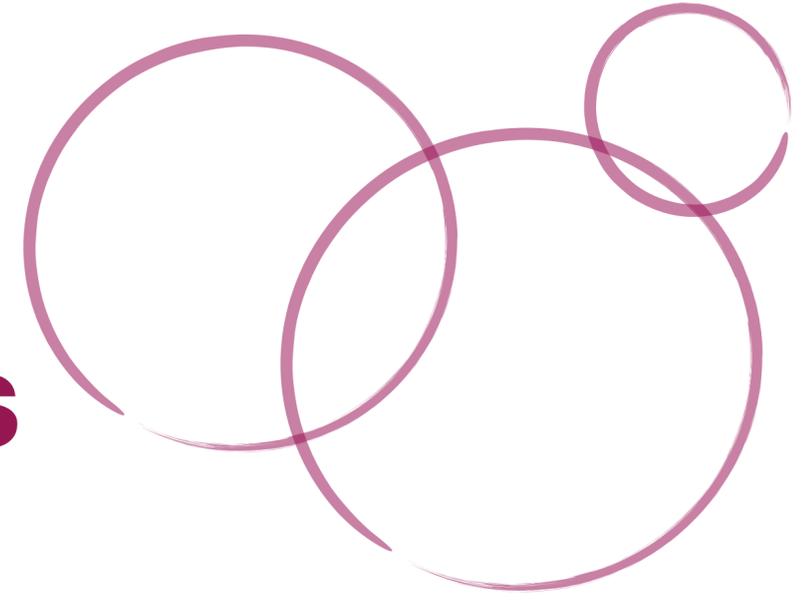# Electroweak baryogenesis

Generation of the matter-antimatter asymmetry during a cosmological phase transition

