Nikhef

EFFECTIVE ELECTROWEAK BARYOGENESIS

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19XX, 1811.11104, 1710.04061
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EFFECTIVE ELECTROWEAK BARYOGENESIS

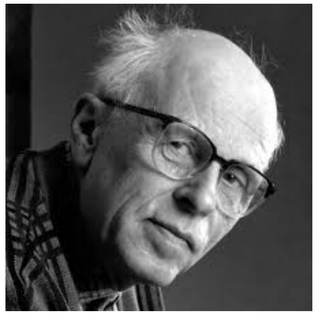
BARYON ASYMMETRY

$$Y_b = \frac{n_b - \cancel{n_{\bar{b}}}}{s} = 8.65 \pm 0.09 \times 10^{-11}$$ (Planck)

BARYOGENESIS

Sakharov conditions:

1. Baryon number violation
2. C- and CP-violation
3. Out of equilibrium



Sakharov 1976

BARYOGENESIS

Sakharov conditions:

1. Baryon number violation ✔
2. C ✔- and CP-violation ✗
3. Out of equilibrium ✗

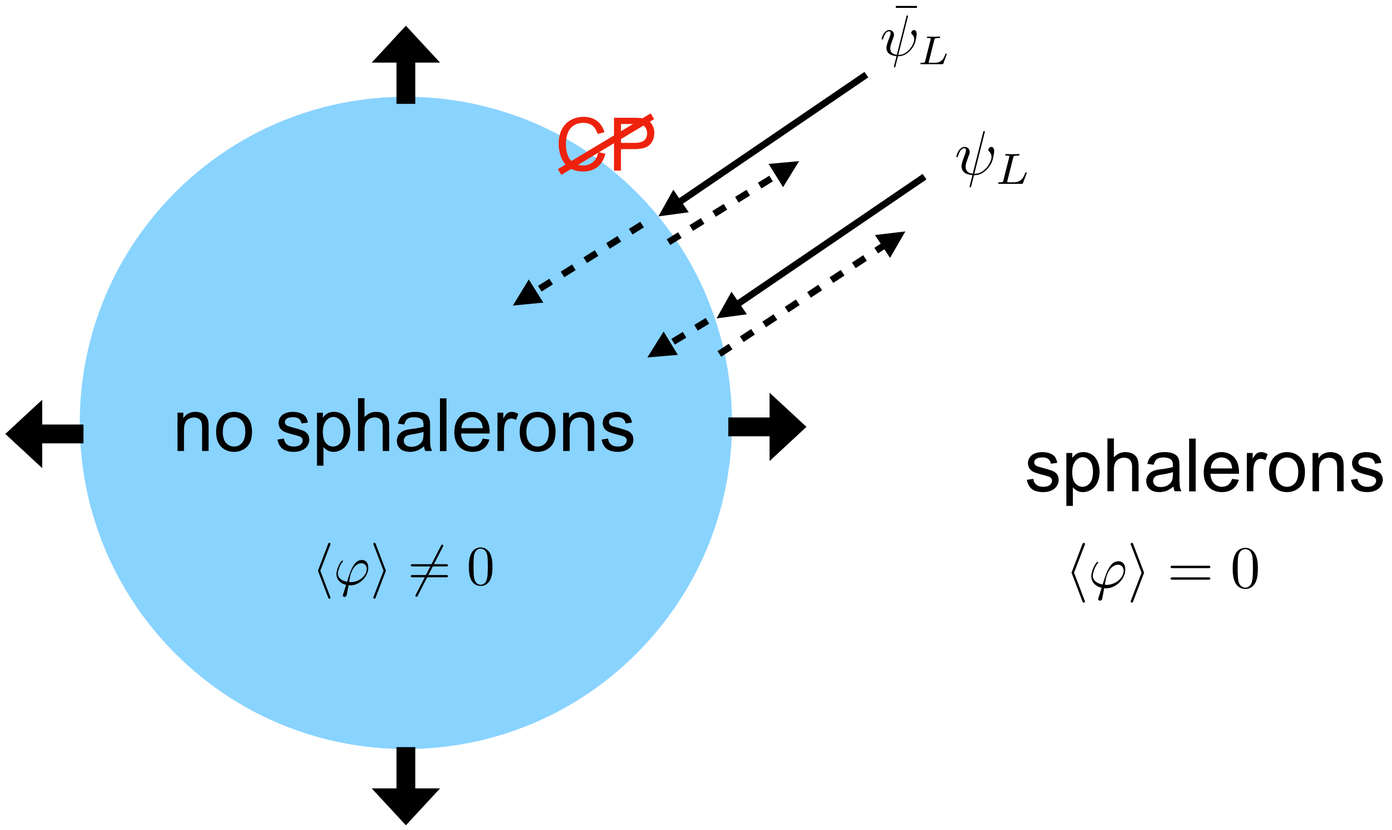
sphalerons

new ~~CP~~ sources

1st order phase

New physics beyond SM!

