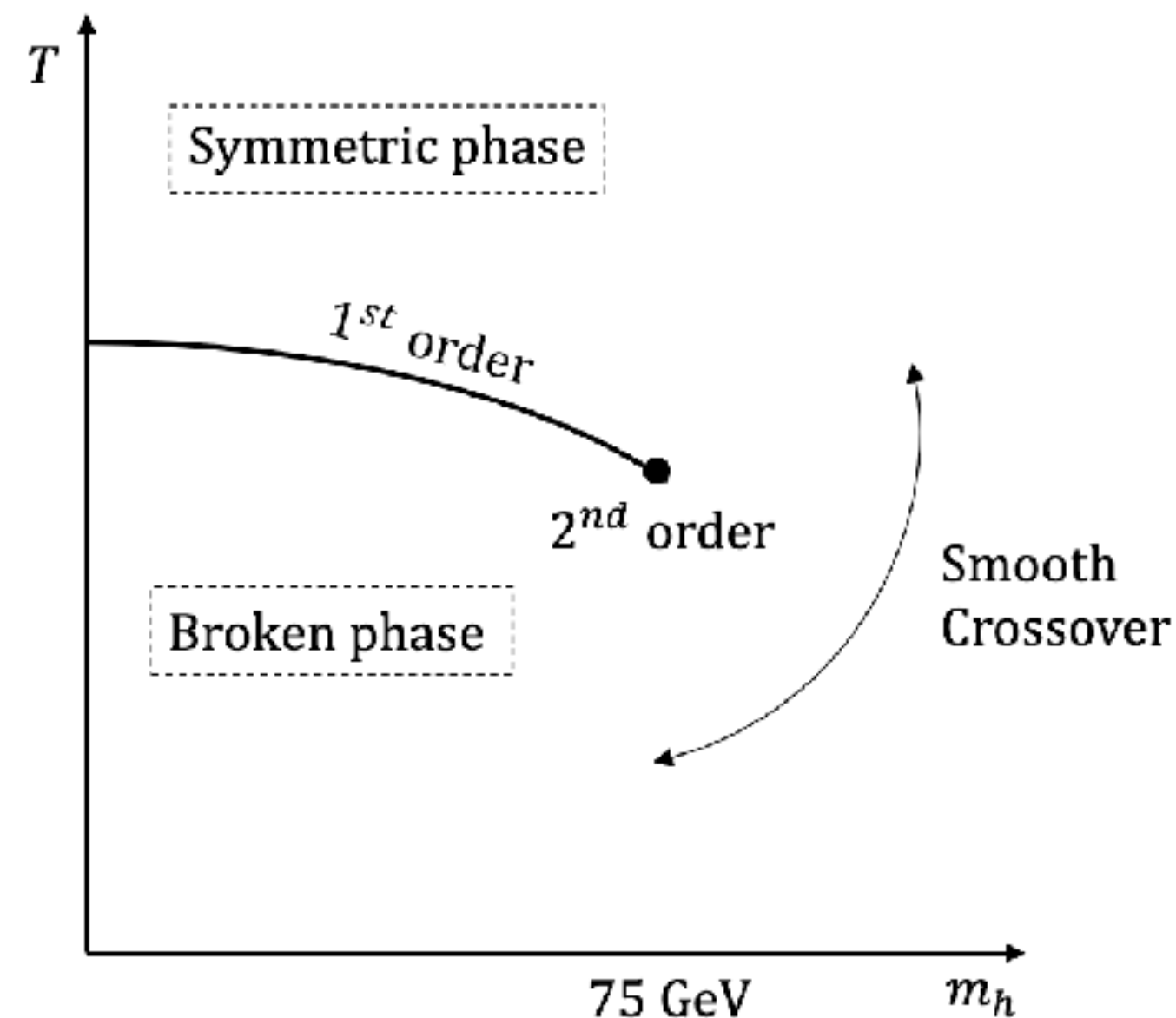
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At some point, as the Universe was expanding and cooling down, the mechanism of electroweak symmetry breaking must have occurred, and if it was violent enough, this transition would have been a strong first order phase transition (SFOPT), similar to the transition from liquid to gas at room temperature and pressure. **Thus, the Universe could have been literally boiling when the electroweak symmetry broke spontaneously** and particles acquired their masses. If this was indeed the case, we hope to observe the echoes of this violent process by measuring a stochastic background of gravitational waves emitted during the collision of bubbles of the real electroweak vacuum. This possibility is fascinating because it would provide the out-of-thermal-equilibrium conditions needed to explain the baryon asymmetry.

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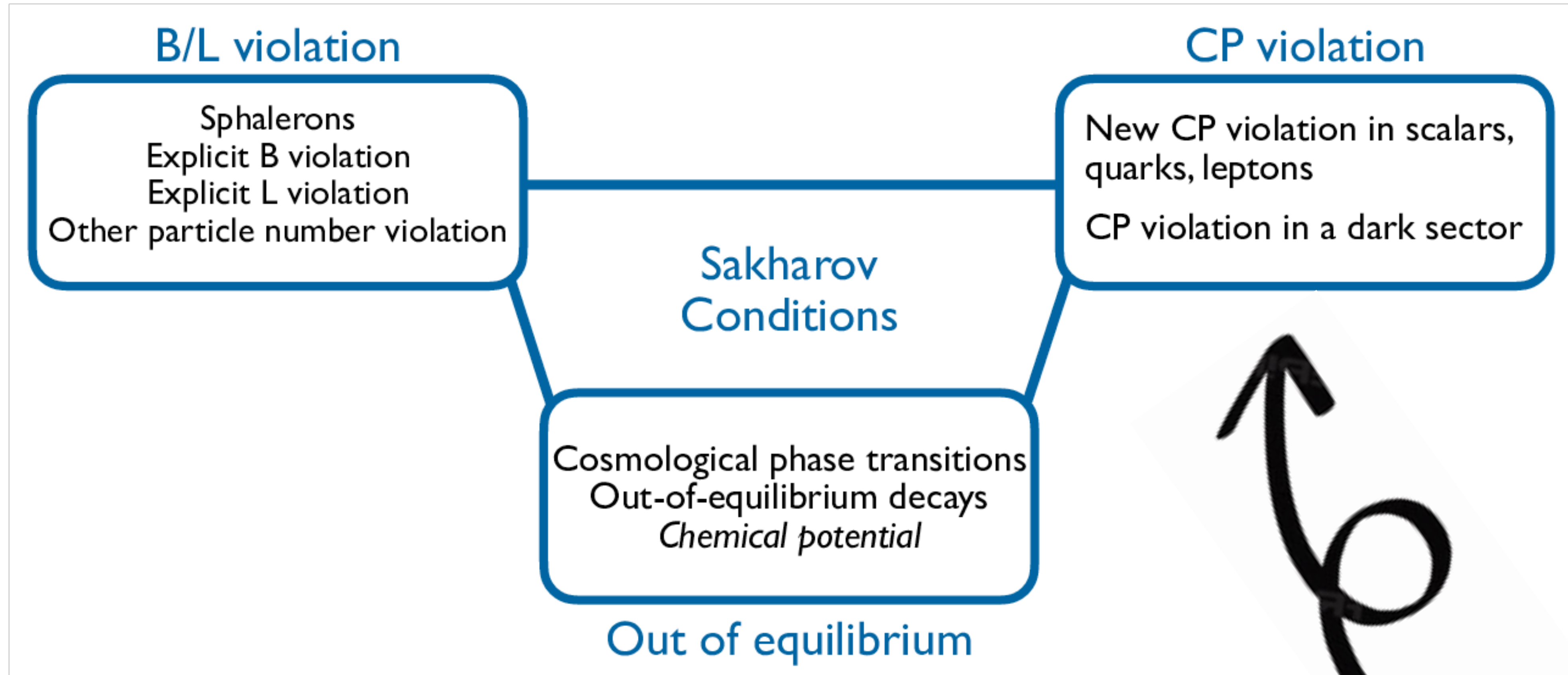


The SFOPT is excluded in the Standard Model because all the parameters of the potential are set by the measured Higgs mass, and the strength of the transition is not enough for it to be first order.

Sakharov in the SM

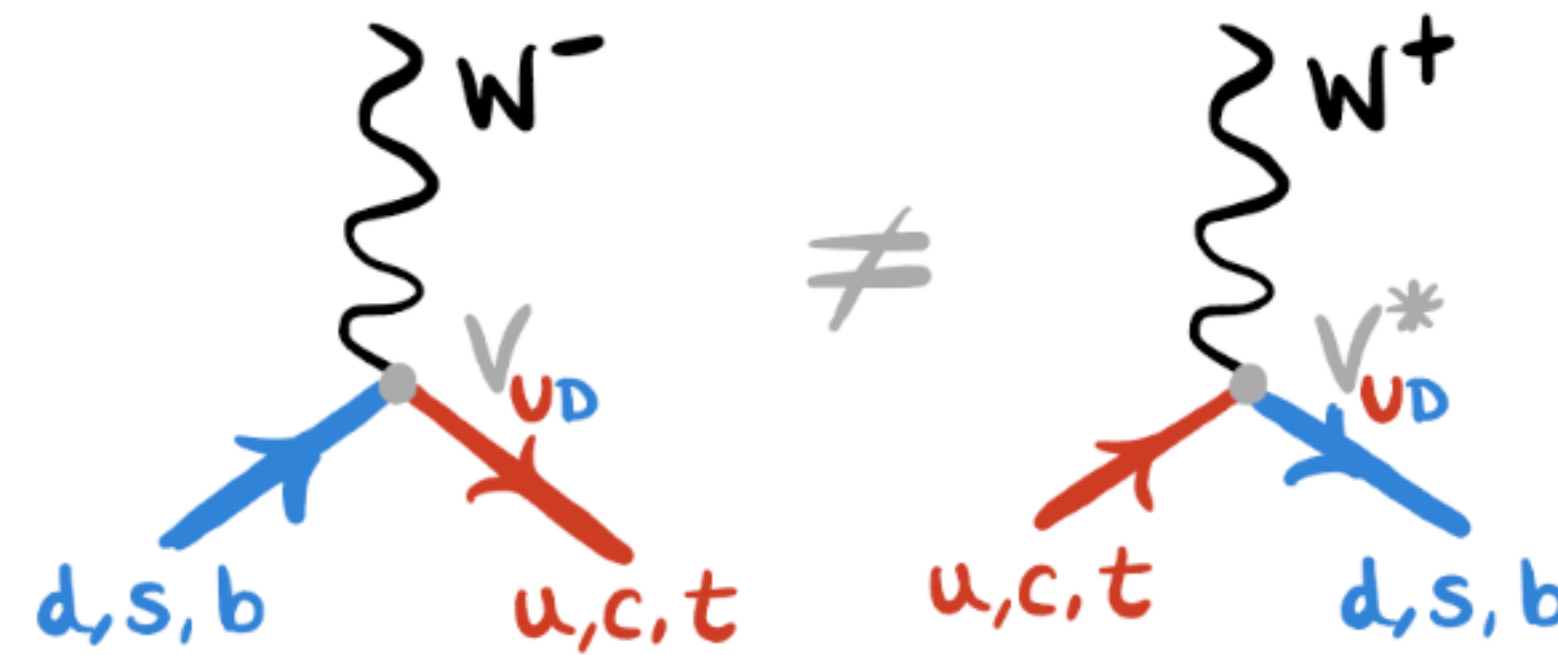
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- In Thermal equilibrium there is no direction of time
 - Baryon number would then vanish



Puzzle #2: CP violation in the SM

- Why is there only CP violation in the weak interaction?



$$Y_B = \frac{J_{CKM}}{T_{EW}^{12}} \sim 10^{-20}$$

- Amount of CP violation in CKM matrix seems orders of magnitude too little
- Strong CP violation (too small)? New sources of CP?

CP violation in the SM

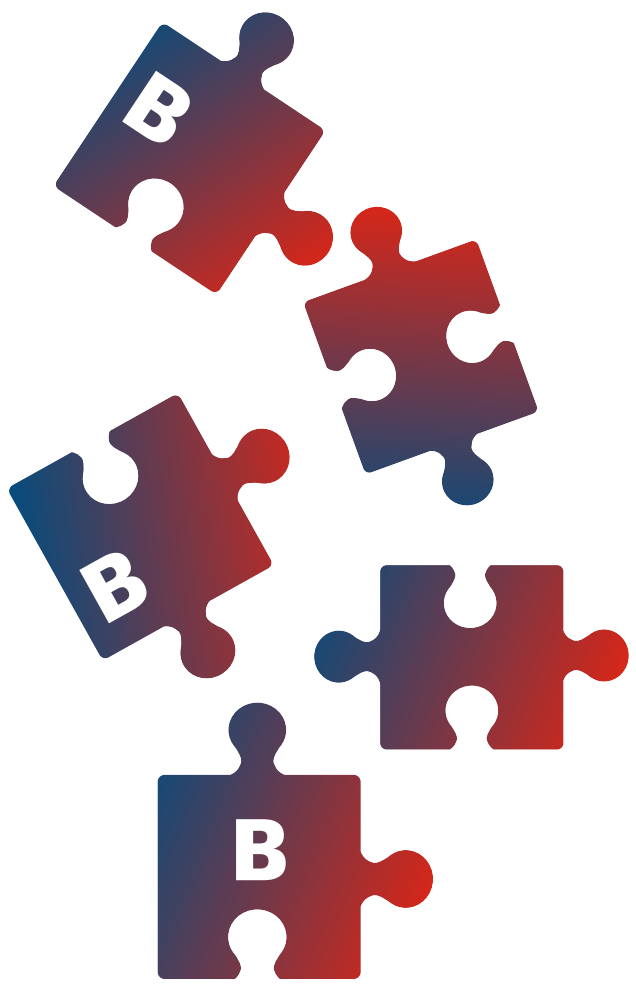
$$Y_B = \frac{J_{CKM}}{T_{EW}^{12}} \sim 10^{-20}$$

Using $T_{EW} = 100 \text{ GeV}$

$$J_{CKM} = J_{inv} \times (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$

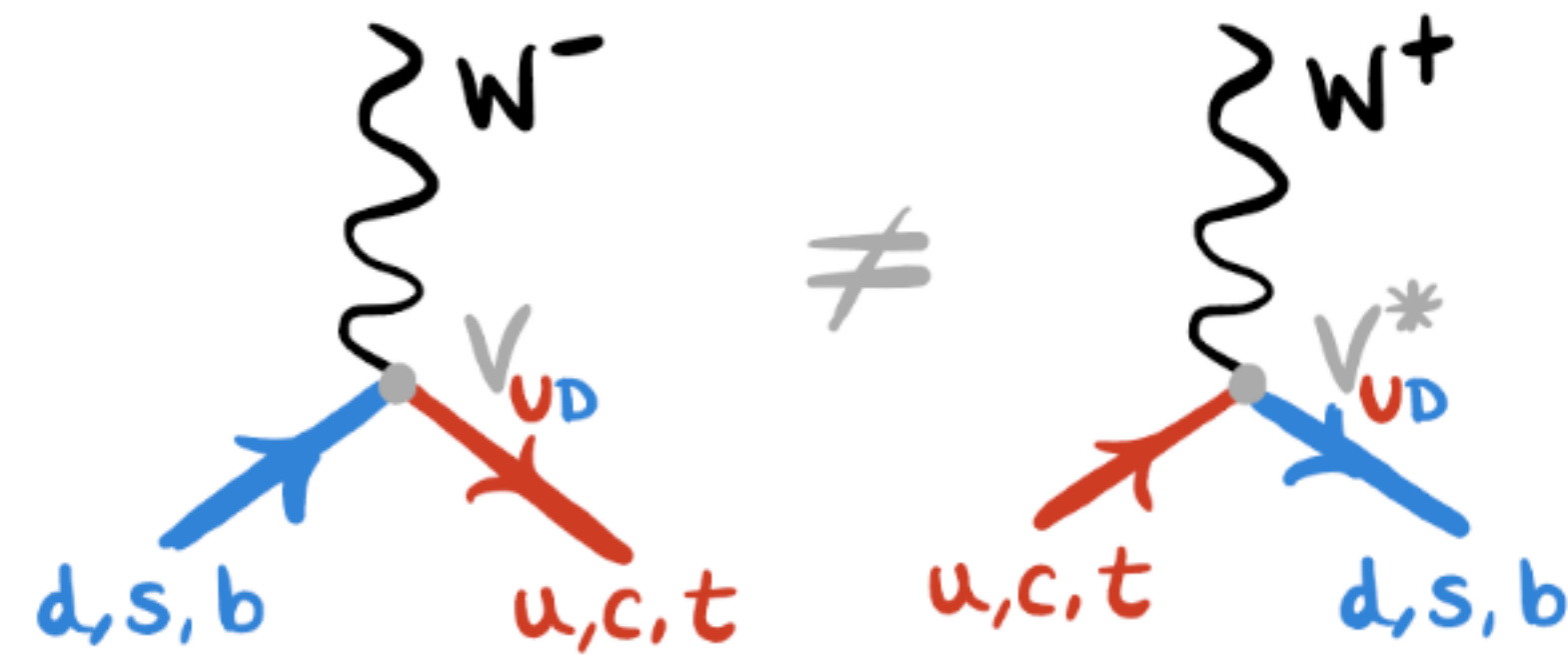
$$J_{inv} = \text{Im}(V_{us}V_{cb}V_{ub}^*V_{cs}^*) \sim 10^{-5}$$

- In general not enough to explain $Y_B = \sim 10^{-10}$
- Why EW scale? Otherwise there the sphalerons are not large enough!



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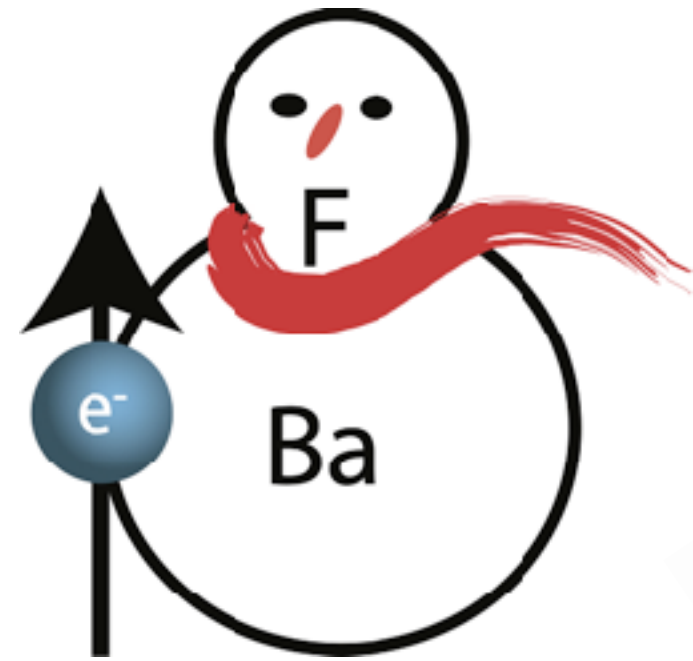
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Need to understand CP violation in the SM

Nik|hef

Searches for CP violation



Grav. Waves



ALICE



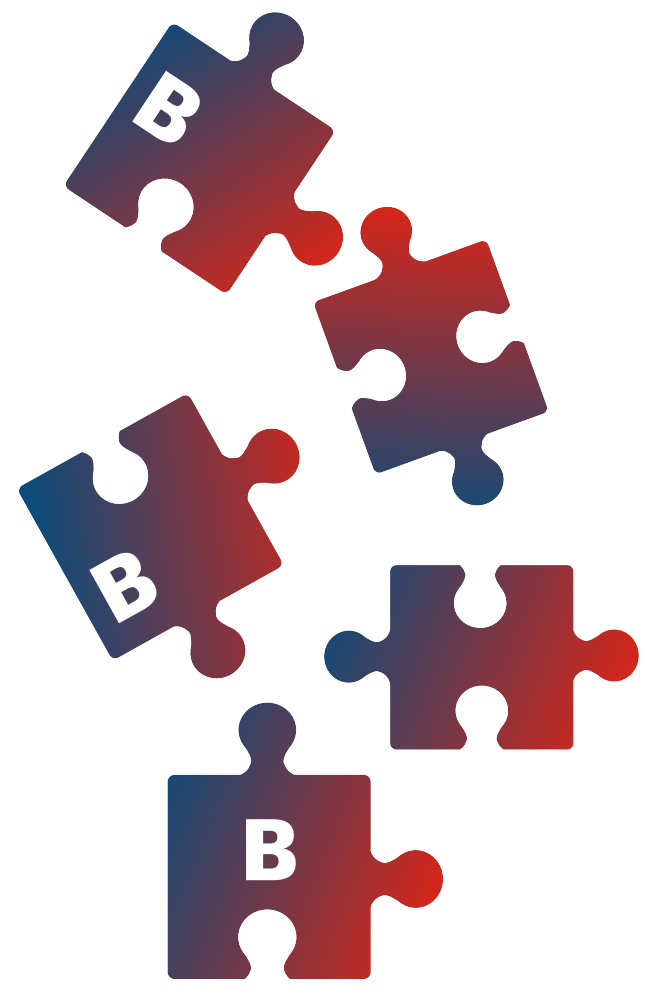
Baryogenesis mechanisms

Mechanism to explain the baryon asymmetry of the Universe

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Mechanism to explain the baryon asymmetry of the Universe

GUT baryogenesis, baryogenesis from primordial black holes, Affleck-Dine (AD) baryogenesis, baryogenesis at preheating, **baryogenesis via leptogenesis**, spontaneous baryogenesis, gravitational baryogenesis, defect mediated baryogenesis, B-ball baryogenesis, baryogenesis from CPT breaking, baryogenesis through quantum gravity, axiogenesis, baryogenesis by brane collision, **mesogenesis**, **electroweak baryogenesis**, etc.