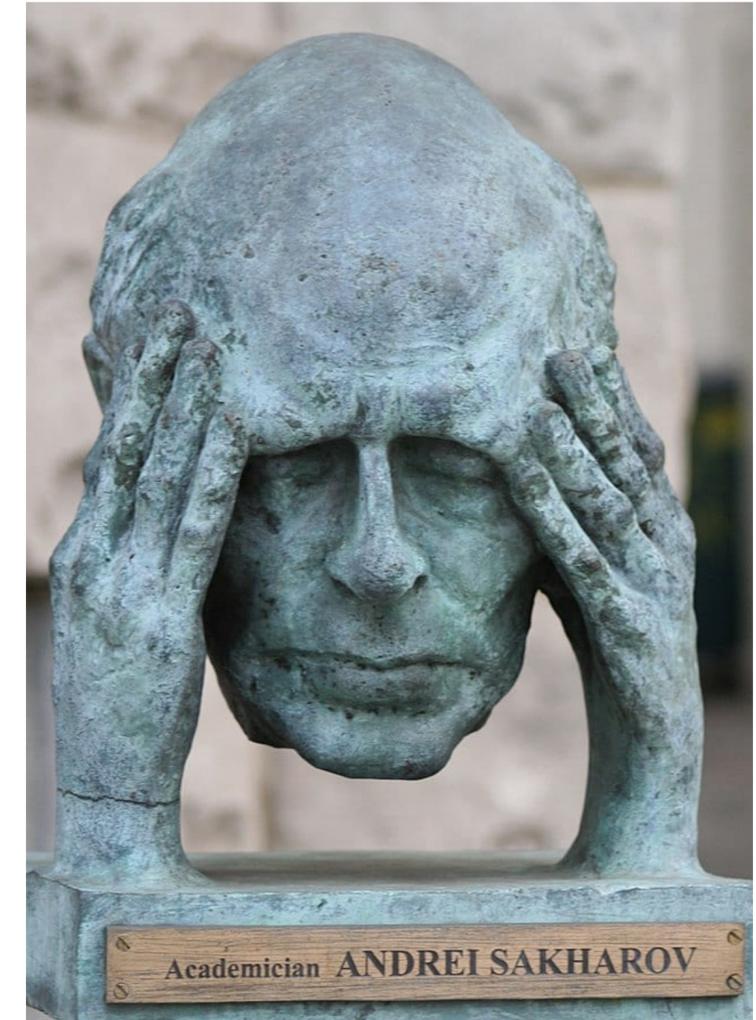## EDMs2025

Jorinde van de Vis, March 3, 2026

CERN

Baryon asymmetry of the universe

- Baryon asymmetry of the universe:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10} \quad \text{Planck, 2018}$$
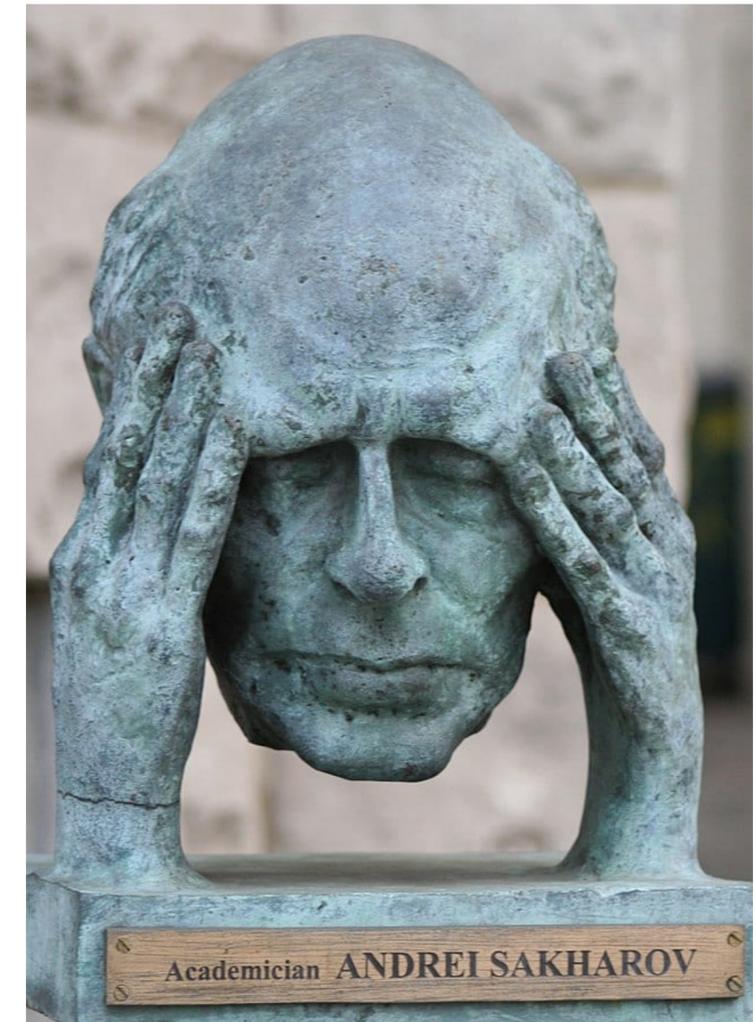
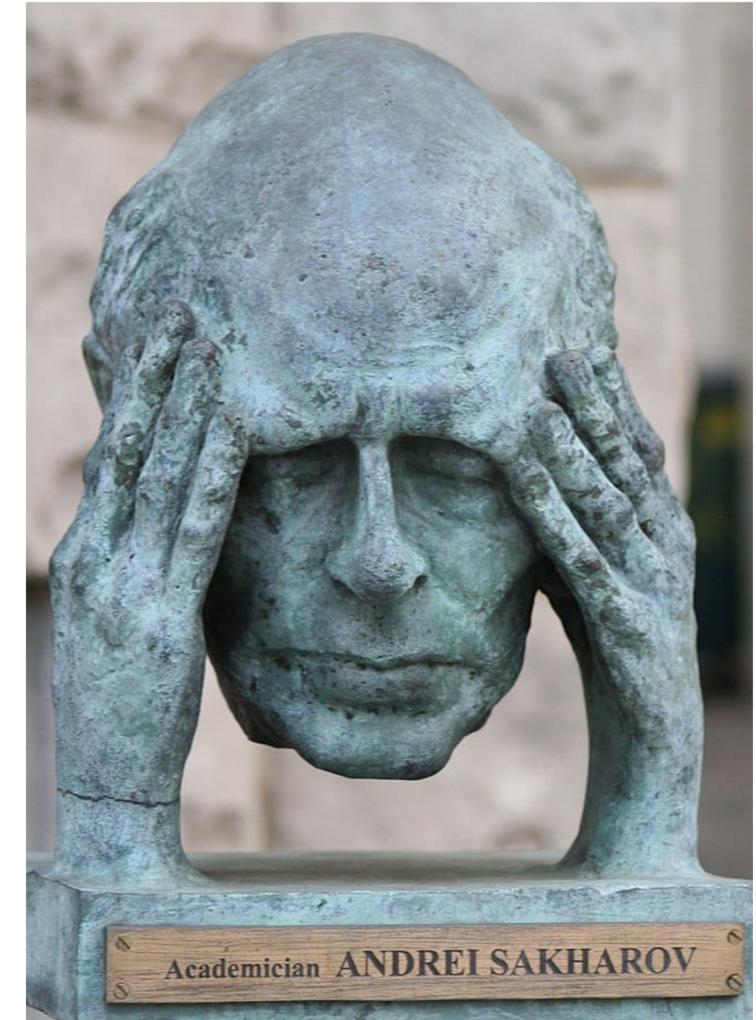# Conditions for generation of the asymmetry