ELECTROWEAK BARYOGENESIS



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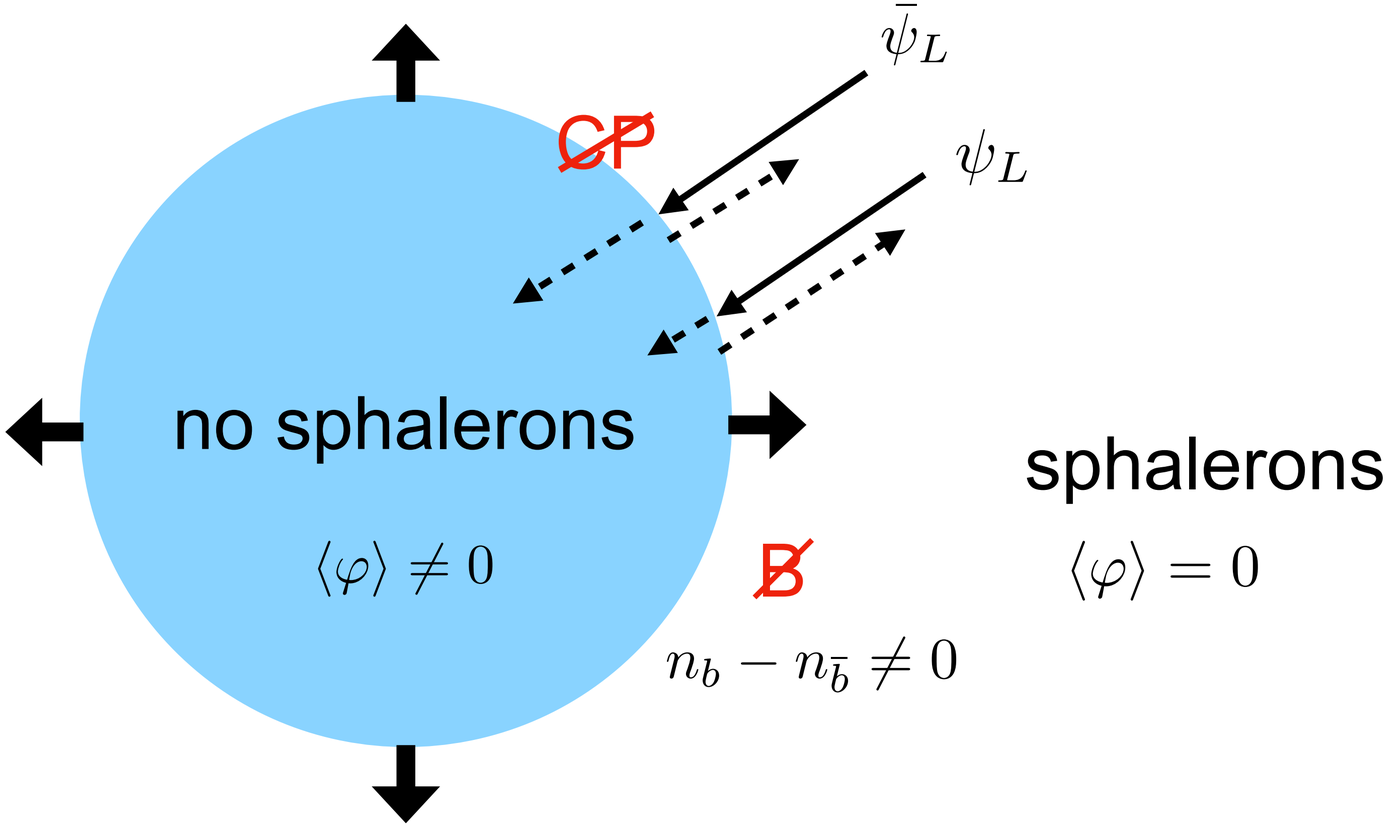