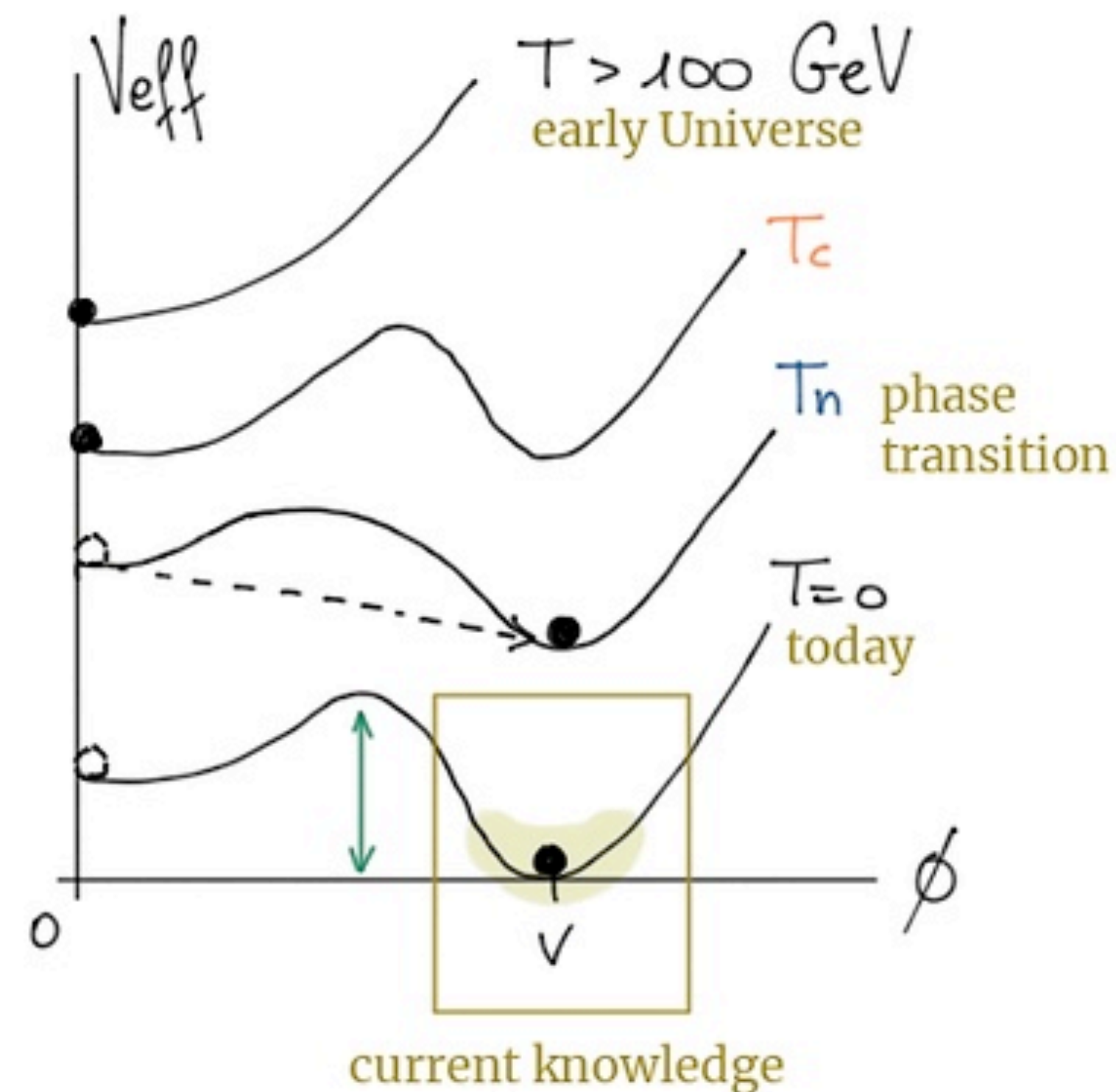
Electroweak Baryogenesis in a Nutshell

EW baryogenesis: Ingredients

Generation of baryon asymmetry during the electroweak phase transition

- Out-of-equilibrium: strong first order phase transition

At zero temperature we have the Mexican hat potential, but there are quantum corrections through exchanges with the vacuum, therefore the corrections become temperature dependent.

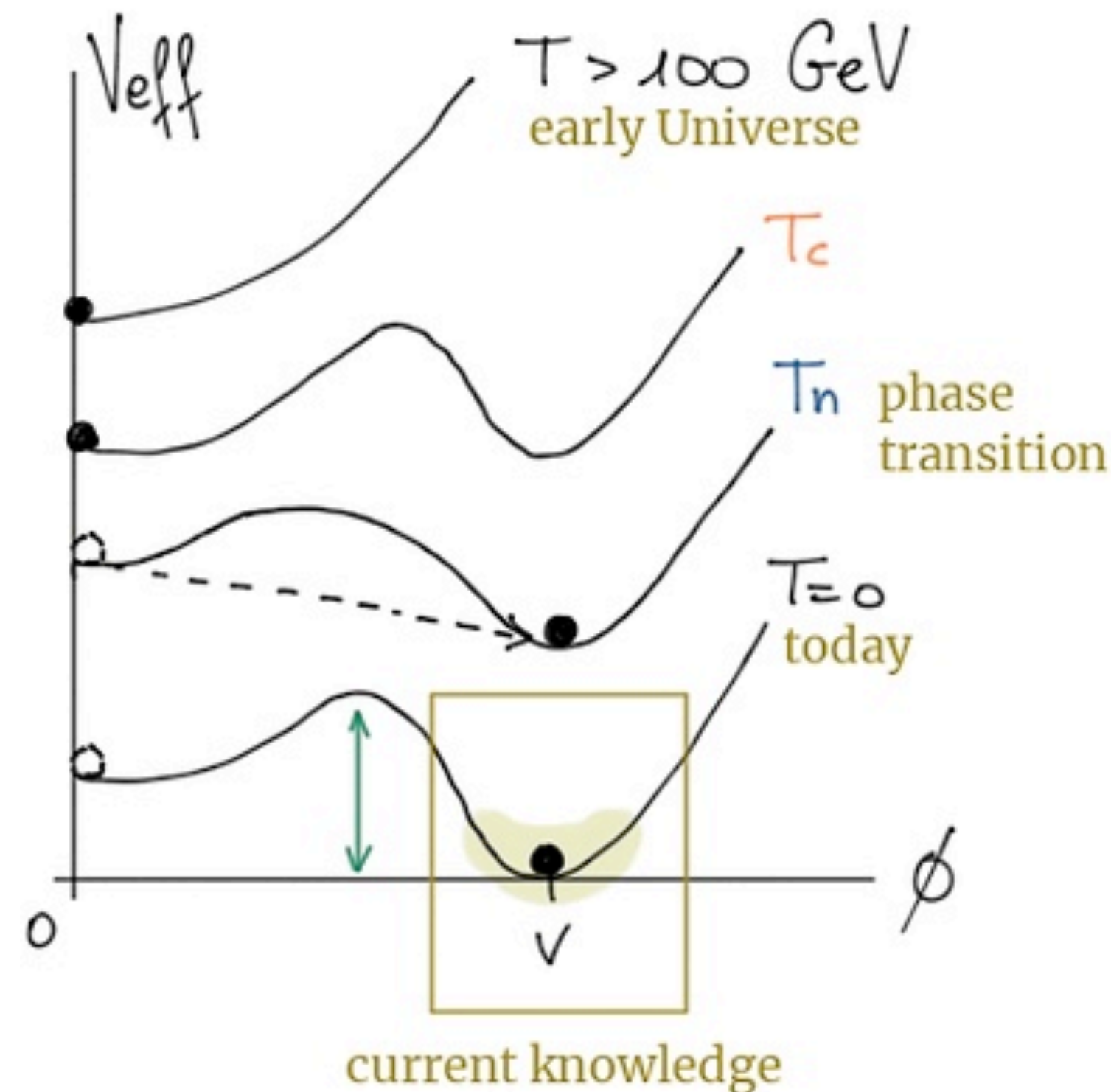


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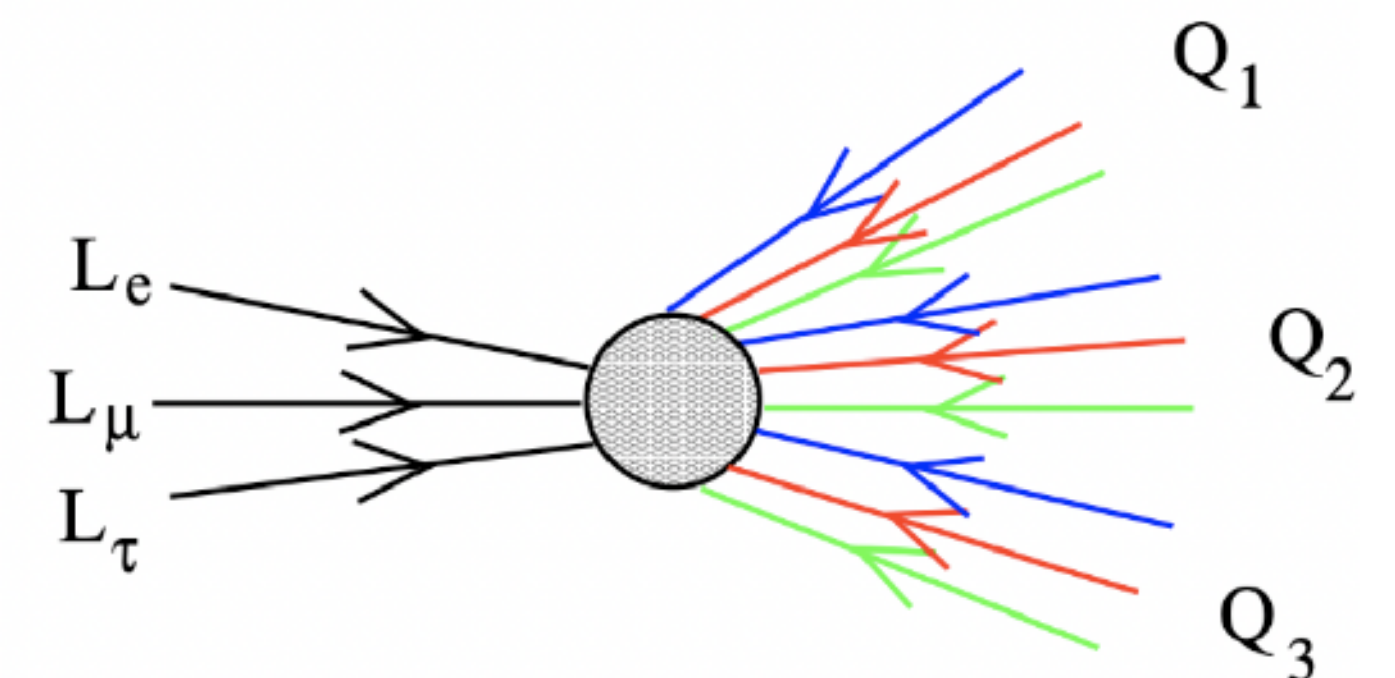
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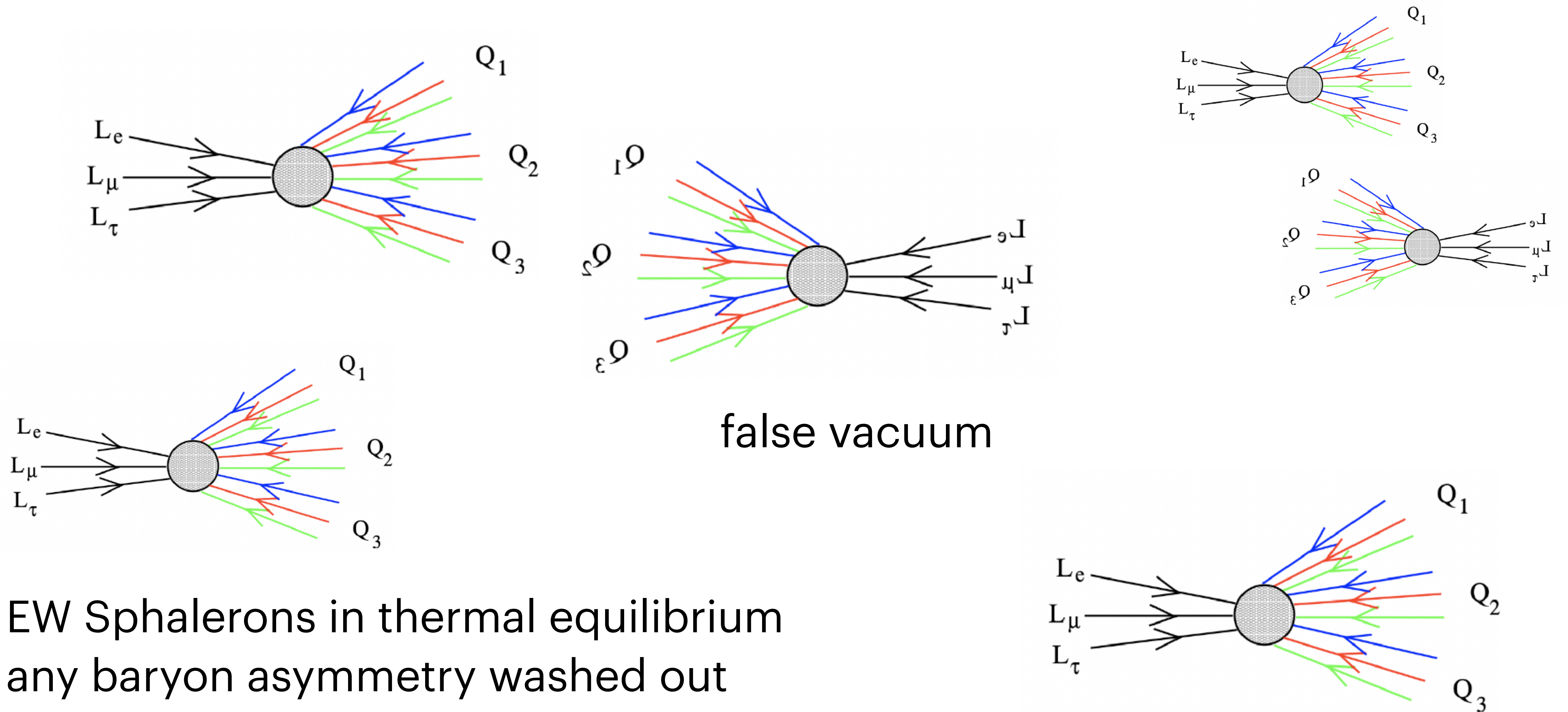
EW baryogenesis: Ingredients

Generation of baryon asymmetry during the electroweak phase transition

- Out-of-equilibrium: strong first order phase transition **New Physics!**
- Additional CP-violation **New Physics!**
- Electroweak Sphalerons (only involve left-handed fermions)



EW baryogenesis: Mechanism



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EW Sphalerons in equilibrium \longrightarrow universe cools to Electroweak scale

FOPT \longrightarrow Tunnelling to true vacuum \longrightarrow bubble creation with true and false vacuum

\longrightarrow Higgs vev zero and non-zero

true vacuum
inside bubble

$$\langle \varphi \rangle \neq 0$$

$$\langle \varphi \rangle = 0$$

false vacuum

Bubble wall

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$\psi_L + \psi_R$

false vacuum

CP-violation

n_L

Bubble wall

CP violation in the bubble wall gives different distributions of particles and antiparticles in front of and behind the wall

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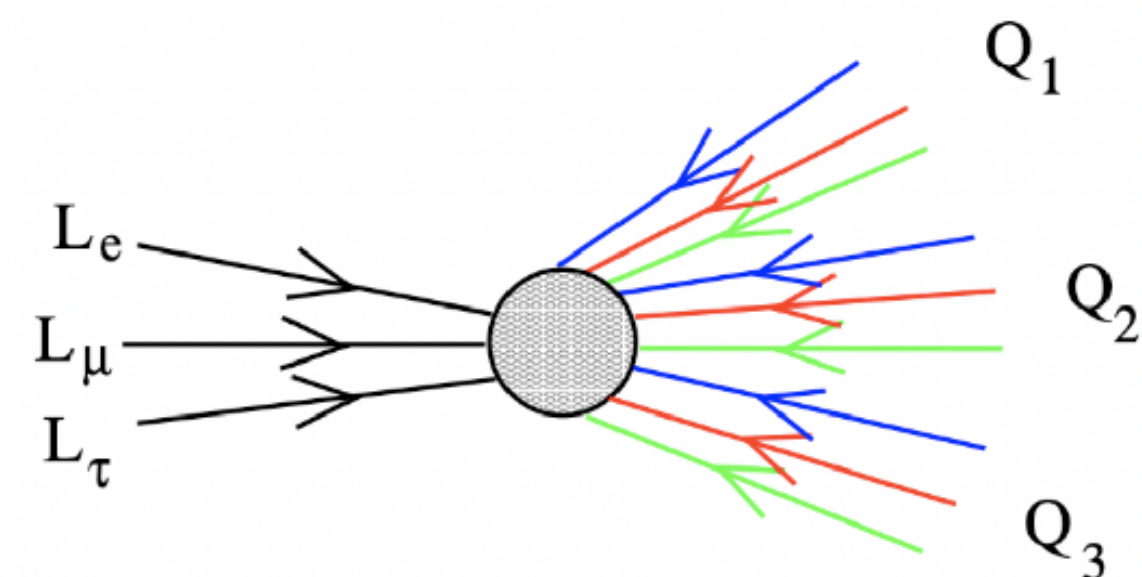
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n_I

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Bubble wall



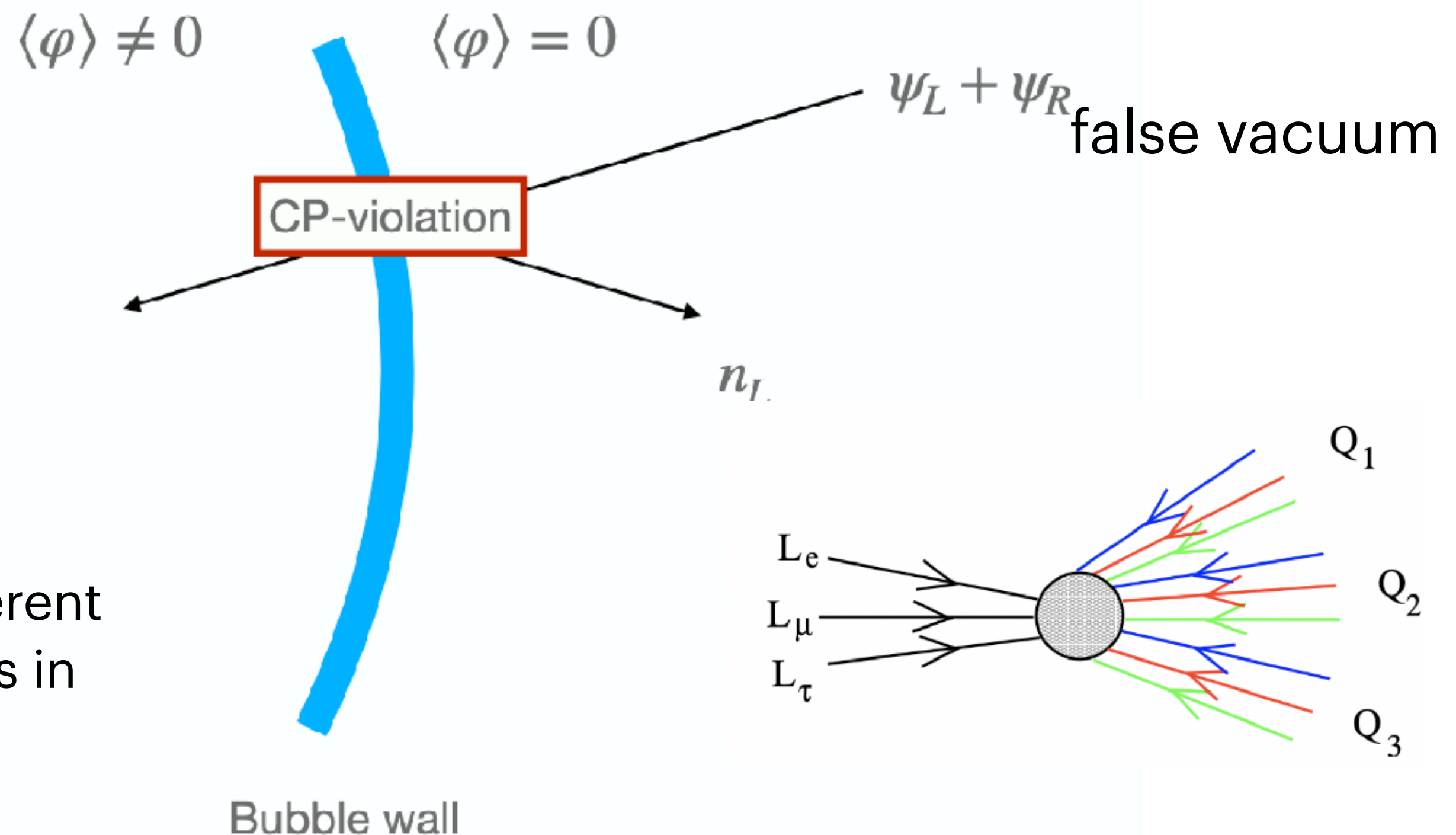
EW baryogenesis: Mechanism

CP violation \longrightarrow Example: more left-handed antiparticles outside bubble