Academician ANDREI SAKHAROV

Conditions for generation of the asymmetry

- Violation of baryon number

- Violation of Charge and Charge-Parity

- Out-of-equilibrium dynamics

Academician ANDREI SAKHAROV

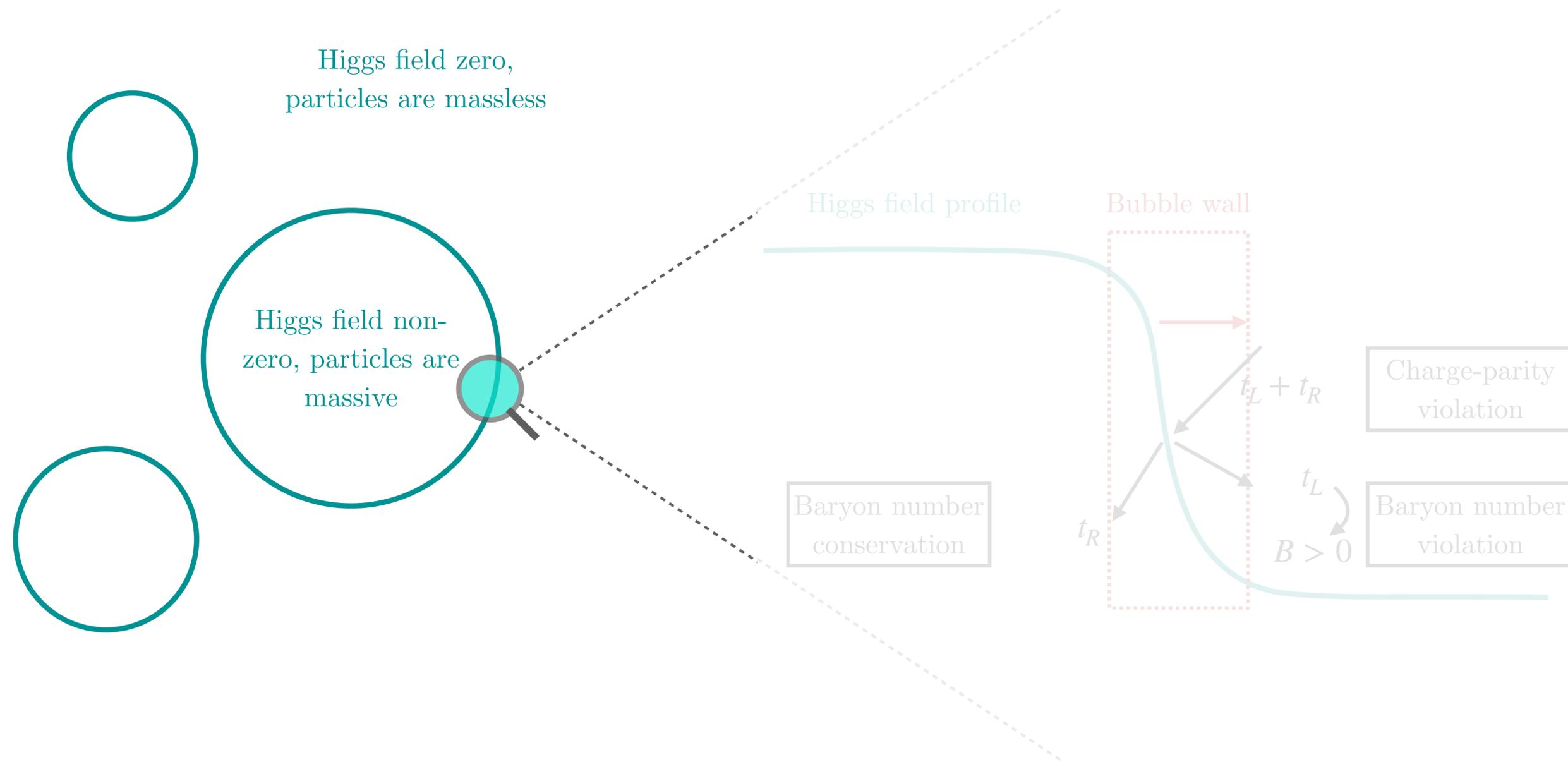# Conditions for generation of the asymmetry