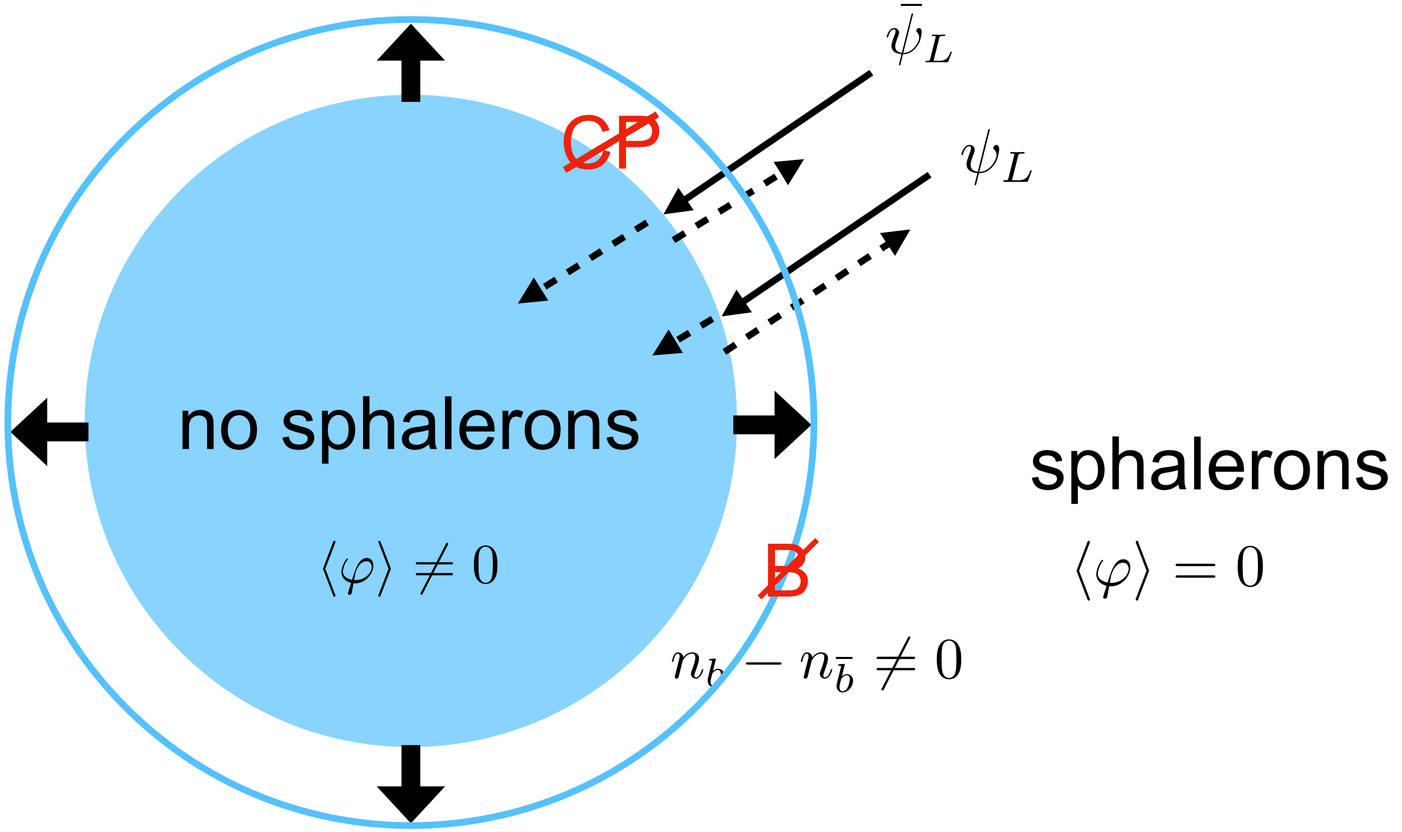
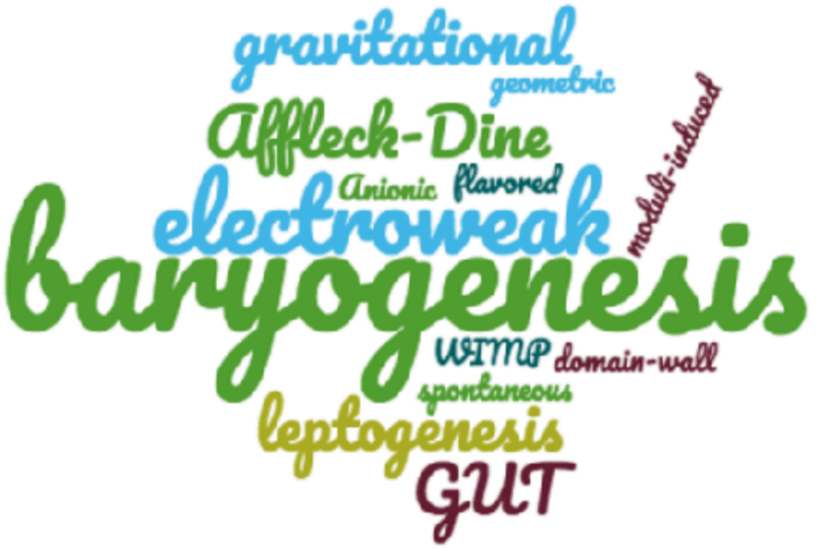