EW Sphalerons only involve left-handed fermions \longrightarrow LH antiparticles are destroyed

\longrightarrow baryon asymmetry is created!

true vacuum
inside bubble



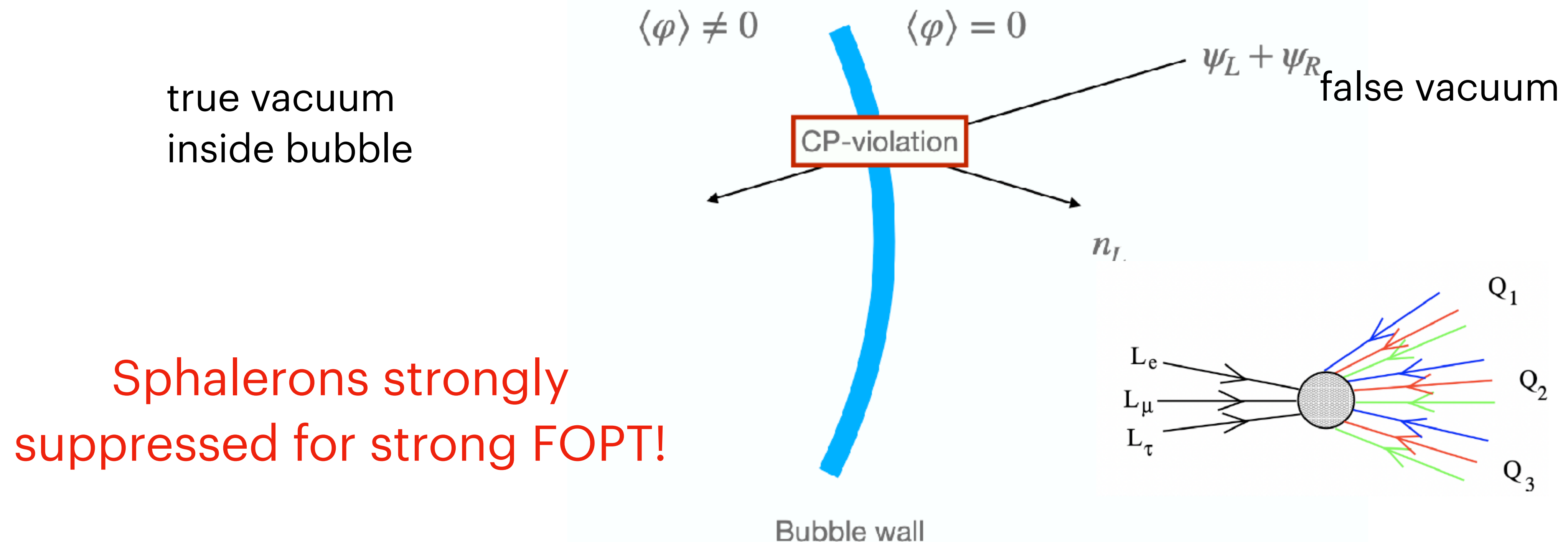
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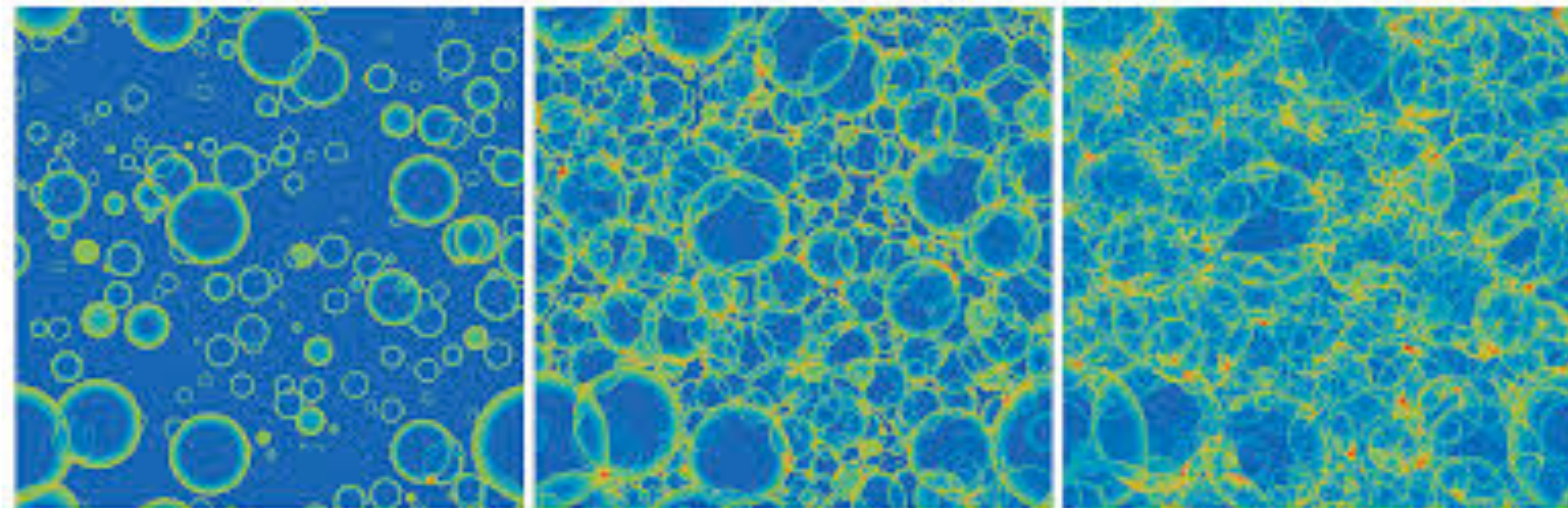
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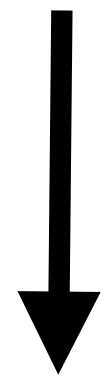


EW baryogenesis: Mechanism

Before the asymmetry is washed out the baryons are swept up by the expanding bubbles.

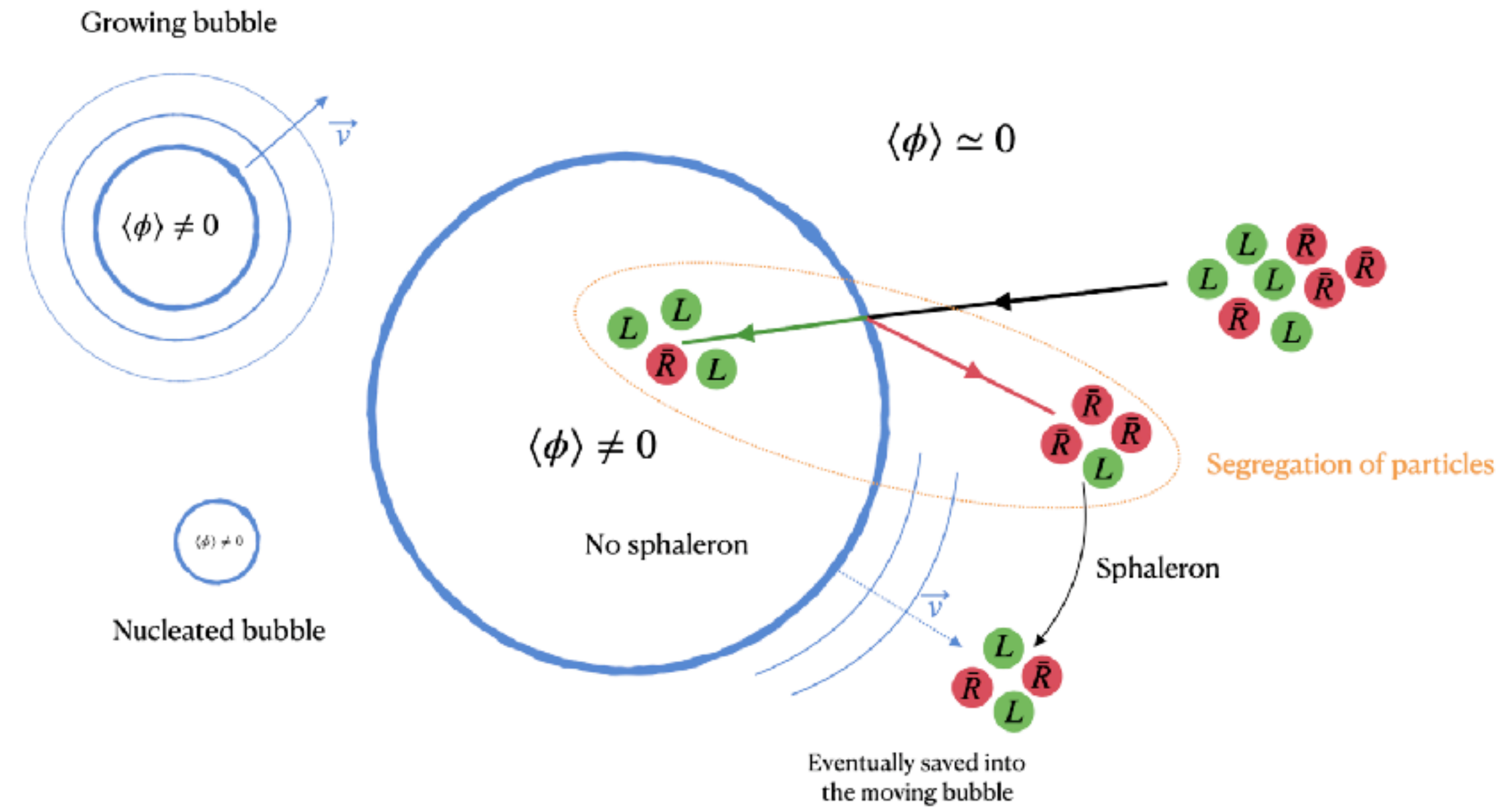
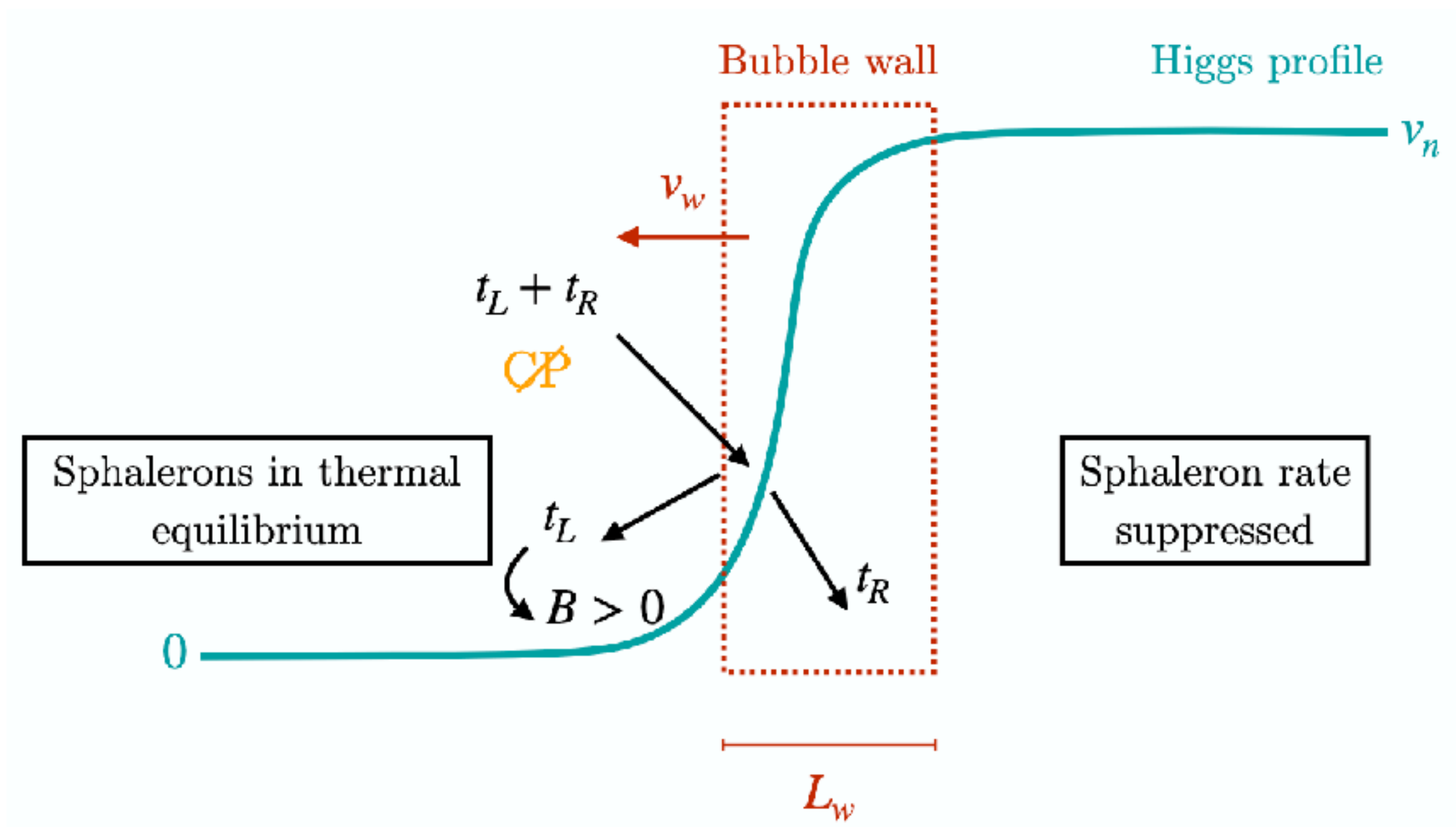


At the end of the PT, the bubbles collide



net baryon number!

More graphs:



Signals of EW baryogenesis

- Collider signatures of new scalars/different Higgs couplings
- Additional CP-violation could show up in EDM measurements
- Gravitational wave background due to fluids colliding with the bubbles
- Tiny effects in precision measurements in flavour physics

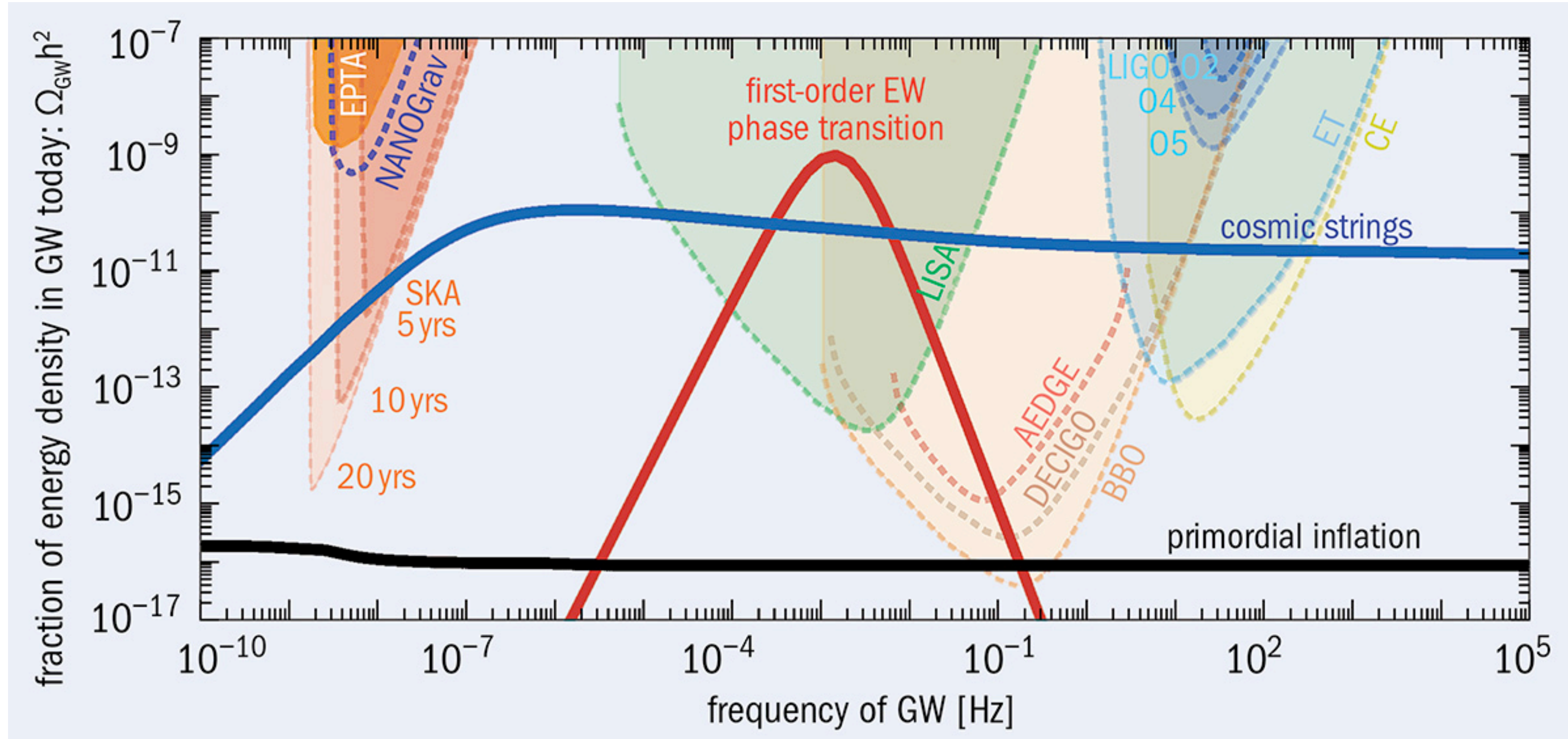
EDM constraints

- Very powerful probes for all sorts of CP violation
- Basically a null-test as the SM part is very suppressed

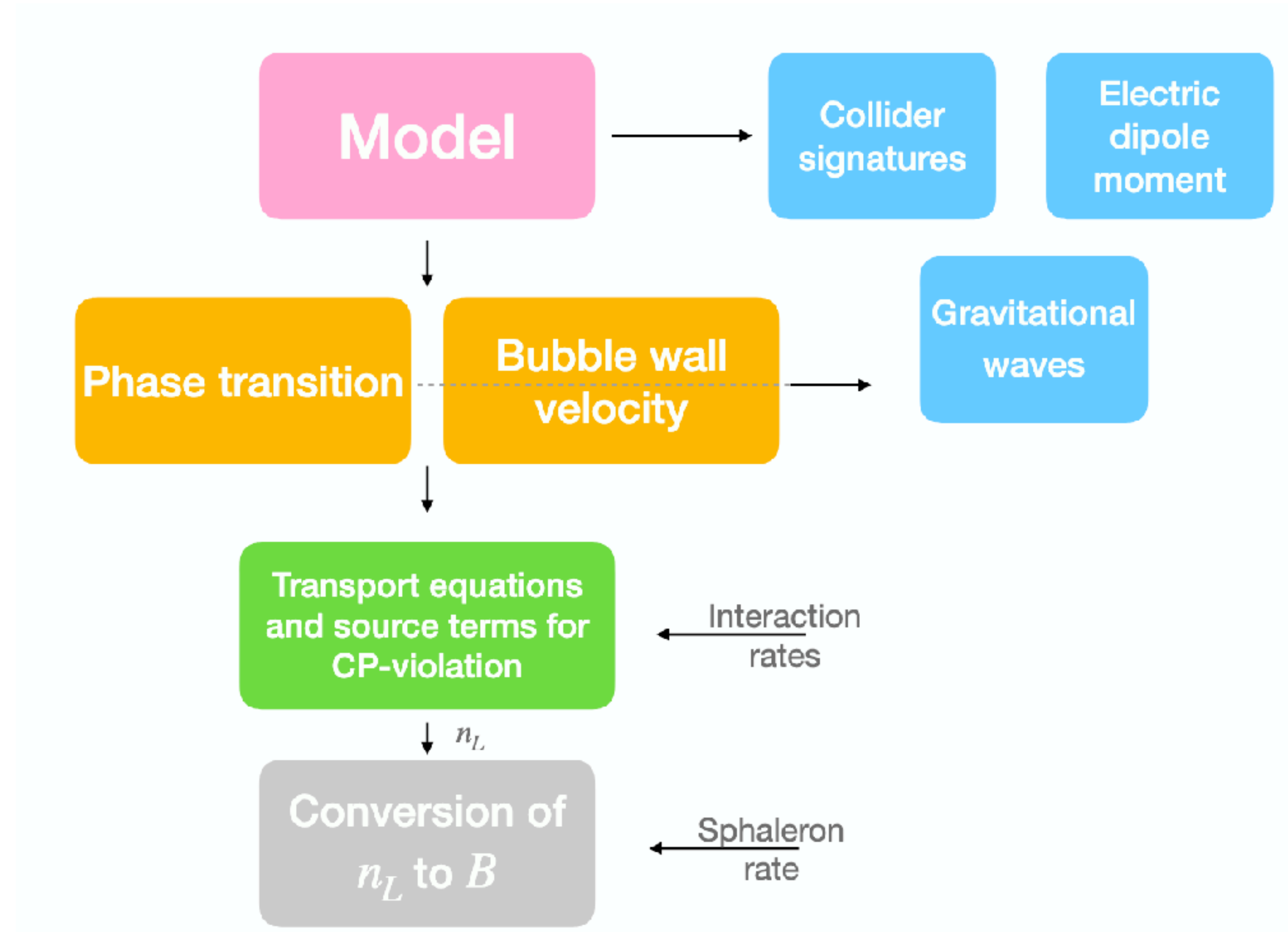
EDM constraints

- Very powerful probes for all sorts of CP violation
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- Most simple EWBG scenarios with BSM physics around the TeV scale to generate a first-order electroweak phase transition and new CP violation are stringently constrained by EDM experiments.
 - Also for two-Higgs doublet models, where EDMs are induced at the two-loop level
- Need to take EDM constraints into account!