- Violation of baryon number ✅

- Violation of Charge ✅ and Charge-Parity 🟠

- Out-of-equilibrium dynamics ❌


Academician **ANDREI SAKHAROV**

Electroweak baryogenesis
Generation of the matter-antimatter asymmetry in the electroweak phase transition

Higgs field zero, particles are massless

Higgs field non-zero, particles are massive

Higgs field profile

Bubble wall

$t_L + t_R$

Charge-parity violation

t_L

t_R

$B > 0$

Baryon number conservation

Baryon number violation

- Recent review: JvdV, Postma, de Vries 2025

Potential energy at finite temperature
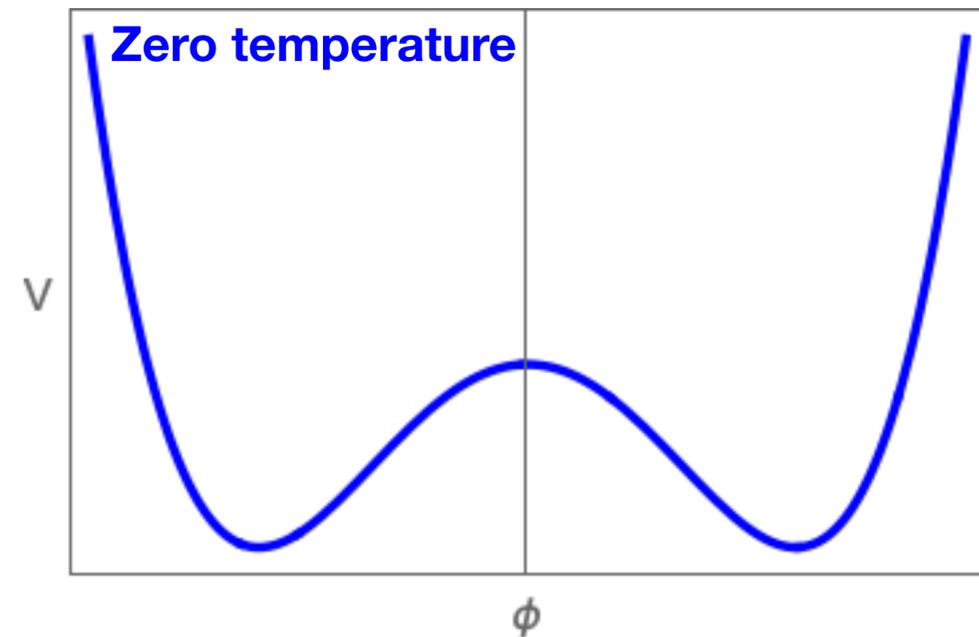
Zero temperature