ELECTROWEAK BARYOGENESIS



ELECTROWEAK BARYOGENESIS

motivation: can be probed by experiment



EFFECTIVE ELECTROWEAK BARYOGENESIS

- Can we test EWBG in a model-independent way using effective field theory (SM-EFT) ?

- What is the most effective way to produce the baryon asymmetry?

SM-EFT

effective Lagrangian: $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{d_i - 1}}$

light SM d.o.f.

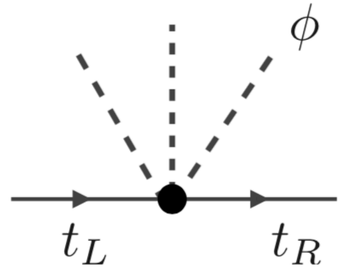
scale of new physics

requirement: separation of scales!

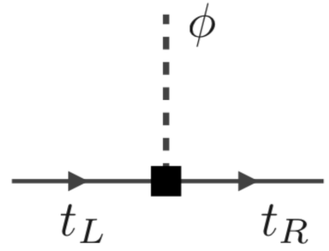
SM-EFT AND ELECTROWEAK BARYOGENGESIS

- 1st order phase transition $\mathcal{L}_{6,\mathrm{PT}} = \frac{1}{\Lambda^2}(\phi^\dagger\phi)^3$ $\Lambda \sim 800\,\mathrm{GeV}$

- two scenarios for ~~CP~~
  - $\mathcal{L}_{6,A} = -\frac{iy_t}{\Lambda^2_{\mathrm{CP}}}\bar{Q}_L\tilde{\phi}t_R(\phi^\dagger\phi) + \mathrm{h.c.}$ $\Rightarrow$



  - $\mathcal{L}_{6,B} = -\frac{i\alpha}{\Lambda^2_{\mathrm{CP}}}\bar{Q}_L D^2\tilde{\phi}t_R + \mathrm{h.c.}$ $\Rightarrow$



SM-EFT AND ELECTROWEAK BARYOGENGESIS

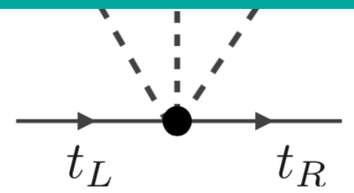
- 1st order phase transition $\mathcal{L}_{6,\mathrm{PT}} = \frac{1}{\Lambda^2}(\phi^\dagger\phi)^3$ $\Lambda \sim 800\,\mathrm{GeV}$

- two scenarios for ~~CP~~

e.o.m

EFT valid: $\mathcal{L}_{6,\mathrm{B}} = \mathcal{L}_{6,\mathrm{A}} + \frac{c_8}{\Lambda^2 \cancel{\Lambda^2_{\mathrm{CP}}}}\mathcal{O}_8$

- $\mathcal{L}_{6,A} = -\frac{iy_t}{\Lambda^2_{\mathrm{CP}}}\bar{Q}_L\tilde{\phi}t_R(\phi^\dagger\phi) + \mathrm{h.c.}$ $\Rightarrow$



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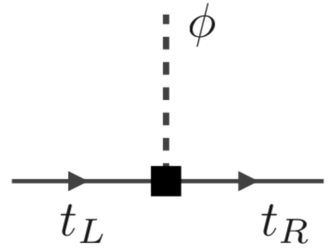
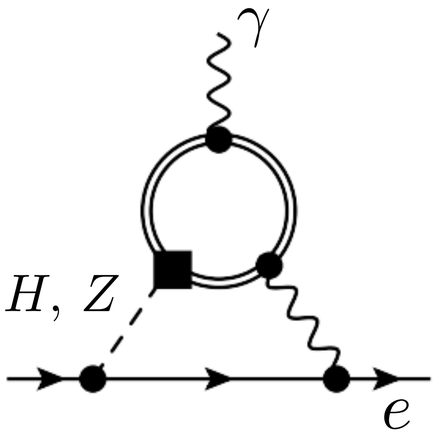


ELECTRIC DIPOLE MOMENT OF ELECTRON



EFT ✔ → same bound for A & B

ACME bound: $\Lambda_{\rm CP} \geq 7.1\,\mathrm{TeV}$

TRANSPORT EQUATIONS

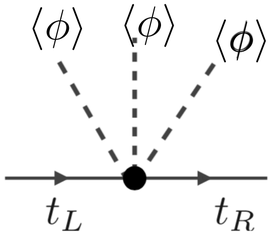
$$q \equiv n_{Q_L} - n_{\bar{Q}_L}$$

$$v_w q' - D_q q'' = S_q - \Gamma_M(\mu_q - \mu_t) - \Gamma_y(\mu_q - \mu_t + \mu_\phi) - \Gamma_{ss}(2\mu_q + ...)$$