GW signals of EW baryogenesis



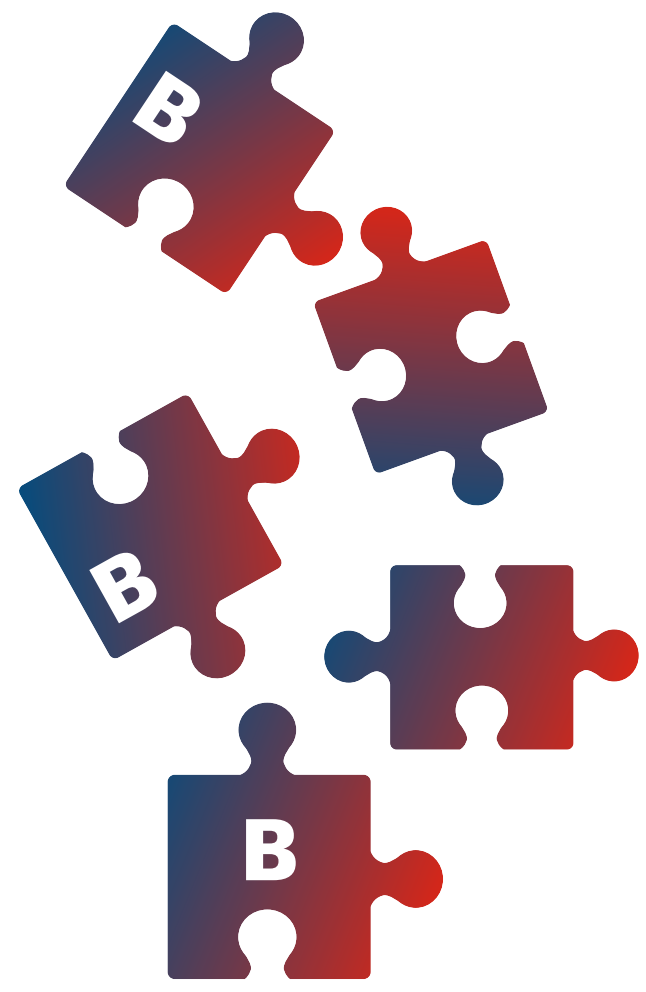
Model Building



Further reading:

- Baryogenesis, J.M. Cline [0609145]
- Bubble Trouble, J. De Vries, J. Van Der Vis, M. Postma [<https://arxiv.org/abs/2508.09989>] “best review on EW baryogenesis”
- D. E. Morrissey, M. J. Ramsey-Musolf, Electroweak baryogenesis, New J. Phys. 14 (2012) 125003. arXiv:1206.2942
- W. Bernreuther, CP violation and baryogenesis, Lect. Notes Phys. 591 (2002) 237–293. arXiv:hep-ph/0205279.
- <https://indico.physik.uni-bielefeld.de/event/100/contributions/315/attachments/277/455/ElectroweakBaryogenesisJvdVis.pdf>

**Could CP violation in B decays
solve the matter-antimatter asymmetry?**



Baryogenesis from B mesons

Baryogenesis from B mesons

- Amount of the SM CP violation in B mesons could be enough!
- Proposes a mechanism to convert to baryon asymmetry



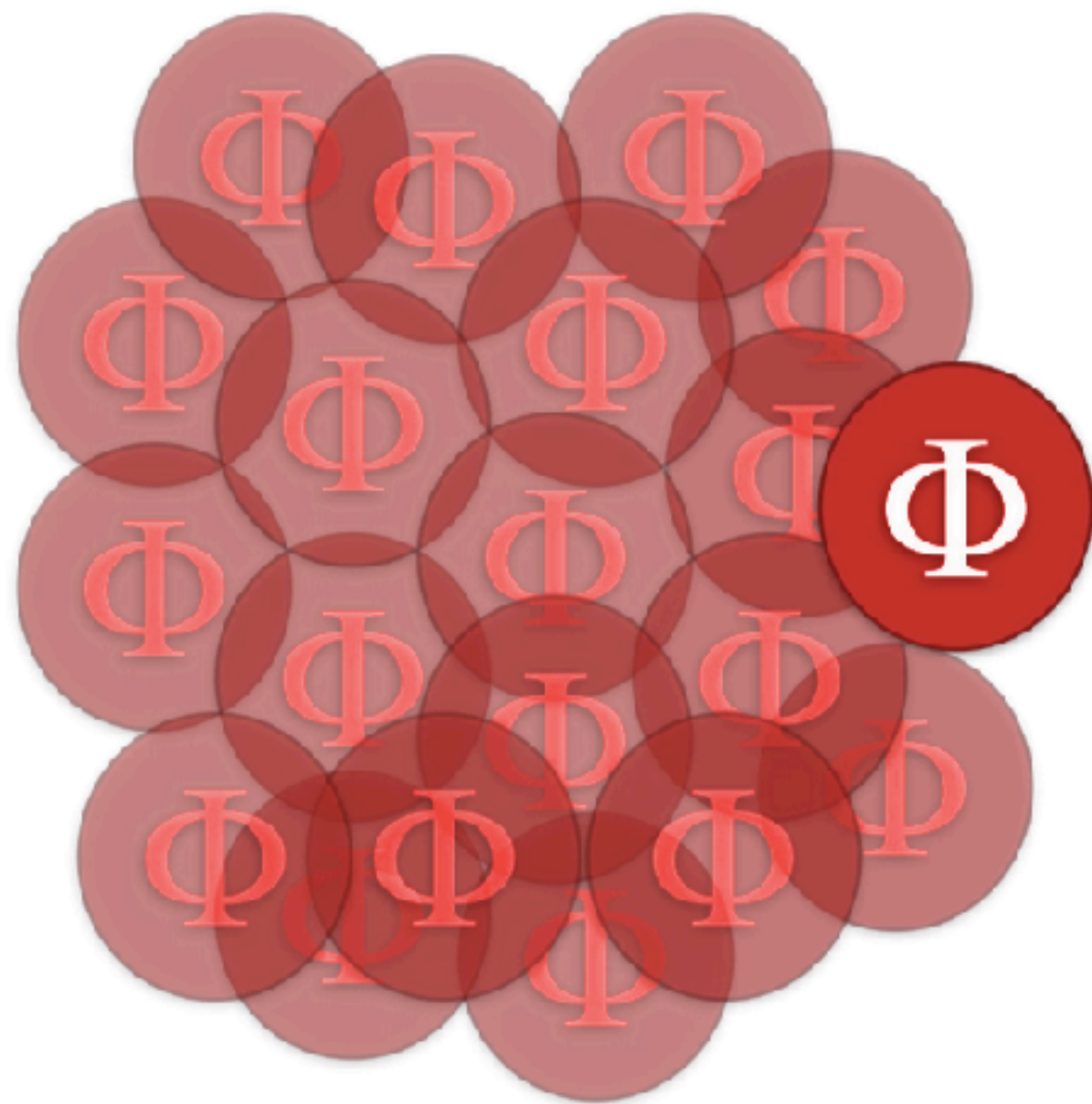
- Low-scale baryogenesis + dark matter candidate
- Testable at LHC!

Big thanks to Marta Burgos for allowing me to borrow her slides!

Baryogenesis from B mesons

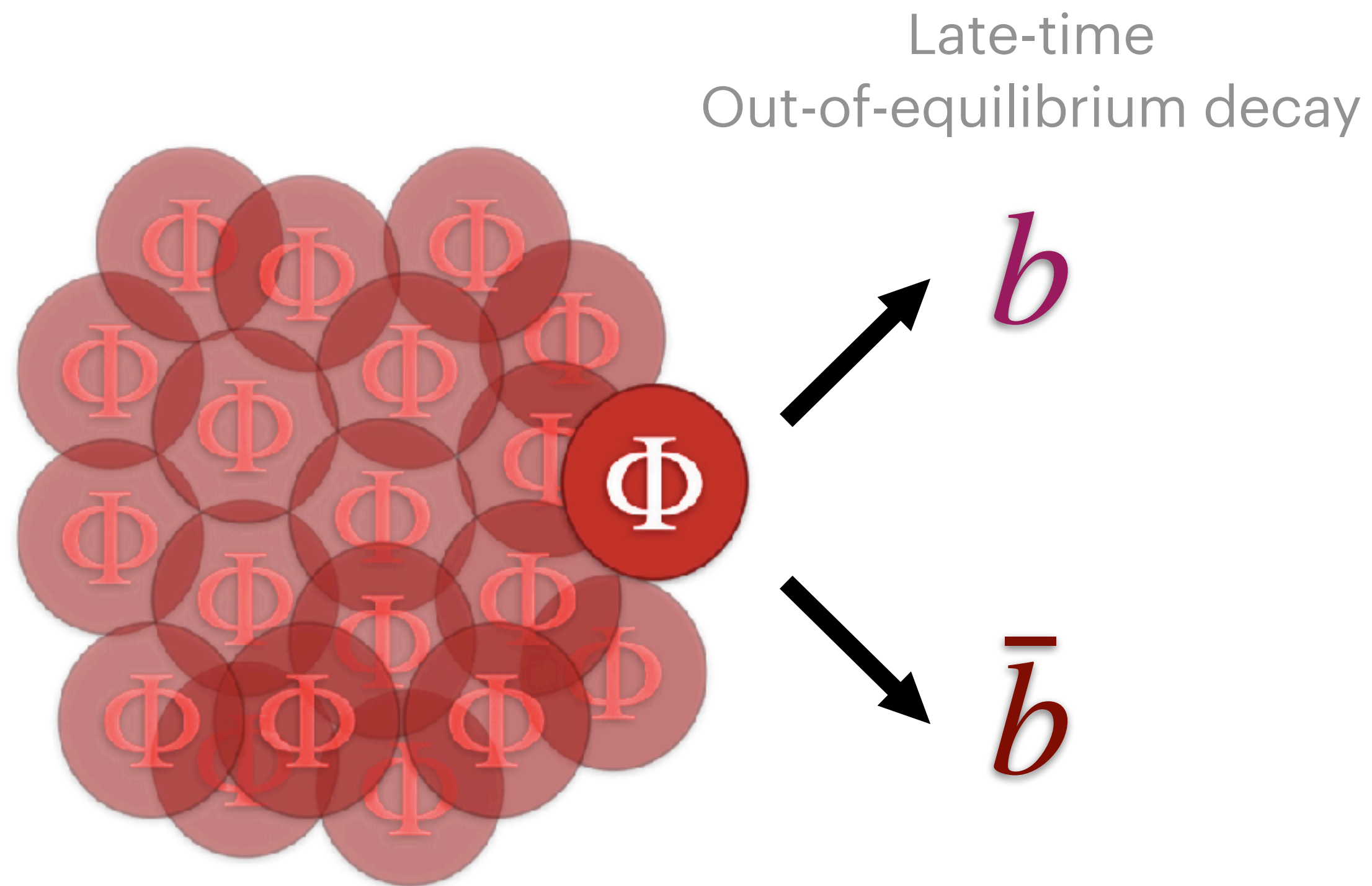
- Introduce a new scalar field

Late-time
Out-of-equilibrium decay



Baryogenesis from B mesons

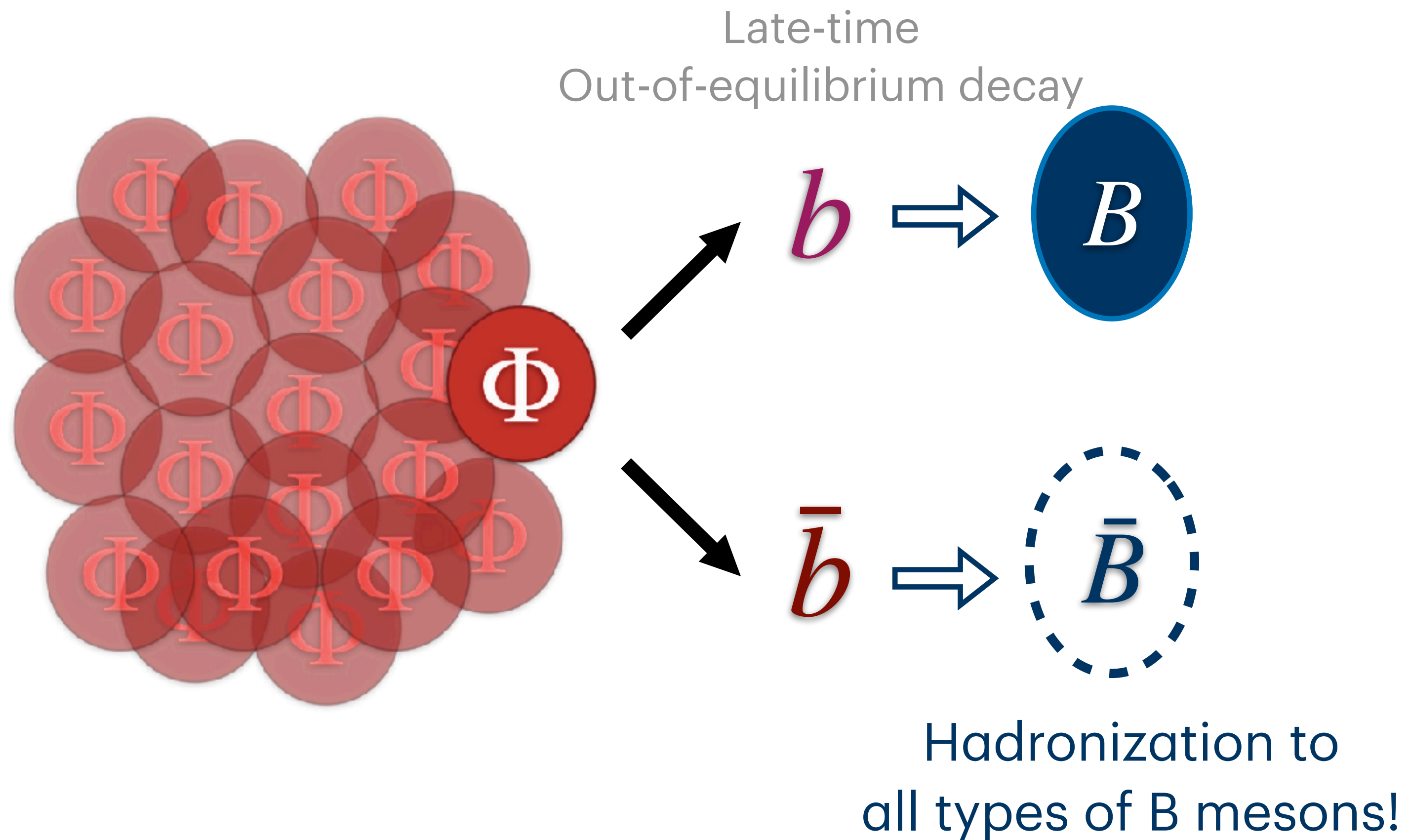
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Decay into b quarks at
 $T_{\text{reh}} \sim 100 \text{ MeV} < \Lambda_{\text{QCD}}$

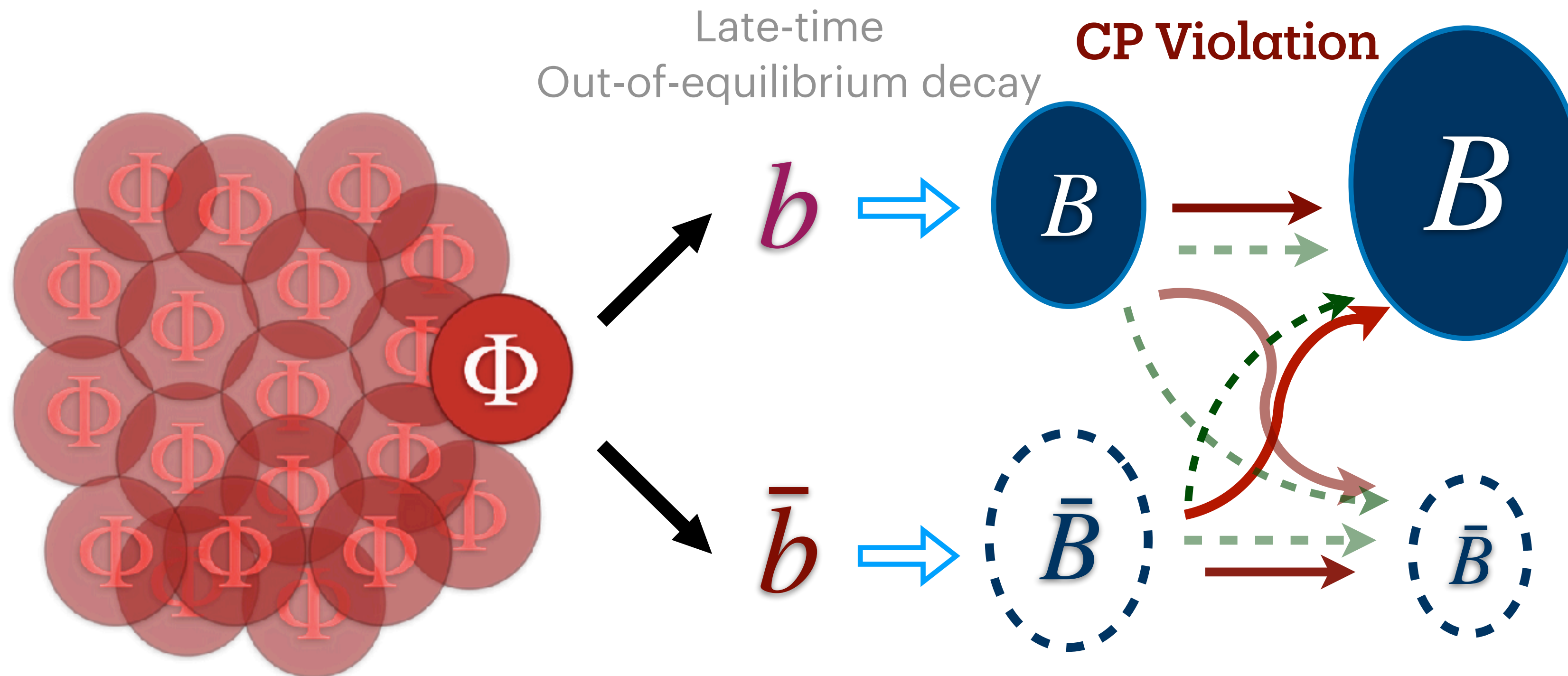
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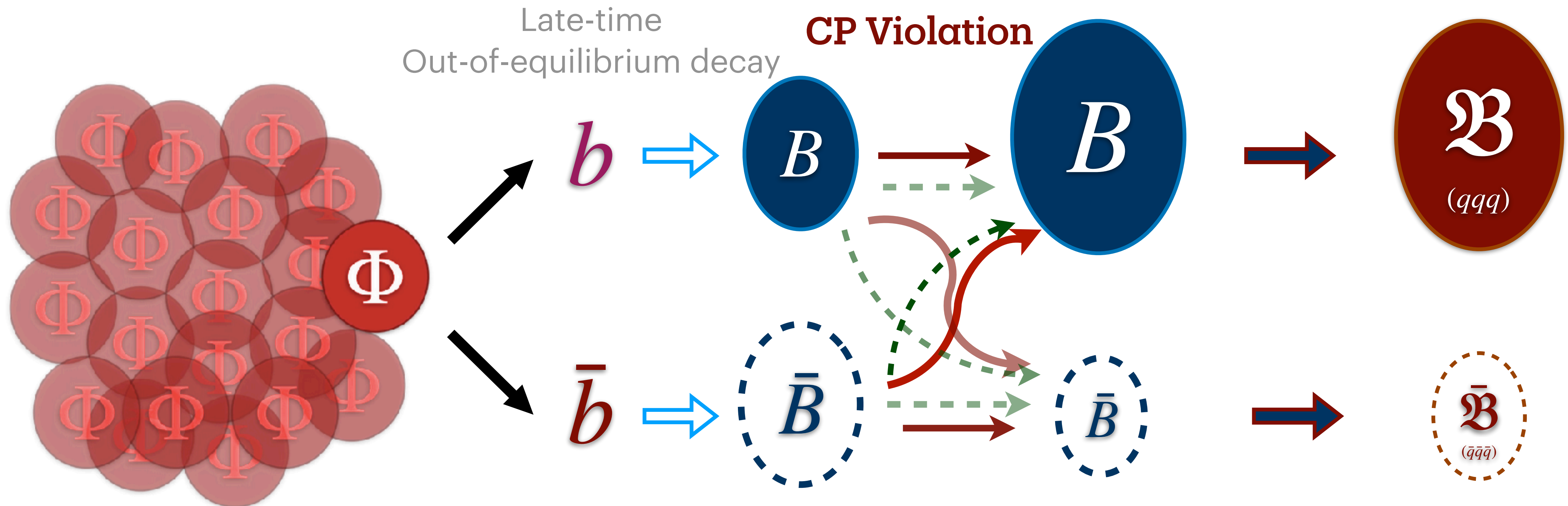
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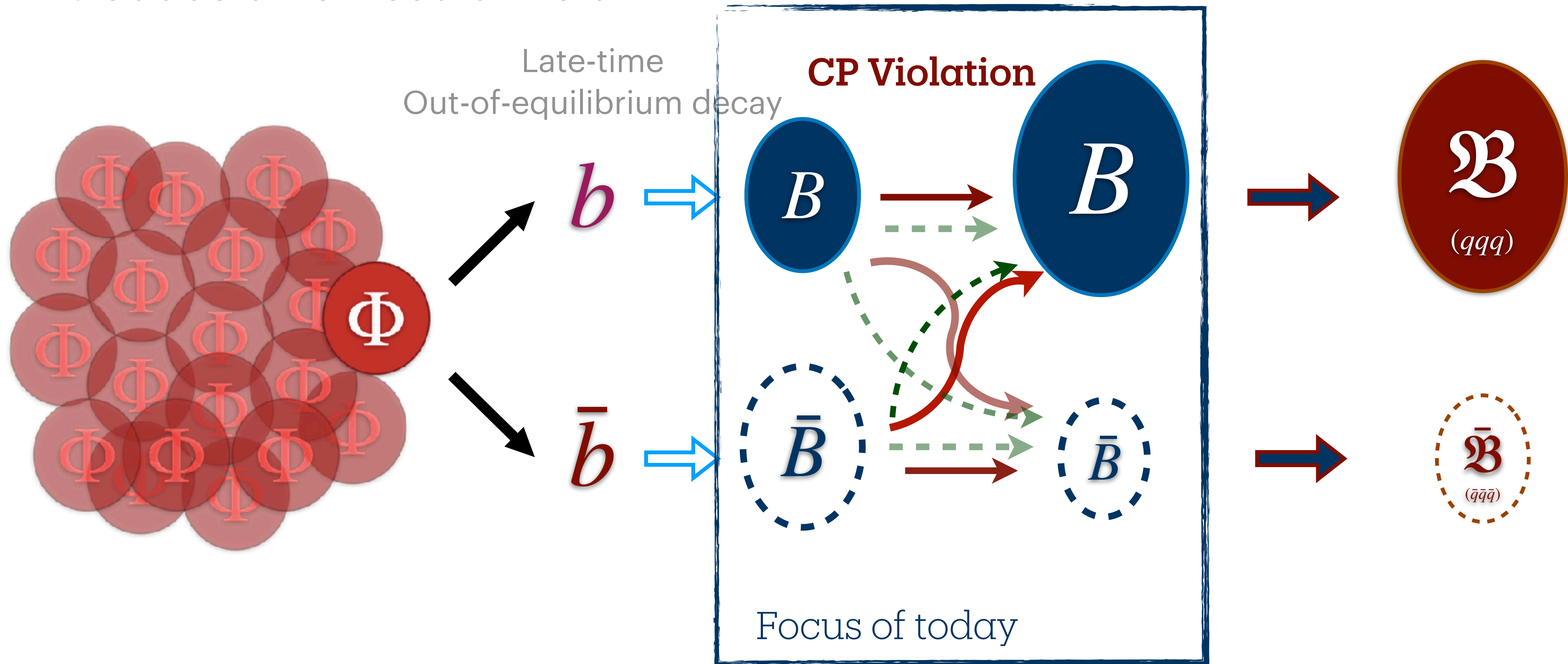
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Decay to SM baryons!
Signs at LHC?