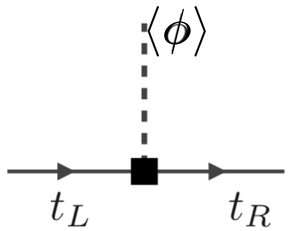
diffusion

~~CP~~ source

wash out



or

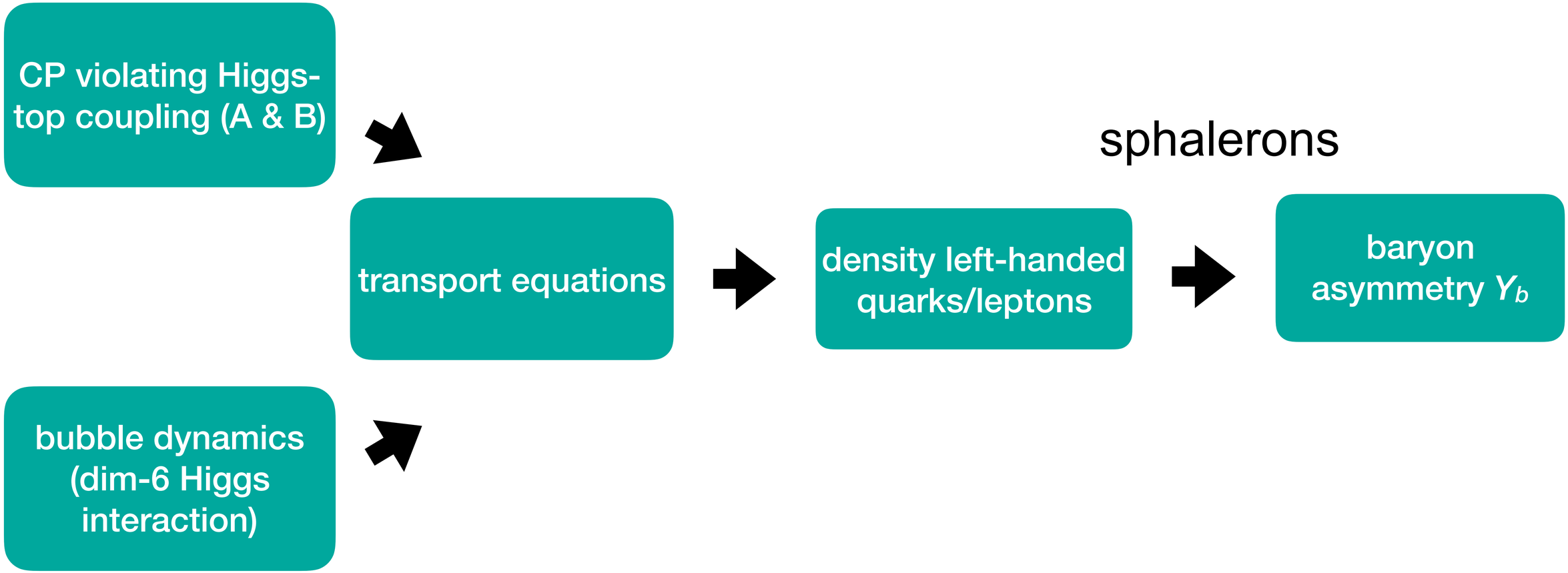


scenario A

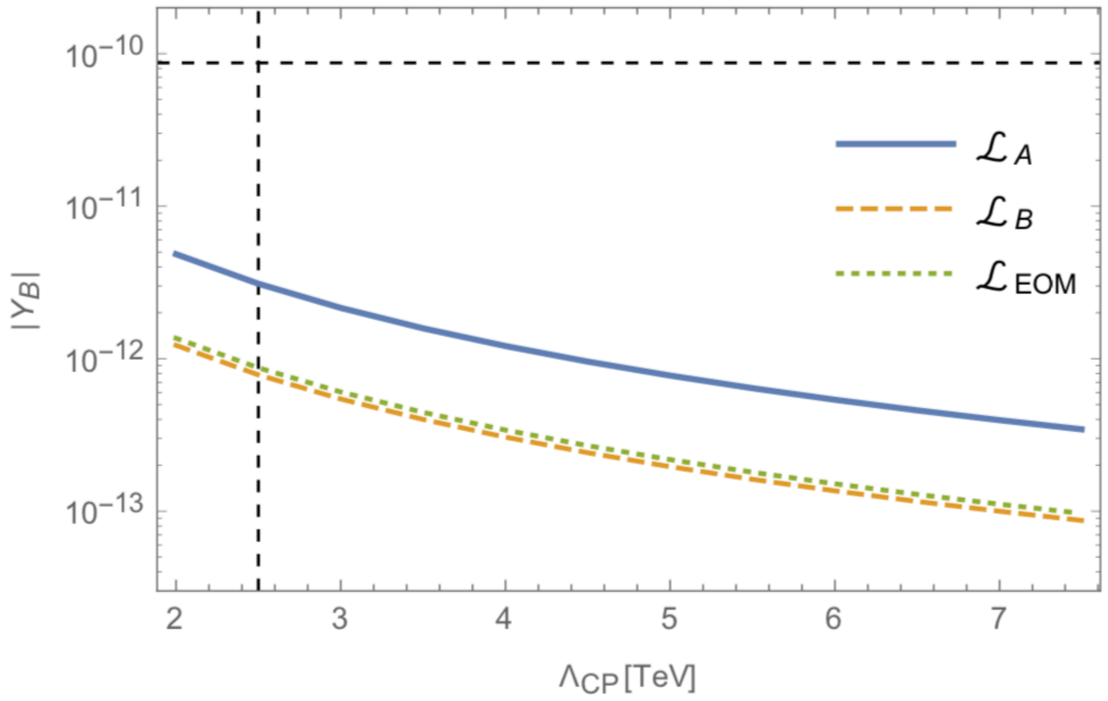
scenario B

$$\mu_q = \frac{n_q}{k_q}$$

RECAP


CP violating Higgs-top coupling (A & B)
bubble dynamics (dim-6 Higgs interaction)
transport equations
sphalerons
density left-handed quarks/leptons
baryon asymmetry Y_b

RESULTS FOR BARYON ASYMMETRY

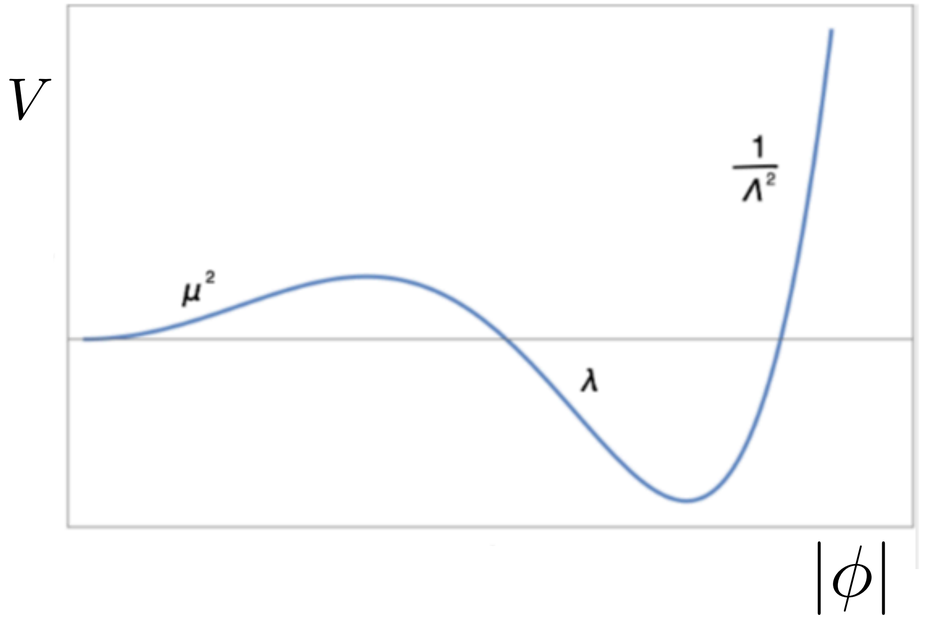


EFT valid? No!

BREAKDOWN OF EFT

$$V = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 + \frac{1}{\Lambda^2}(\phi^\dagger\phi)^3$$

+ thermal corrections



no separation of scales in Higgs sector: new light d.o.f.

BREAKDOWN OF EFT

dimension-8 effects

EWBG: $$\mathcal{L}_B \supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R \varphi_b \left[1 + \frac{i\varphi_b^2}{2\Lambda_{\rm CP}^2}\left(1 + \frac{T^2}{2\lambda\Lambda^2} + \frac{\varphi_b^2}{2\lambda\Lambda^2}\right)\right] + \text{h.c.}$$

EDM: $$\mathcal{L}_B \supset -\frac{i m_t}{\Lambda_{\rm CP}^2}\bar{t}_L t_R \varphi_0 \left[\varphi_0 h + \frac{3}{2}h^2\left(1 + \frac{2\varphi_0^4}{m_h^2\Lambda^2}\right)\right] + \text{h.c.}$$

no separation of scales in Higgs sector: new light d.o.f.

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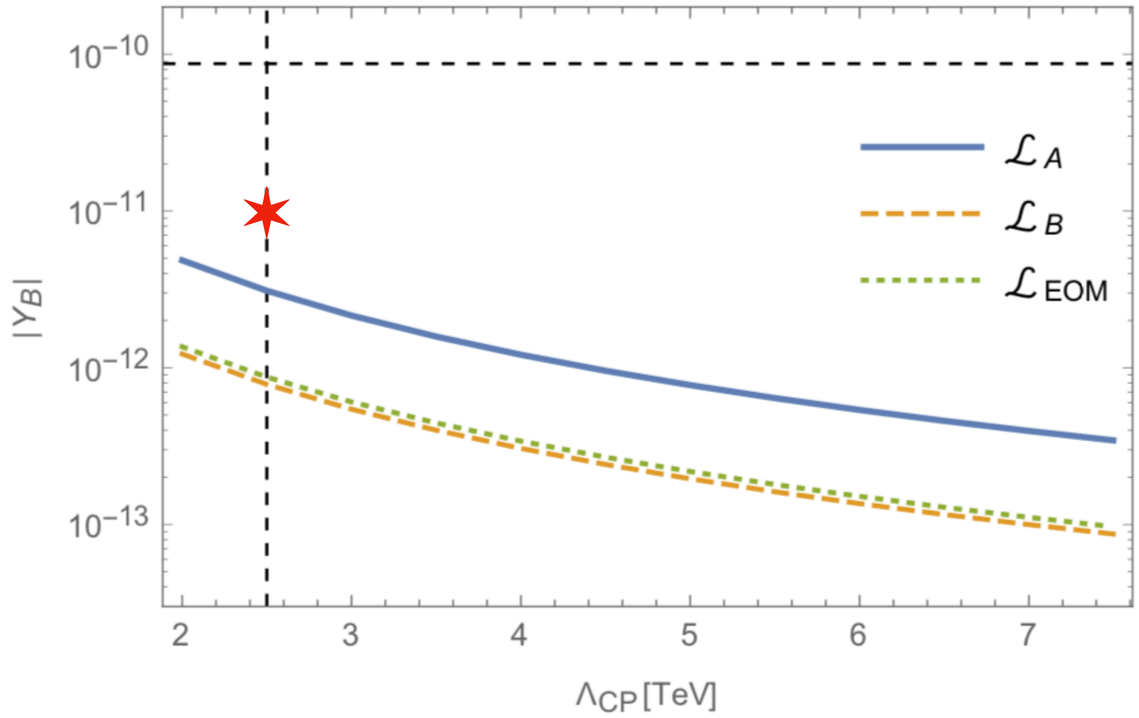
No!