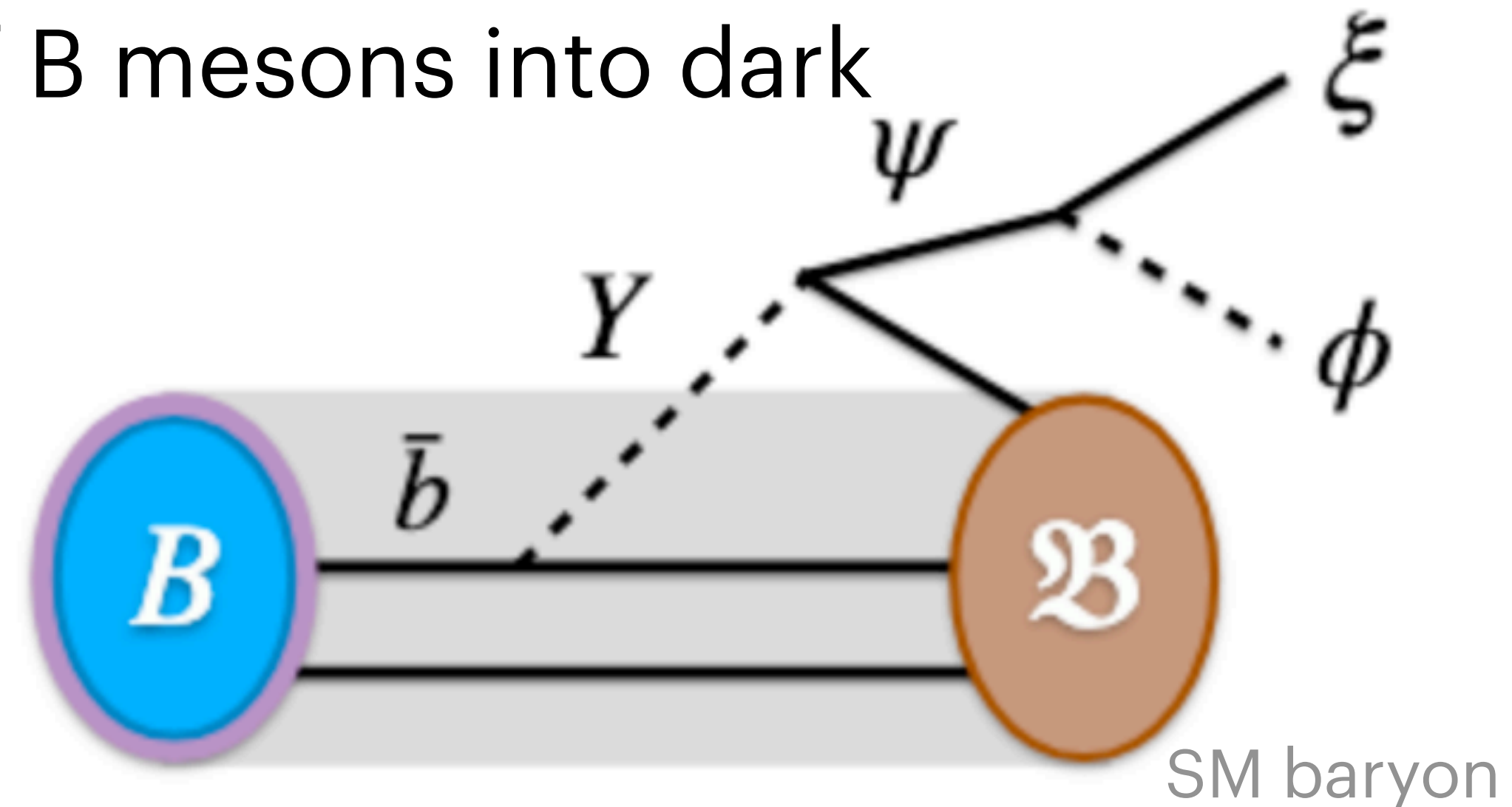
Baryogenesis from B mesons

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Baryogenesis and Sakharov conditions

- C and CP violation: Neutral B oscillations and direct CPV [SM]
- Out of equilibrium: very low temperatures/late time
- Baryon number violation:
Actually conserved, but new decay mode of B mesons into dark matter and baryon
 - create visible baryon number violation
 - processes could be observed at LHC!



Signs at the LHC?

Slide from Miguel Escudero

There is no available dedicated search for these processes!

Ways to constrain these new decay modes:

1) Indirectly from inclusive searches involving Baryons

$$\text{Br}(B \rightarrow \psi + \text{Baryon} + \mathcal{M}) \lesssim 10\% \quad (\text{ARGUS, CLEO \& BaBar})$$

2) Direct exclusive searches at B factories

sensitivity should be given that

$$\text{Br}(B \rightarrow \psi + \text{Baryon}) \sim 10^{-6} - 10^{-5}$$

$$\text{Br}(B \rightarrow K\bar{\nu}\nu) \sim 10^{-6} - 10^{-5}$$

There are ongoing searches at BaBar, Belle and Belle-II Echenard et al. Strube et al.

3) Searches for resonances at LHCb Cid Vidal et al.

4) Searches for b-flavor baryon decays LHCb Georgieva Chobanova, Martinez Santos et al.

➔ **5) At ALEPH! Inclusive search for missing energy of b decays** hep-ex/0010022

➔ **6) Indirectly at ATLAS and CMS** by constraining the mediator that should be $M < 10 \text{ TeV}$

$$\text{Br}(B \rightarrow \psi + \text{Baryon} + \mathcal{M}) \lesssim 6 \times 10^{-3}$$

Operator	Initial State	Final state	ΔM (MeV)
$\psi b u s$	B_d	$\psi + \Lambda(USD)$	4163.95
	B_s	$\psi + \Xi^0(uss)$	4025.03
	B^+	$\psi + \Sigma^+(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi b u d$	B_d	$\psi + n(udd)$	4340.07
	B_s	$\psi + \Lambda(uds)$	4251.21
	B^+	$\psi + p(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi b c s$	B_d	$\psi + \Xi_c^0(csd)$	2807.76
	B_s	$\psi + \Omega_c(css)$	2671.69
	B^+	$\psi + \Xi_c^+(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi b c d$	B_d	$\psi + \Lambda_c + \pi^-(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0(cds)$	2895.02
	B^+	$\psi + \Lambda_c(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \bar{D}^0$	3754.7

Necessary CP violation

$$Y_{\mathfrak{B}} = \frac{n_{\mathfrak{B}} - n_{\bar{\mathfrak{B}}}}{s} \simeq 8.7 \times 10^{-11}$$

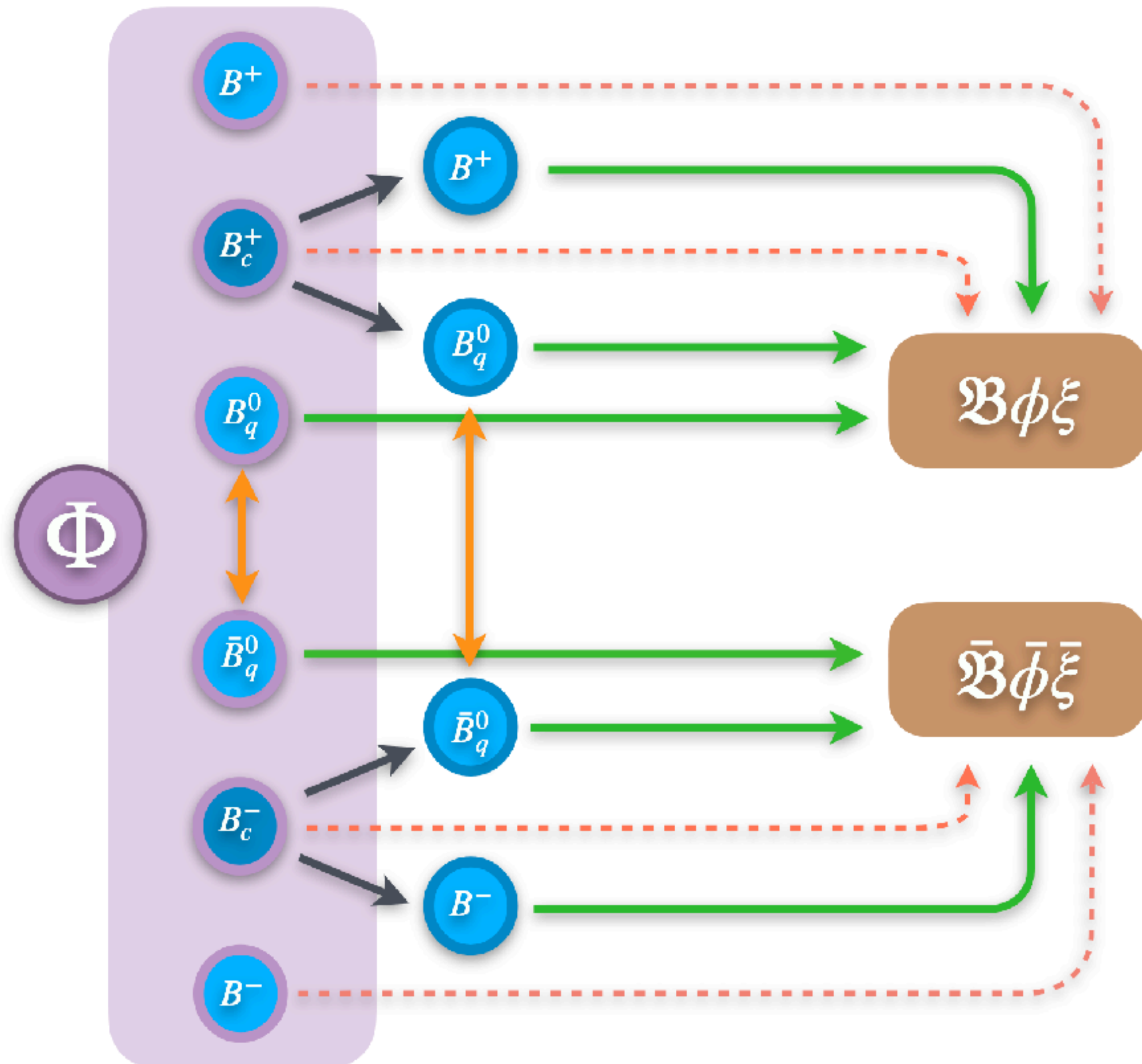
See Elor, Nelson, Escudero, McGehee, et al. [2019-2025]

$$Y_{\mathfrak{B}} = \alpha (T_{\text{reh}}) \frac{T_{\text{reh}}}{M_{\Phi}} \Delta_B \longrightarrow \alpha (T_{\text{reh}}) \frac{T_{\text{reh}}}{M_{\Phi}} \sim 10^{-5} - 10^{-3}$$