- What is the most effective way to produce the baryon asymmetry?

RESULTS FOR BARYON ASYMMETRY



Planck bound

✶ - including tau leptons

TOP QUARK SOURCE

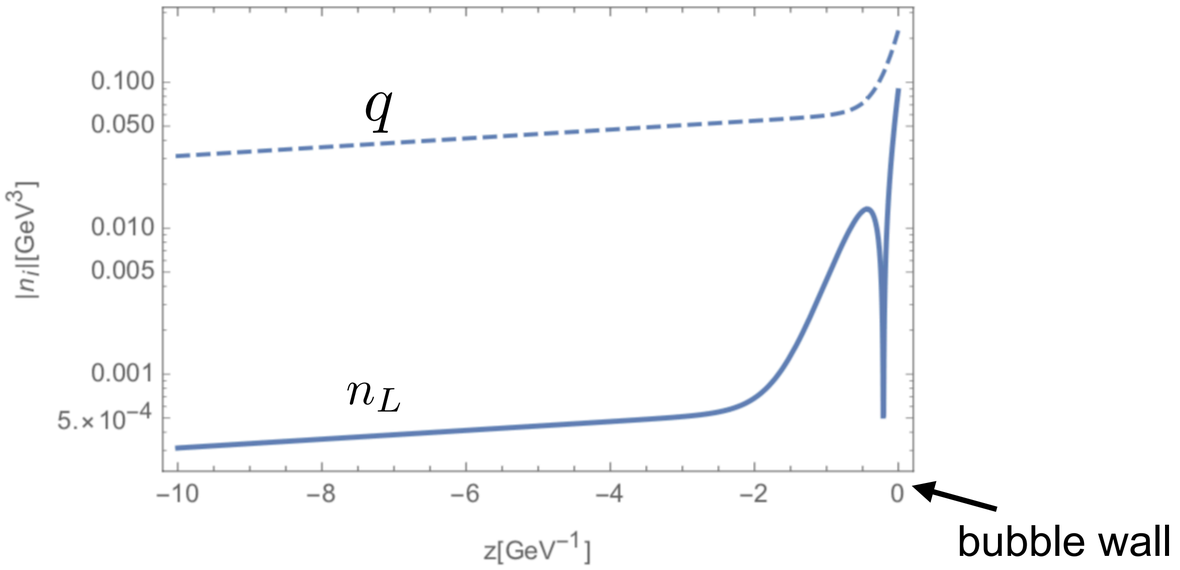
pro ▸ large source

con ▸ strong EDM bound

▸ slow diffusion

▸ large washout

▸ chiral suppression



TOP QUARK SOURCE VS. TAU LEPTON SOURCE

pro
- large source

con
- strong EDM bound
- slow diffusion
- large washout
- chiral suppression

con
- smaller source

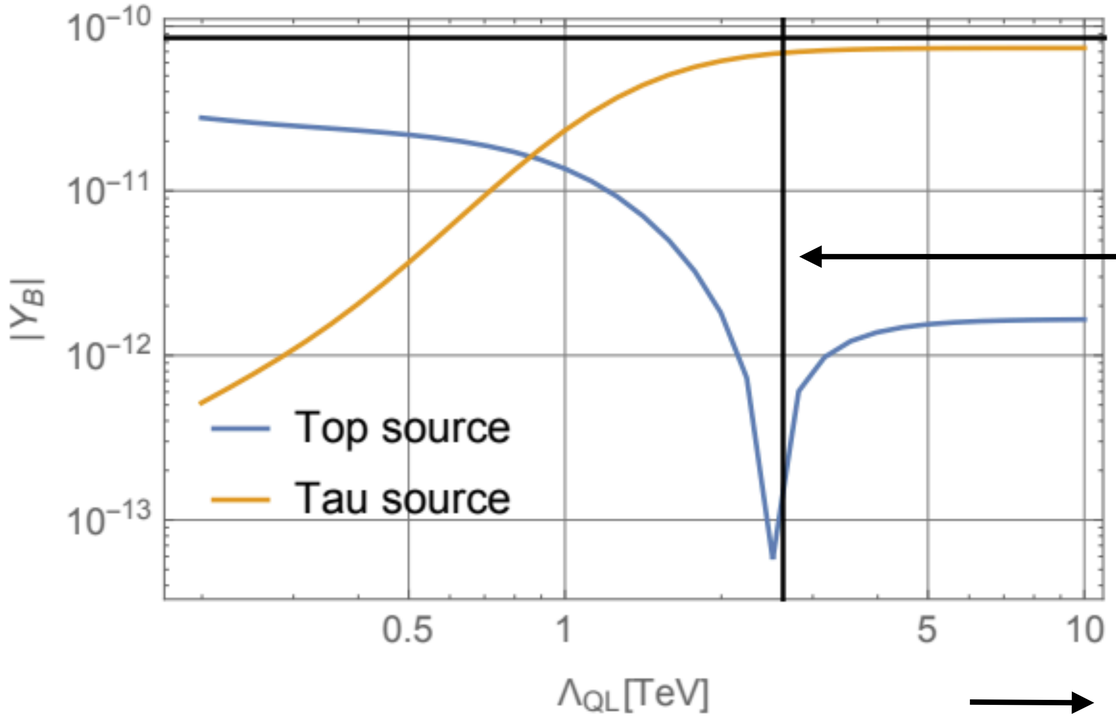
pro
- weaker EDM bound
- faster diffusion
- smaller washout
- no chiral suppression

EFFECTIVE BARYON PRODUCTION: USE LEPTONS

1. CP-violating source for tau-lepton

2. Transfer chiral asymmetry to lepton sector
   (with top-quark coupling)

EFFECTIVE BARYON PRODUCTION: USE LEPTONS



Planck bound

strength tau-yukawa interaction

cutoff: $\Lambda_t = 7.1\,\mathrm{TeV}$

$\Lambda_\tau = 1\,\mathrm{TeV}$

top-tau interaction $\mathcal{L} \supset \frac{1}{\Lambda_{\mathrm{QL}}^2}\bar{\tau}_L\tau_R\bar{t}_R t_L + \mathrm{h.c.}$

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- Can we test EWBG in a model-independent way using effective field theory (SM-EFT) ?

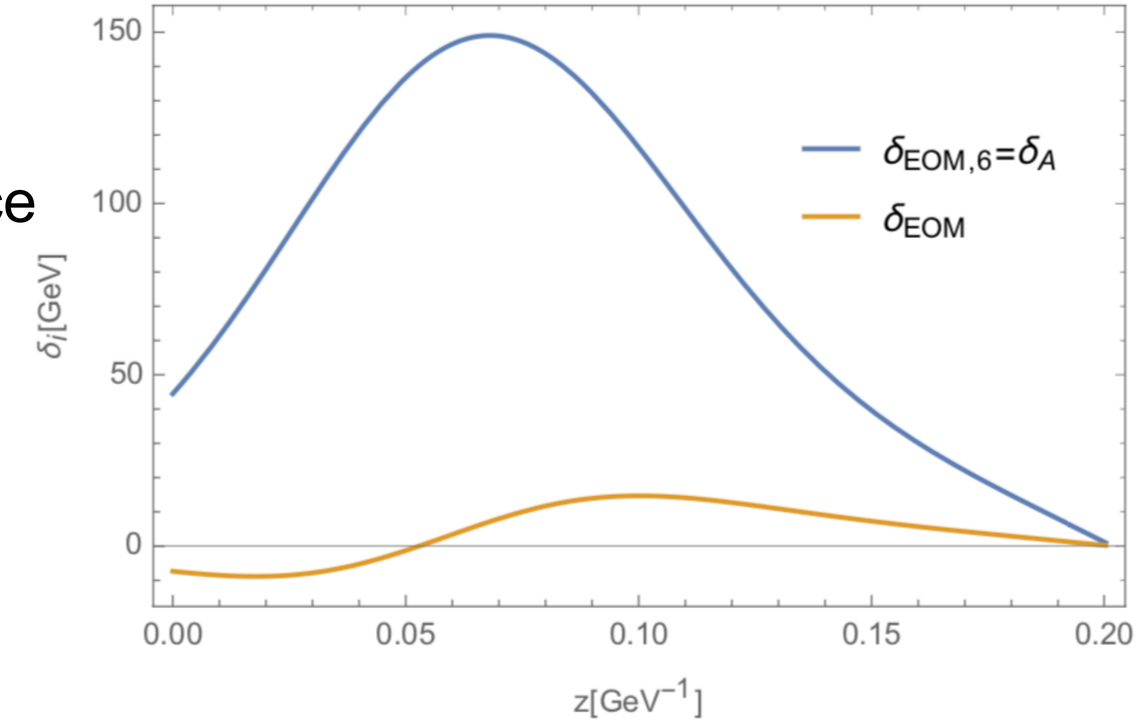
No!

- What is the most effective way to produce the baryon asymmetry?

Use leptons!

RESULTS FOR BARYON ASYMMETRY

source



EFT valid? No!

TOP QUARK SOURCE

strong sphalerons in equilibrium

$$0 = \sum_{i=1}^{3} (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = \sum_{i=1}^{3} \left(2\frac{q_i}{k_{q_i}} - \frac{u_i}{k_{u_i}} - \frac{d_i}{k_{d_i}} \right)$$

light quarks produced by strong sphalerons

$$q_i = -2u_i = -2d_i = -2d_3 = 2(u_3 + q_3) \quad \text{for } i = 1, 2$$

k-factors at zero temperature

$$k_{u_i} = k_{d_i} = 3 \;\; \& \;\; k_{q_i} = 6$$

- chiral suppression

$$n_L = \sum_{i=1}^{3} q_i = 0 + \text{temperature corrections}$$