Difference between B and \bar{B} needed \longrightarrow

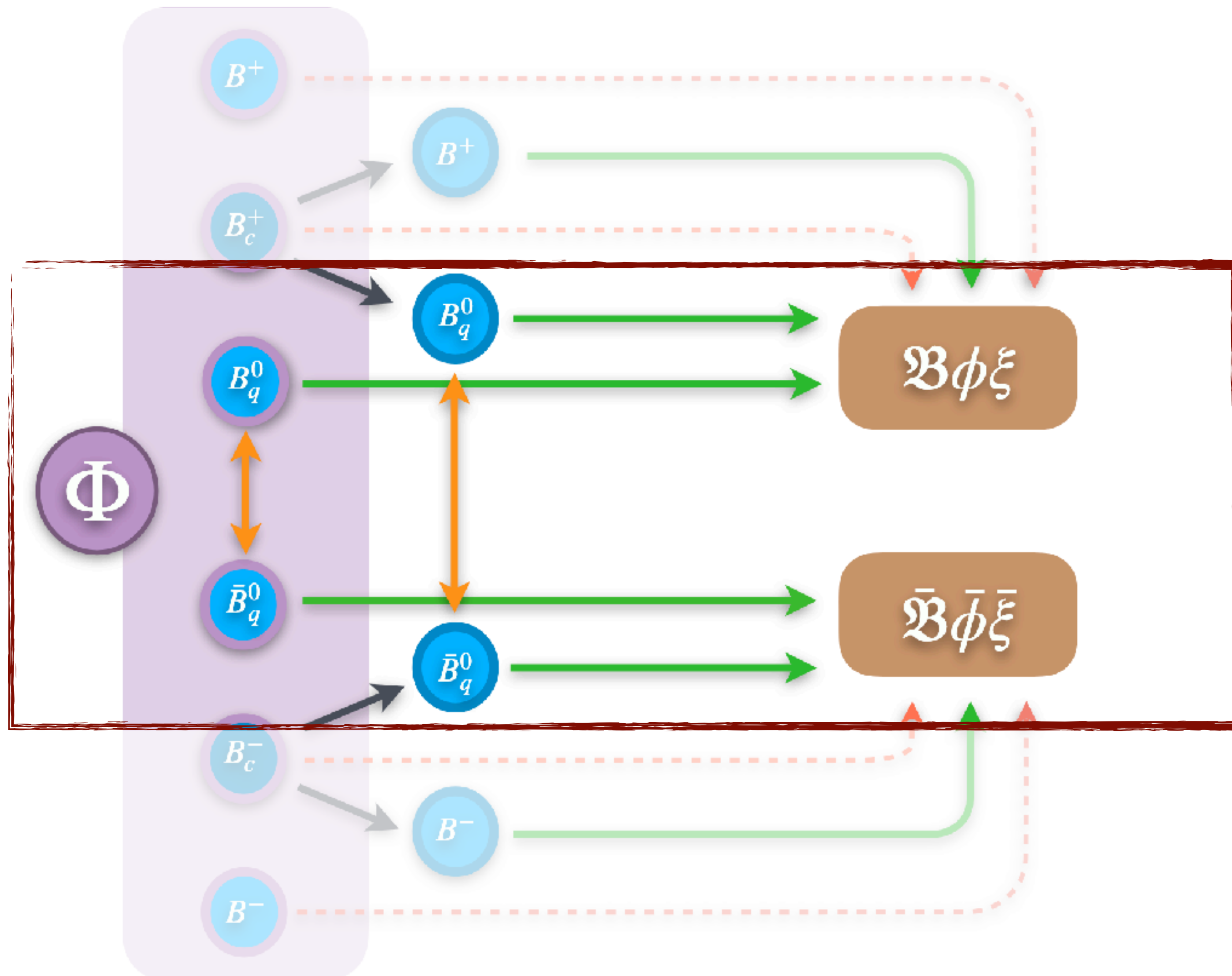
$$\Delta_B \sim 10^{-8} - 10^{-6}$$

Types of B mesogenesis



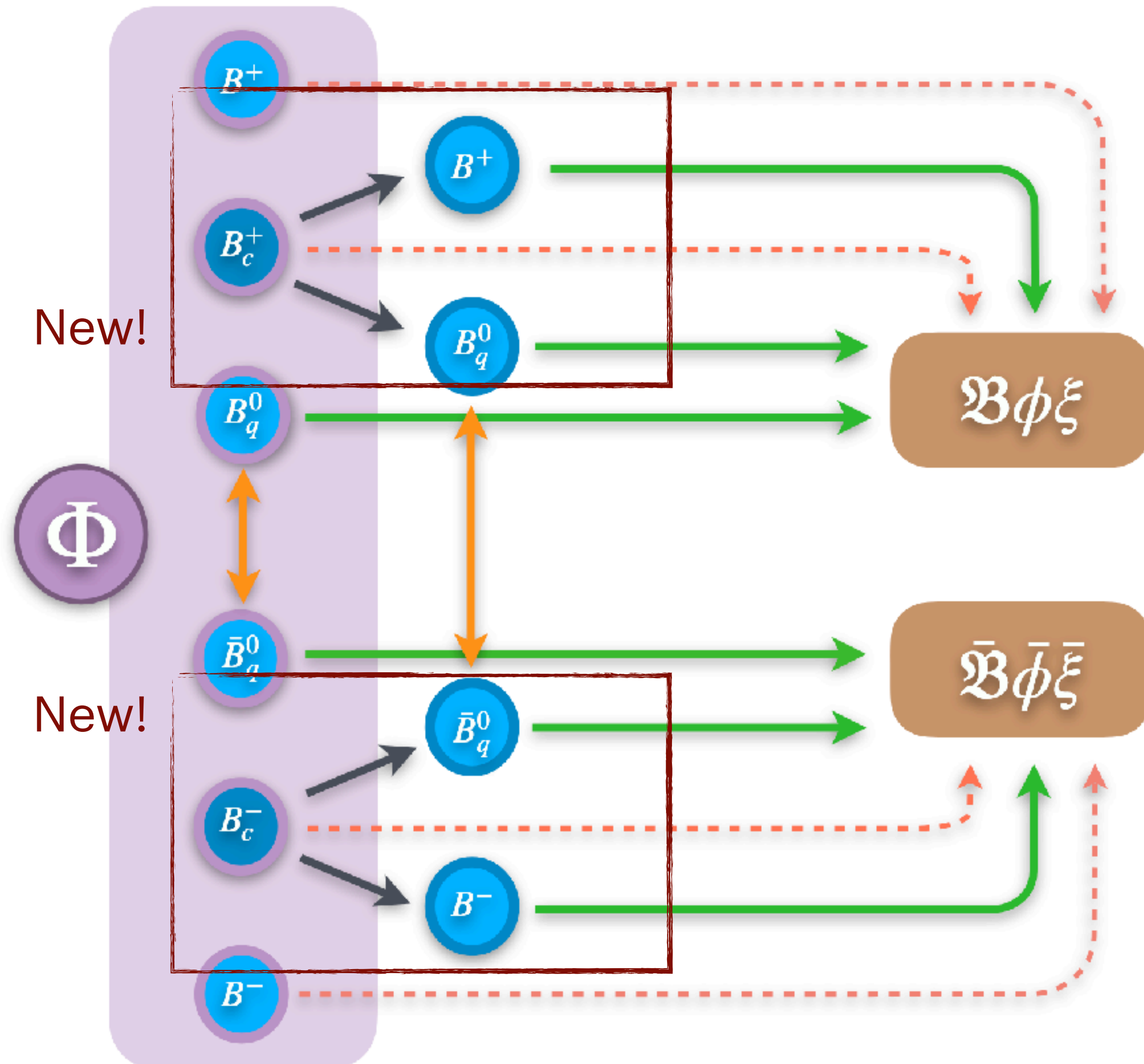
= no contribution to Δ_B

Neutral B mesogenesis



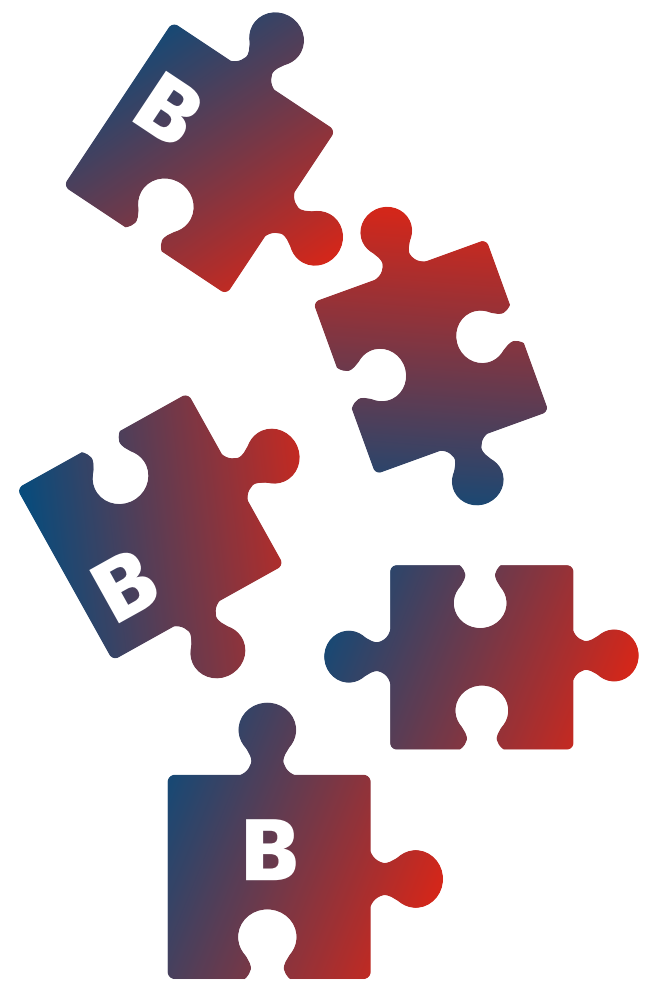
- The standard B mesogenesis
- Difference between B and \bar{B} through B-mixing

Unified B mesogenesis



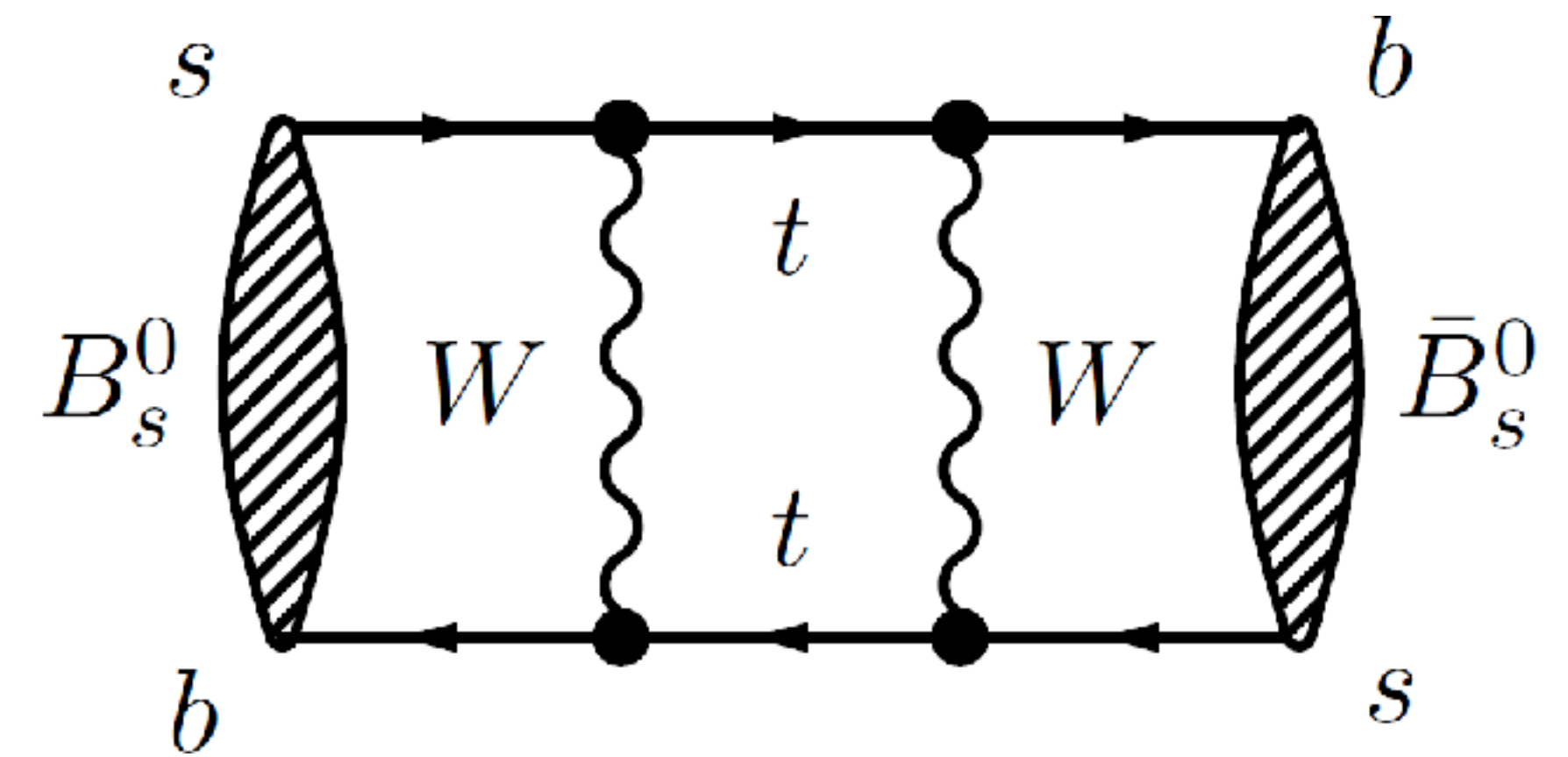
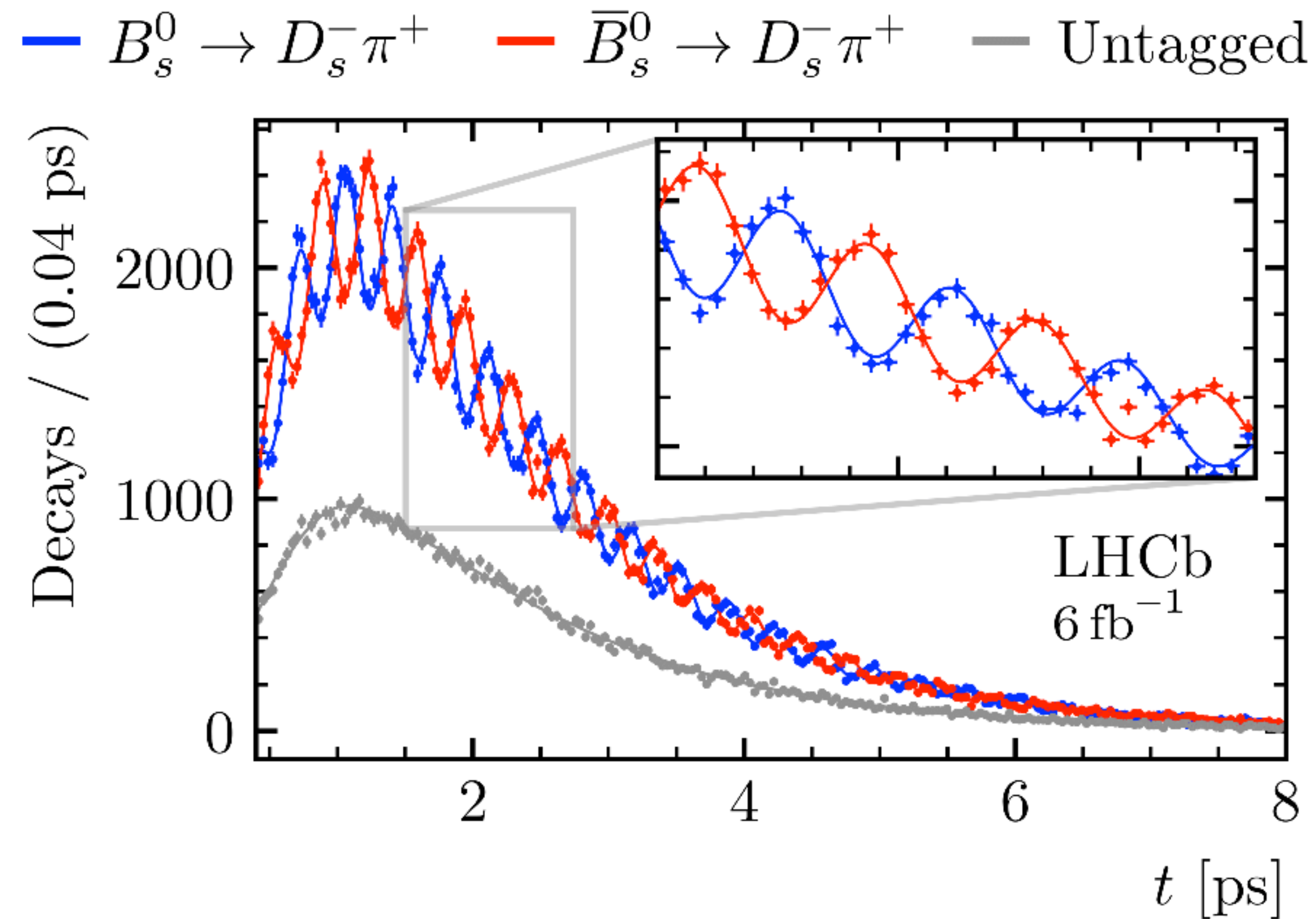
New:
 B_c (charming beauty mesons)
 in the spotlight

Combine all B decays



Neutral Meson Mixing

Matter-antimatter oscillations



$$|B_{q,L}^0\rangle = \mathfrak{p}_q |B_q^0\rangle + \mathfrak{q}_q |\bar{B}_q^0\rangle$$

$$|B_{q,H}^0\rangle = \mathfrak{p}_q |B_q^0\rangle - \mathfrak{q}_q |\bar{B}_q^0\rangle$$

$$\Delta M_q = M_{q,H} - M_{q,L} \simeq 2|M_{12}|, \quad \Delta\Gamma_q = \Gamma_{q,L} - \Gamma_{q,H} \simeq 2|\Gamma_{12}| \cos\phi_{12}.$$

Matter-antimatter oscillations

$$\Gamma(B_q^0(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 e^{-\Gamma_q t} \frac{1}{2} \left\{ \cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + \cos(\Delta M_q t) \right\},$$

$$\Gamma(\bar{B}_q^0(t) \rightarrow \bar{f}) = \mathcal{N}_f |\bar{A}_{\bar{f}}|^2 e^{-\Gamma_q t} \frac{1}{2} \left\{ \cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + \cos(\Delta M_q t) \right\},$$

$$\Gamma(B_q^0(t) \rightarrow \bar{f}) = \mathcal{N}_f |\bar{A}_{\bar{f}}|^2 e^{-\Gamma_q t} (1 - a_q) \frac{1}{2} \left\{ \cosh\left(\frac{\Delta\Gamma_q t}{2}\right) - \cos(\Delta M_q t) \right\},$$

$$\Gamma(\bar{B}_q^0(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \frac{1}{1 - a_q} e^{-\Gamma_q t} \frac{1}{2} \left\{ \cosh\left(\frac{\Delta\Gamma_q t}{2}\right) - \cos(\Delta M_q t) \right\},$$

$$a_q = 1 - \left| \frac{\mathfrak{q}_q}{\mathfrak{p}_q} \right|^2 \quad \text{measures CP violation in mixing}$$

$$x_q \equiv \frac{\Delta M_q}{\Gamma_q}, y_q \equiv \frac{\Delta \Gamma_q}{2\Gamma_q}$$

Matter-antimatter oscillations

$$\mathcal{A}_{\text{CP}}^{\text{TI}}(B_q^0 \rightarrow \mathfrak{B}) \equiv \int_0^\infty \left[\Gamma(B_q^0(t) \rightarrow \mathfrak{B}) - \Gamma(B_q^0(t) \rightarrow \bar{\mathfrak{B}}) \right] dt$$

- Integrate over the full decay time
- Interested in the total asymmetry independent of whether we produced a B or \bar{B}

$$\mathcal{A}_{\text{CP}}^{\text{TI}}(\langle B_q^0 \rightarrow \mathfrak{B} \rangle) \equiv \mathcal{A}_{\text{CP}}^{\text{TI}}(B_q^0 \rightarrow \mathfrak{B}) + \mathcal{A}_{\text{CP}}^{\text{TI}}(\bar{B}_q^0 \rightarrow \mathfrak{B})$$

$$\mathcal{A}_{\text{CP}}^{\text{TI}}(\langle B_q^0 \rightarrow \mathfrak{B} \rangle) = \frac{x_q^2 + y_q^2}{(1 + x_q^2)(1 - y_q^2)} a_q \mathcal{B}(B_q^0 \rightarrow \mathfrak{B})|_{t=0} + \mathcal{O}(a_q^2)$$

Not fully known:

assume 10^{-3}

$$x_q \equiv \frac{\Delta M_q}{\Gamma_q}, y_q \equiv \frac{\Delta \Gamma_q}{2\Gamma_q}$$

Matter-antimatter oscillations

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Known:

1 for Bs, 0.4 for Bd

$$x_q \equiv \frac{\Delta M_q}{\Gamma_q}, y_q \equiv \frac{\Delta \Gamma_q}{2\Gamma_q}$$

Matter-antimatter oscillations

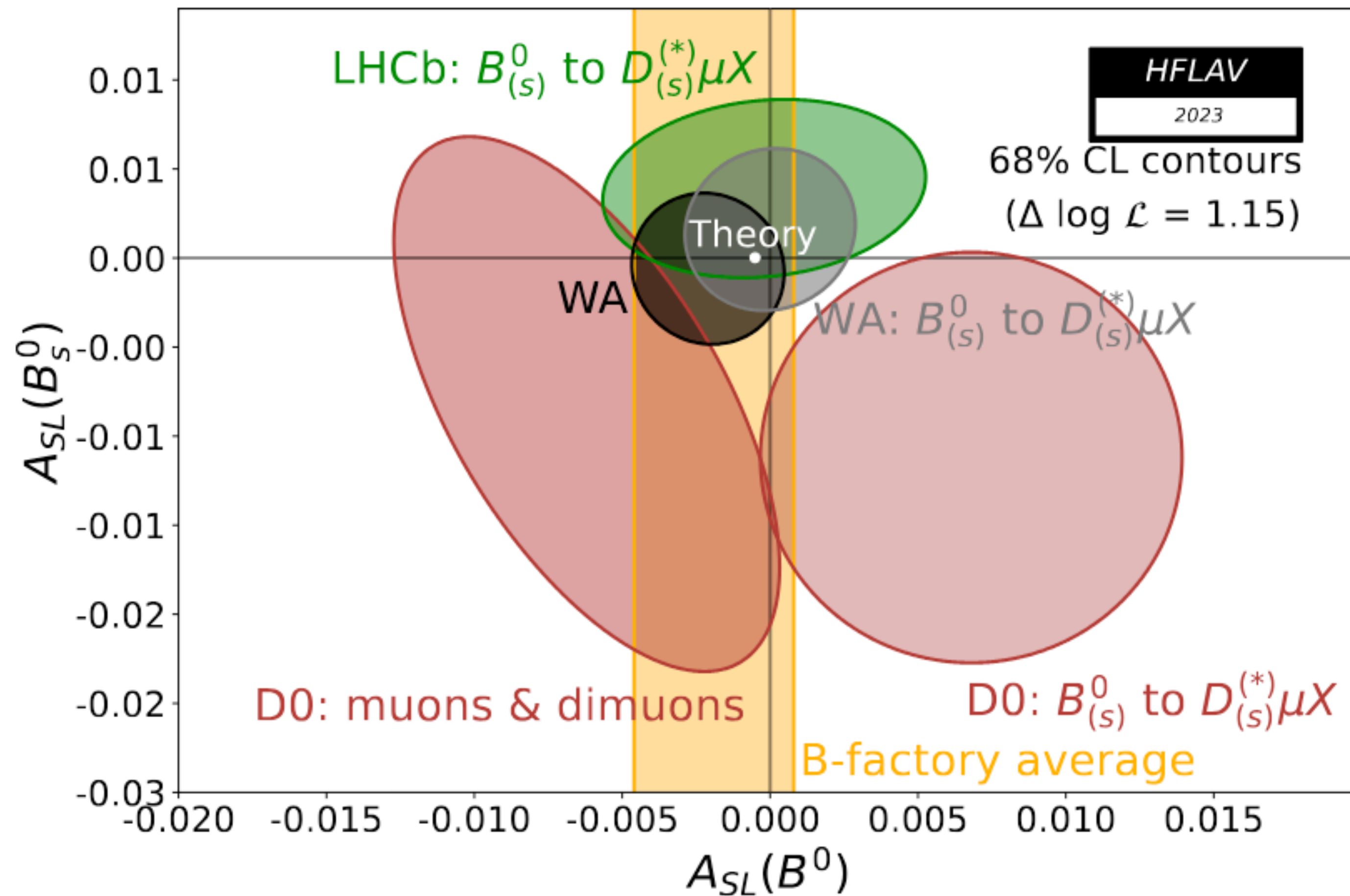
$$\mathcal{A}_{\text{CP}}^{\text{TI}}(B_q^0 \rightarrow \mathfrak{B}) \equiv \int_0^\infty \left[\Gamma(B_q^0(t) \rightarrow \mathfrak{B}) - \Gamma(B_q^0(t) \rightarrow \bar{\mathfrak{B}}) \right] dt$$

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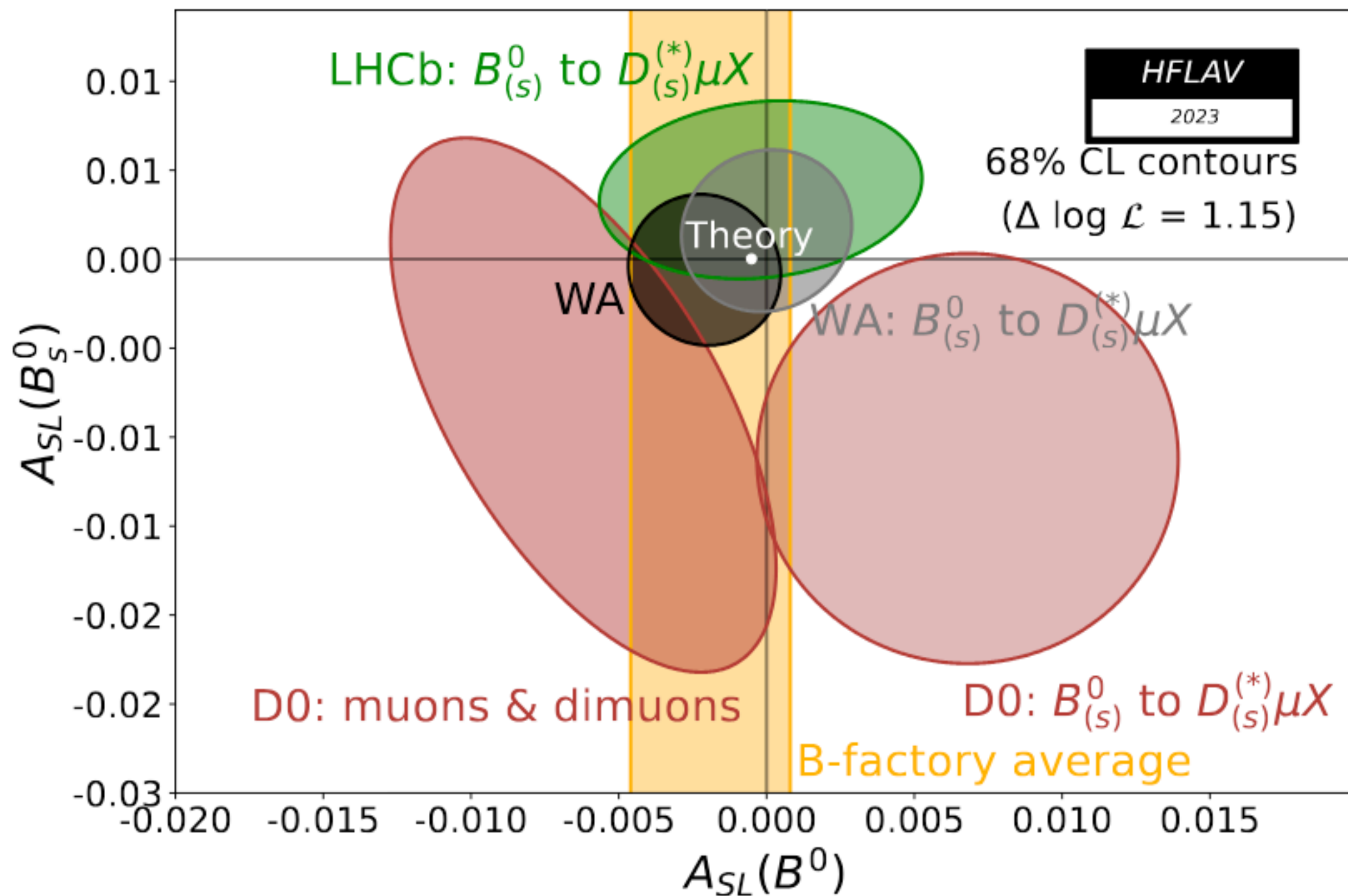
CP violation in mixing



Semileptonic asymmetry

$$\mathcal{A}_{SL}^d = \frac{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) - N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) + N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}$$

CP violation in mixing



Semileptonic asymmetry a_q

$$\mathcal{A}_{SL}^d = \frac{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) - N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) + N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}$$

$$a_d^{\text{exp}} = (-2.1 \pm 1.7) \times 10^{-3},$$

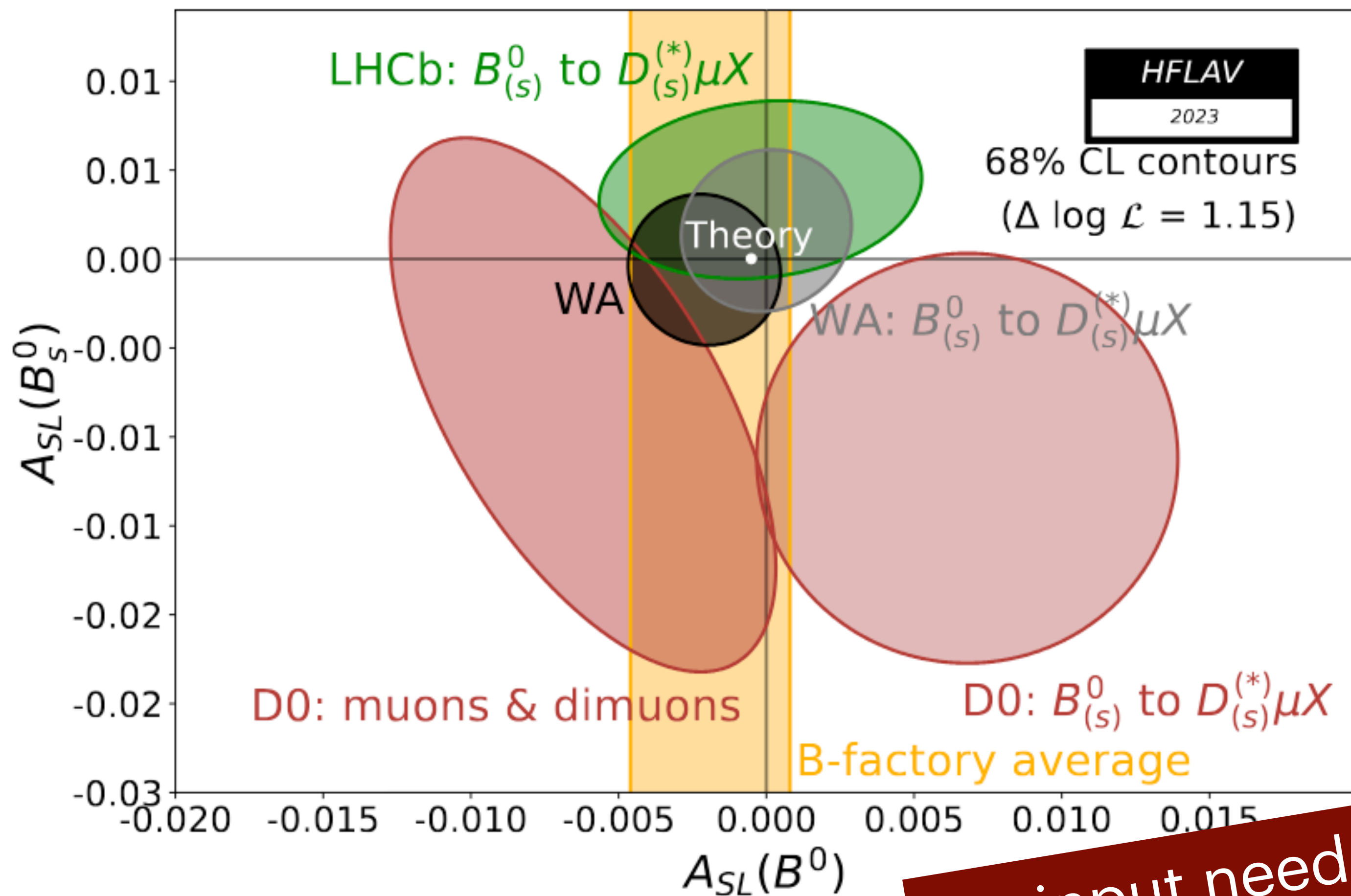
$$a_s^{\text{exp}} = (-0.6 \pm 2.8) \times 10^{-3}$$

Theory:

$$a_d^{\text{theo}} = (-5.1 \pm 0.5) \times 10^{-4},$$

$$a_s^{\text{theo}} = (2.2 \pm 0.2) \times 10^{-5},$$

CP violation in mixing



Semileptonic asymmetry a_q

$$\mathcal{A}_{\text{SL}}^d = \frac{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) - N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) + N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}$$

$$a_d^{\text{exp}} = (-2.1 \pm 1.7) \times 10^{-3},$$

$$a_s^{\text{exp}} = (-0.6 \pm 2.8) \times 10^{-3}$$

Theory:

$$a_s^{\text{theo}} = (2.2 \pm 0.2) \times 10^{-5},$$

Key input needed to see if B mesogenesis works!

$$\Delta_B \sim 10^{-8} - 10^{-6}$$

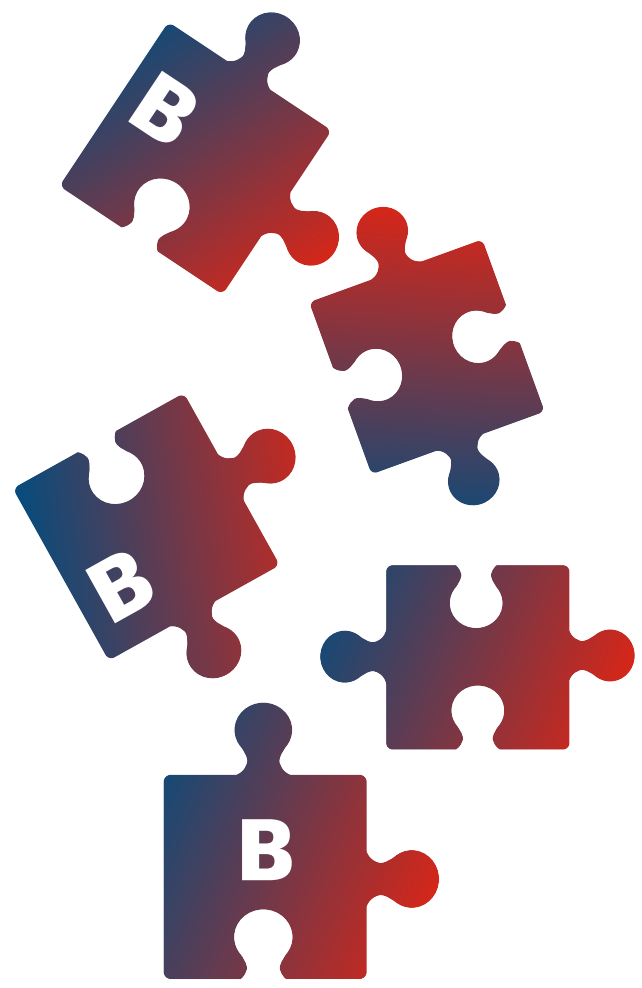
Does it work?

$$\Delta_B \supset f_d \mathcal{A}_{\text{CP}}^{\text{TI}}(\langle B_d^0 \rightarrow \mathfrak{B} \rangle) + f_s \mathcal{A}_{\text{CP}}^{\text{TI}}(\langle B_s^0 \rightarrow \mathfrak{B} \rangle)$$

$$\begin{aligned} \Delta_{B_d^0}^{\text{exp}} &= (-7.8 \pm 6.3 |_{\text{SM}}) \times 10^{-7} & \Delta_{B_s^0}^{\text{exp}} &= (-6 \pm 28 |_{\text{SM}}) \times 10^{-7}, \\ \Delta_{B_d^0}^{\text{theo}} &= (-19 \pm 1.9 |_{\text{SM}}) \times 10^{-8} & \Delta_{B_s^0}^{\text{theo}} &= (2.2 \pm 0.2 |_{\text{SM}}) \times 10^{-8}, \end{aligned}$$

Experiment: Predicts a negative asymmetry(?) but with large uncertainty

Theory: Needs many more Bs than Bd's to work



B_c mesogenesis

Two possible mechanisms

$B_c \rightarrow B^+$ decays



Only direct CP violation
could contribute

$B_c \rightarrow B^0$ decays

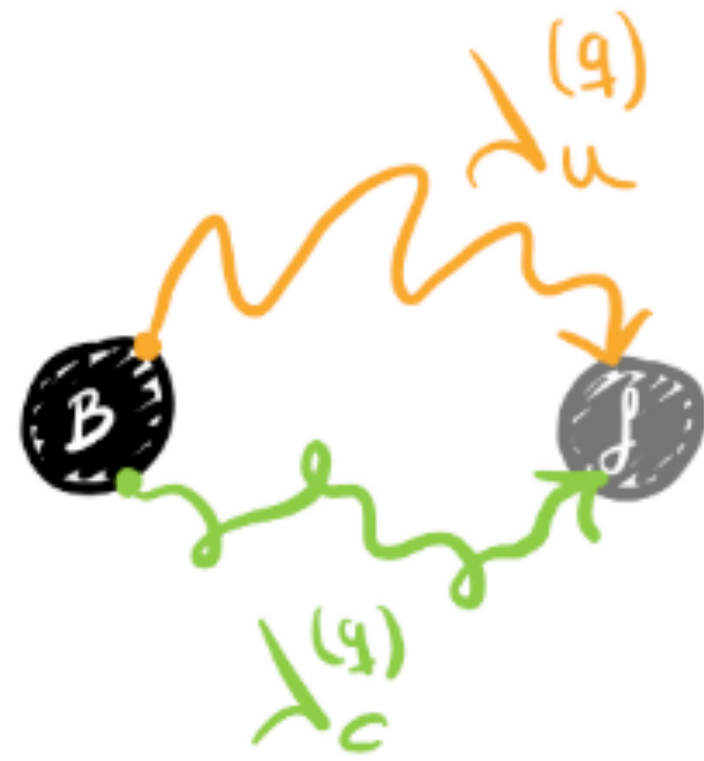


First mix and
then direct CP violation in neutral B!

Hybrid Scenario!

Direct CP violation in Bc decays

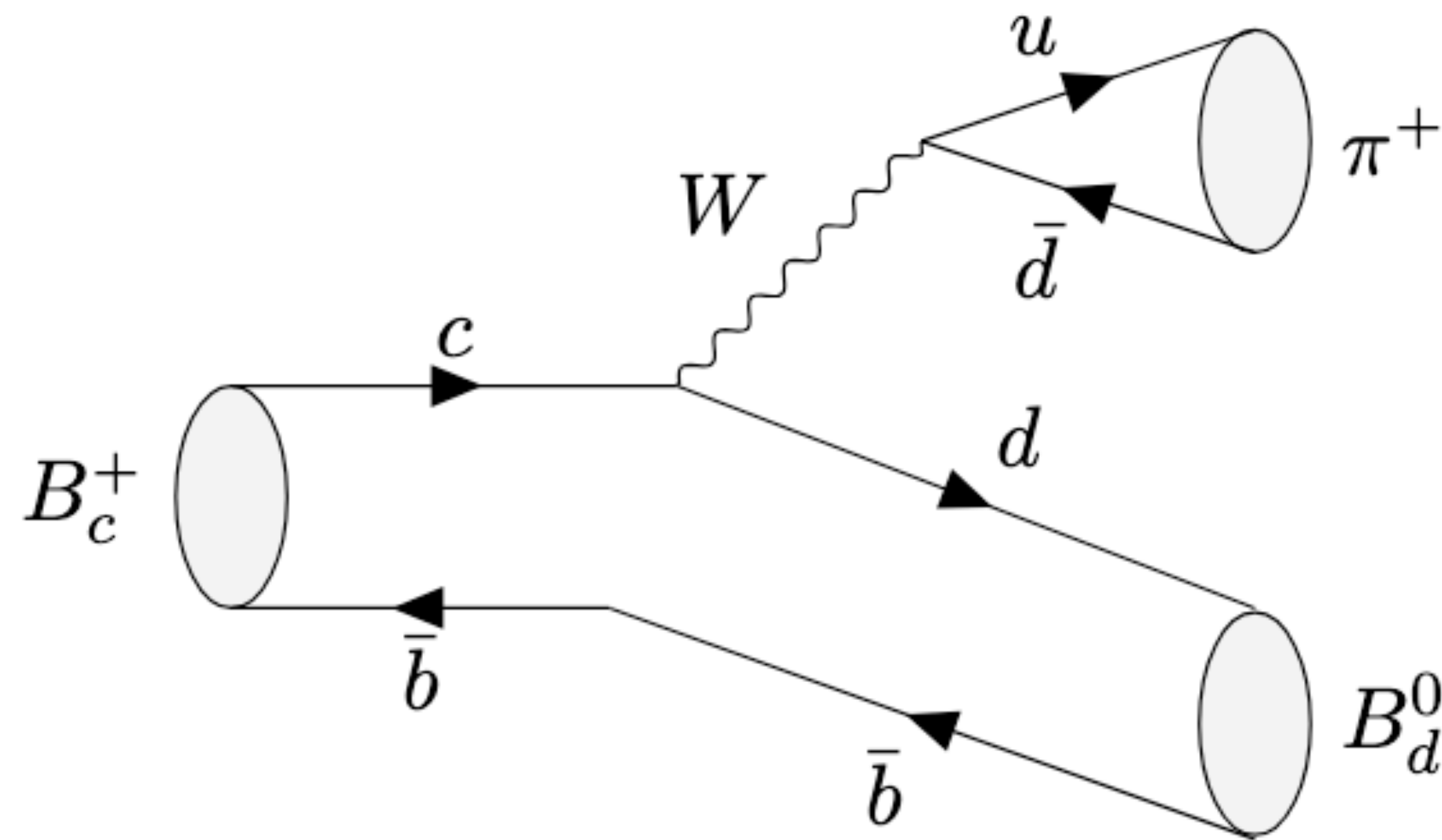
$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow B^+ M^0) = \frac{\Gamma(B_c^+ \rightarrow B^+ M^0) - \Gamma(B_c^- \rightarrow B^- \bar{M}^0)}{\Gamma(B_c^+ \rightarrow B^+ M^0) + \Gamma(B_c^- \rightarrow B^- \bar{M}^0)},$$



$$\Delta_B \supset f_c \sum_{M^0} \mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow B^+ M^0) \mathcal{B}(B_c^+ \rightarrow B^+ M^0) \mathcal{B}(B^+ \rightarrow \mathfrak{B})$$

Requirements for direct CP violation: weak phase difference and strong phase difference!

Gives possible very big CP violation in B decays, but ...



- b quark acts as spectator
- c is the weakly interacting quark:
same structure as $D \rightarrow hh$
- These are charm decays!

Charm CP violation in the SM

$$\mathcal{A}(B_c^+ \rightarrow BM) = i \frac{G_F}{\sqrt{2}} \left(V_{cD}^* V_{uD'} \mathcal{T}_i + V_{cb}^* V_{ub} \mathcal{P}_i \right)$$

Only SCS have 2 amplitudes and give CP violation!

Requirements for direct CP violation: weak phase difference and strong phase difference!

$$\mathcal{A}_{\text{CP}}^{\text{dir}} = -2 \text{Im} \frac{\lambda_b}{\lambda_D} \text{Im} \frac{\mathcal{P}_i}{\mathcal{T}_i} \sim \mathcal{O}(10^{-3}) \text{Im} \frac{\mathcal{P}_i}{\mathcal{T}_i}$$

Reminder:

Cabibbo Favoured (CF) $V_{cs}^* V_{ud} \sim 1$

Singly Cabibbo Suppressed (SCS)

$V_{cs}^* V_{ud}, V_{cd}^* V_{us} \sim \lambda = 0.22$

Doubly Cabibbo Suppressed (DCS) $V_{cd}^* V_{us} \sim \lambda^2$

Charm CPV very suppressed in SM!

Hybrid Bc mesogenesis?

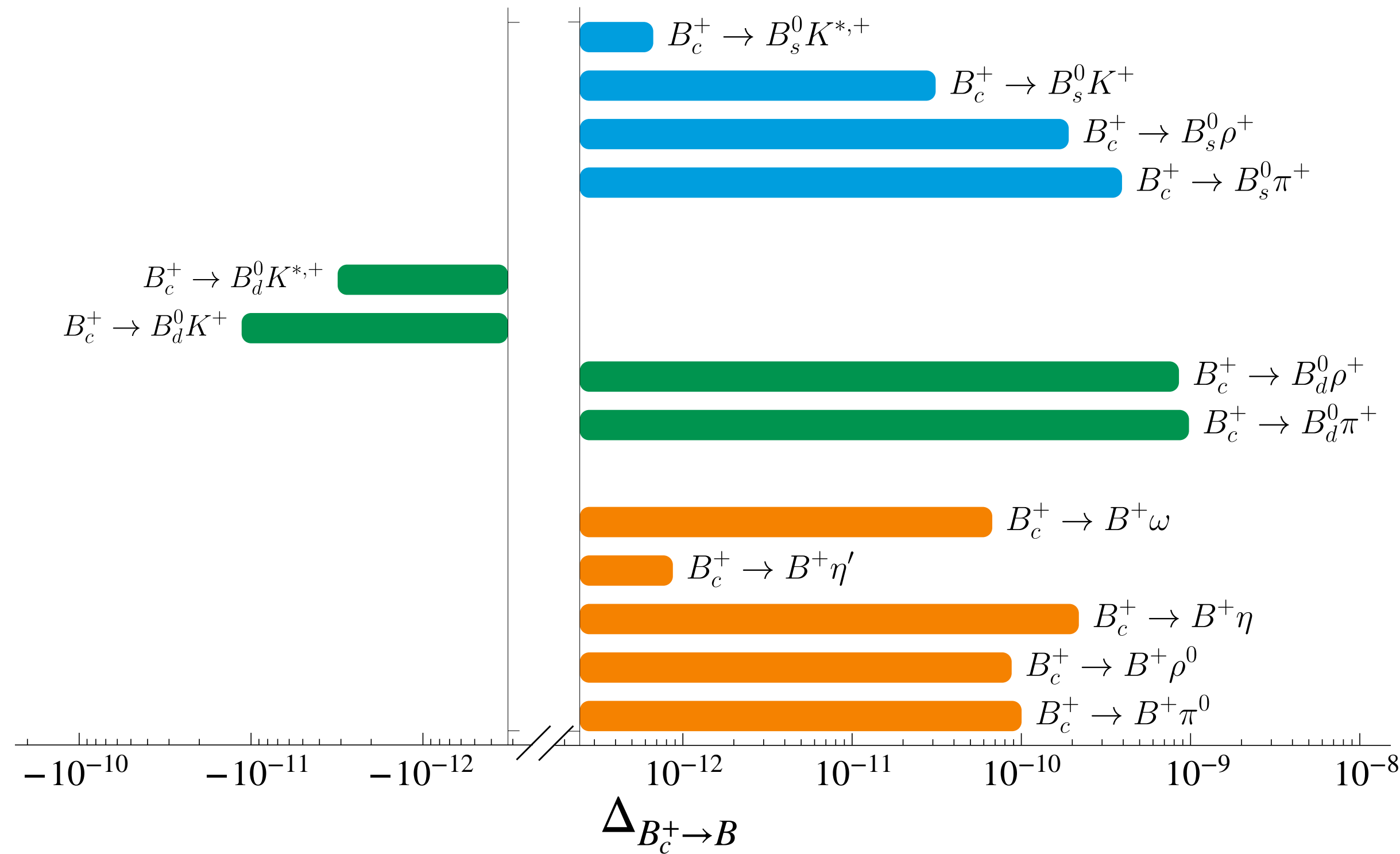
- Framework same as for B0 and Bs mesogenesis (so mixing)
- No branching ratio measurements available!
- We estimated the branching ratios using factorization

Hybrid Bc mesogenesis?

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- No branching ratio measurements available!
- We estimated the branching ratios using factorization

Measurements of Bc decays necessary!

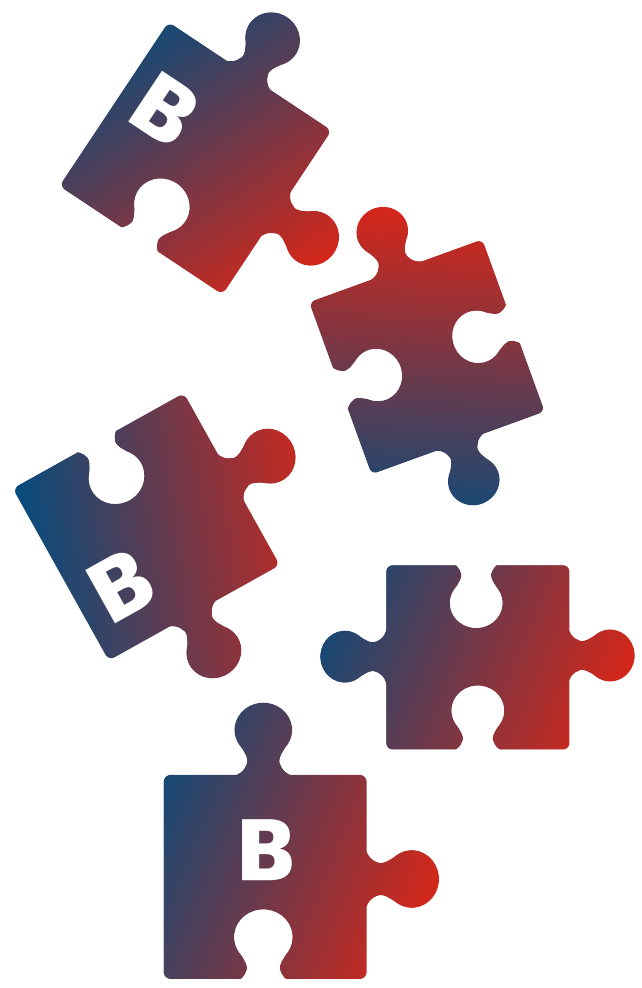
Bc Mesogenesis



$$\Delta_{B_c^+ \rightarrow B^+}^{\text{fac}} = (4.7 \times 10^{-7}) \times \mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow B^+ M^0)$$

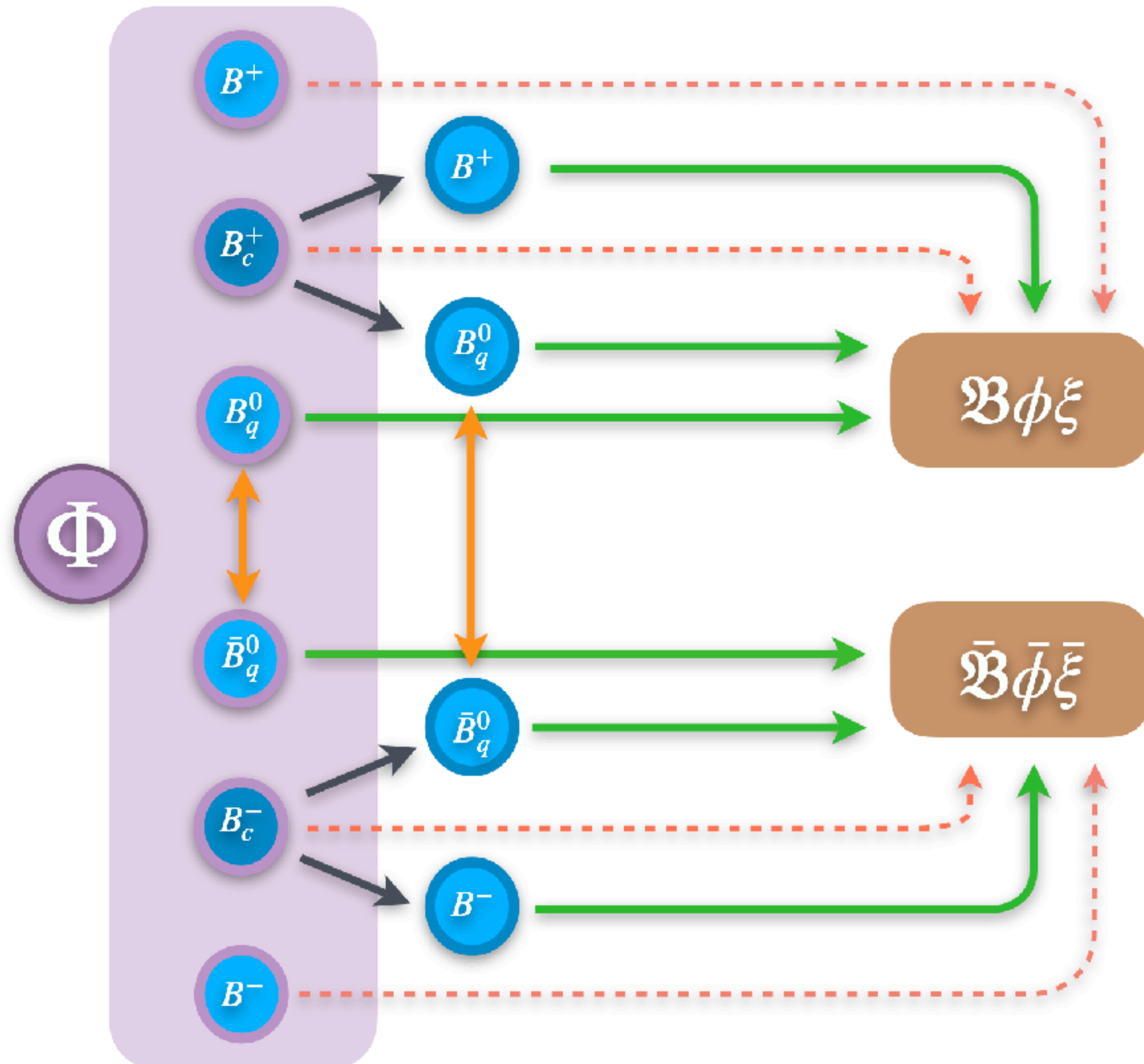
$$\Delta_{B_c^+ \rightarrow B_q^0}^{\text{fac,exp}} = (-0.3 \pm 1.4 |_{\text{SM}}) \times 10^{-7} + 4.2 \times 10^{-6} \mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow B_q^0 M^+)$$

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow BM) \sim 10^{-3}$$



Can SM CP violation explain the matter-antimatter asymmetry?

Unified B mesogenesis



$$\Delta_B \equiv f_d \Delta_{B_d^0} + f_s \Delta_{B_d^0} + f_c \left(\Delta_{B_c^+ \rightarrow B^+} + \Delta_{B_c^+ \rightarrow B_q^0} \right)$$



Fragmentation fractions

Fragmentation functions

- Not really known in the early universe
- Assume just like in colliders?

$$f_d^{\text{coll.}} = f_u^{\text{coll.}} = 0.407, f_s^{\text{coll.}} = 0.101, f_c^{\text{coll.}} = 2.6 \times 10^{-3}$$

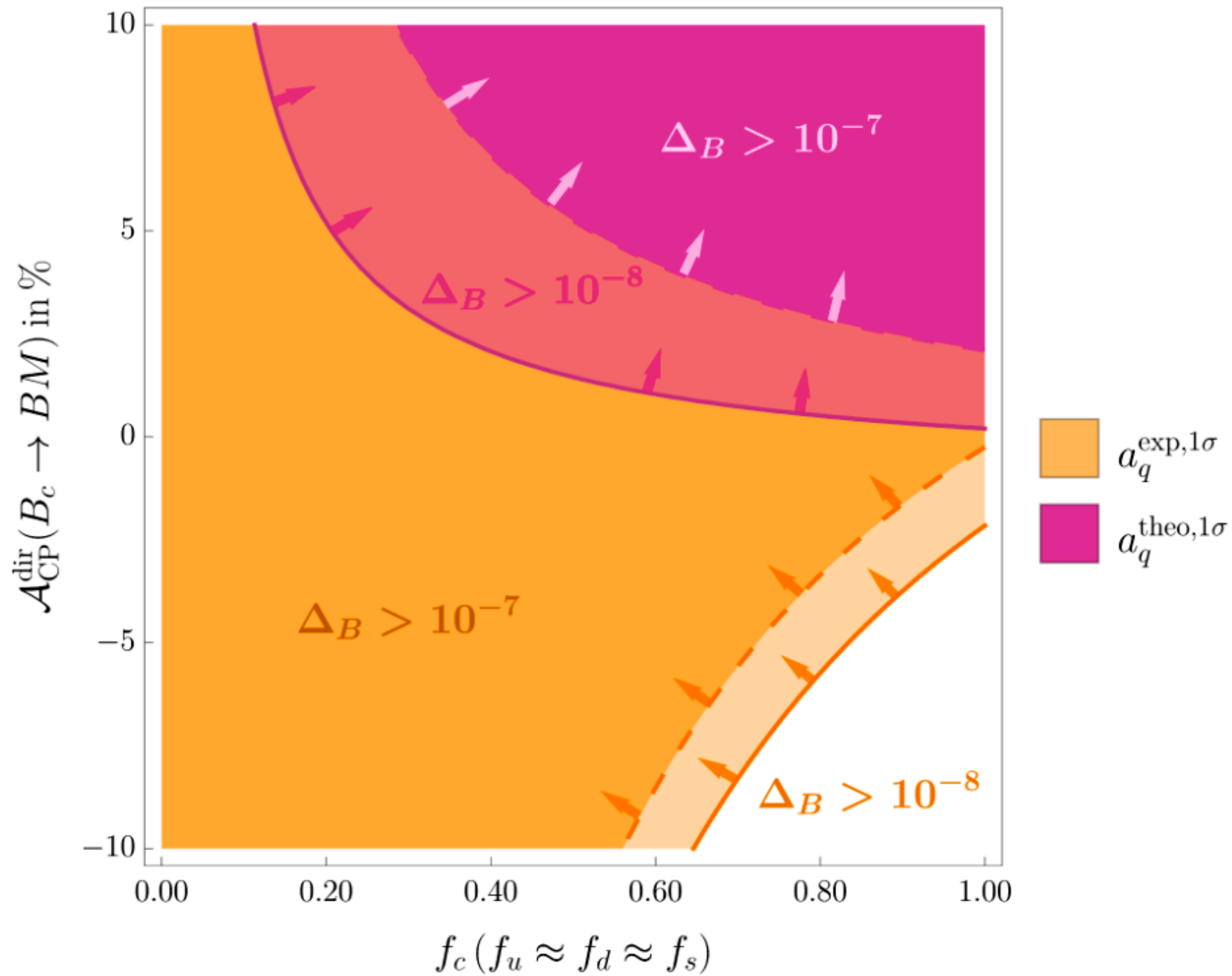
- Bc have very little effect..

$$\Delta_B^{\text{fac,exp}} = (-3.8 \pm 3.8) \times 10^{-7} + 1.2 \times 10^{-8} \mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow BM)$$

$$\Delta_B^{\text{fac,theo}} = (-7.5 \pm 0.8) \times 10^{-8} + 1.2 \times 10^{-8} \mathcal{A}_{\text{CP}}^{\text{dir}}(B_c^+ \rightarrow BM)$$

- Seems challenging to explain asymmetry!


Bc decays as solution to the matter-antimatter asymmetry?



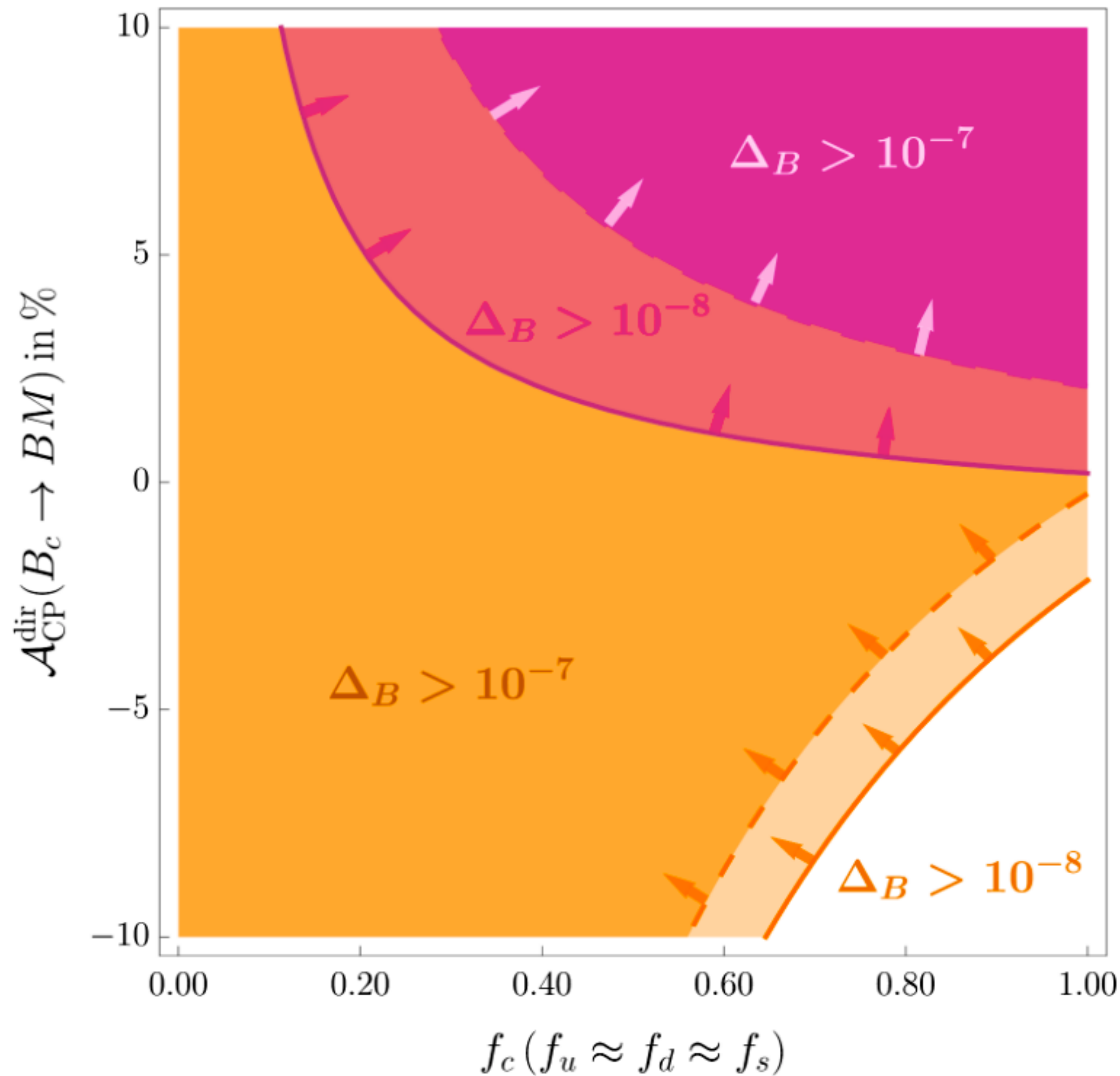
$$f_u \approx f_d \approx f_s$$

Light flavor production suppressed?

Difference between B and \bar{B} needed


 $\Delta_B \sim 10^{-8} - 10^{-6}$

Bc decays as solution to the matter-antimatter asymmetry?



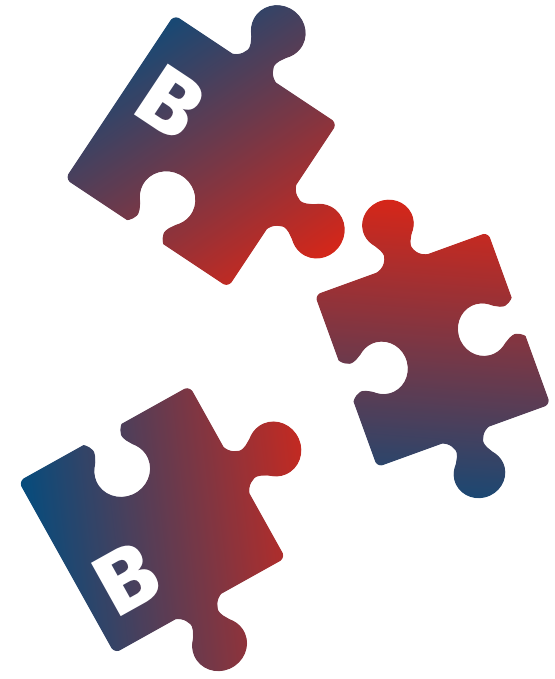
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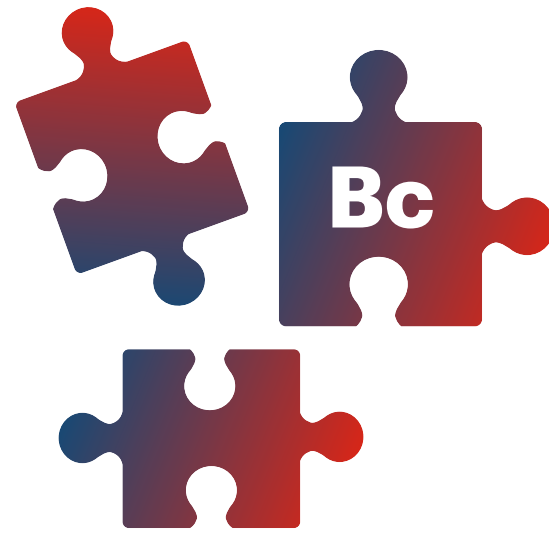
$\Delta_B \sim 10^{-8} - 10^{-6}$

Many regions where this could work!



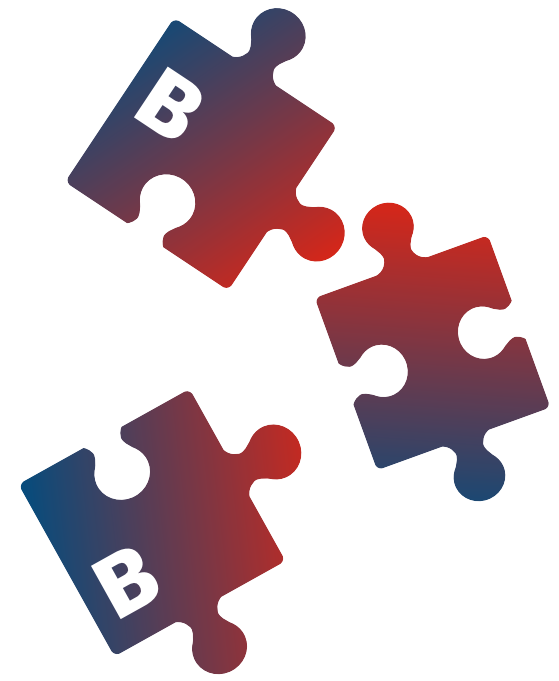
Conclusion

- Mesogenesis could be an interesting mechanism to explain matter-antimatter asymmetry
- SM CP violation could be enough! But need new particle

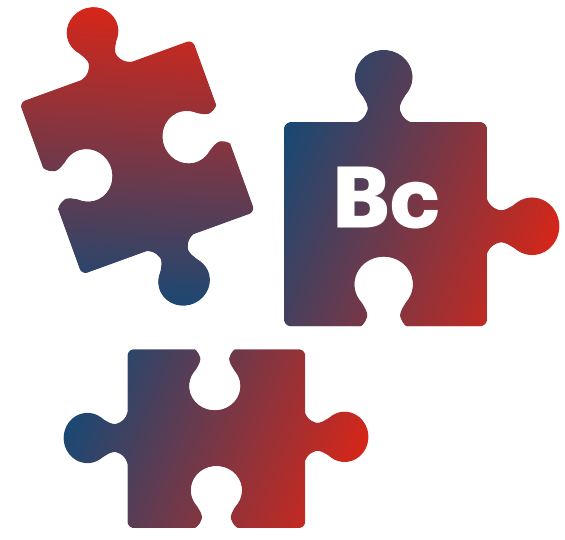


- Requires more precise knowledge of mixing
- Need to measure Bc decays
- Continued search for direct detection of new particles
- Can we study fragmentation studies in the early universe?

How to get Yb?



- The amount of baryons can be extracted from cosmic microwave background measurements. Over densities grow under the action of gravity, and eventually collapse. The collapse is reverted by the photon pressure of the plasma, and this leads to the acoustic oscillations observed in the CMB spectrum.



- The baryons provide the mass for the collapsing and expanding matter, whereas the photons provide the pressure, and the amount of baryons thus influence the height of the acoustic peaks.

Baryogenesis from B mesons

Normally, we say that CPV in SM is not sufficient:

- Early cosmological time ($T \sim 150 \text{ GeV}$): asymmetry is washed out
- Missing mechanism to translate it into baryon asymmetry

B mesogenesis:

- Low-scale baryogenesis
- New Baryon number violation processes
- CP violation in B meson system is enough