V

ϕ

Potential energy at finite temperature

- Field ϕ, e.g. the Higgs, with a broken symmetry at zero temperature

Zero temperature

5
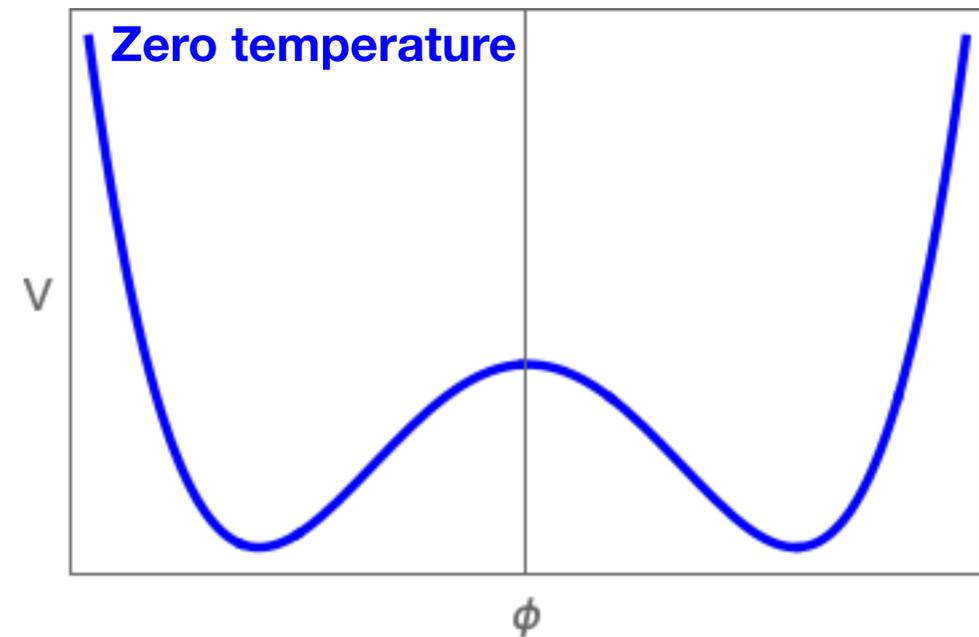
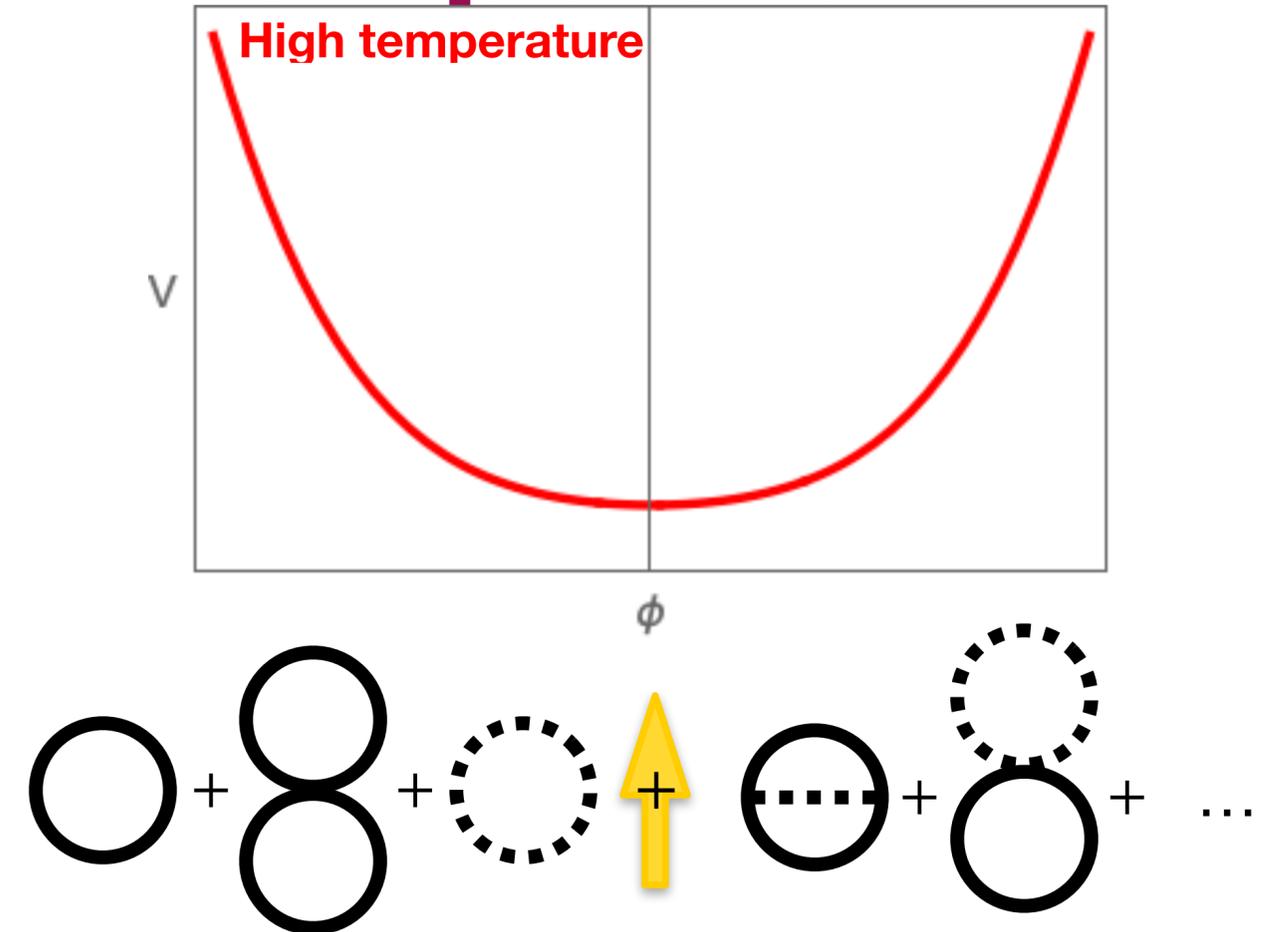# Potential energy at finite temperature

- Field ϕ, e.g. the Higgs, with a broken symmetry at zero temperature

- Temperature-dependent quantum corrections modify the potential and restore the symmetry at high temperature

5

Cosmological first order phase transition

- When the universe cools down, the field transitions

- If a barrier separates the phases, the phase transition is first order

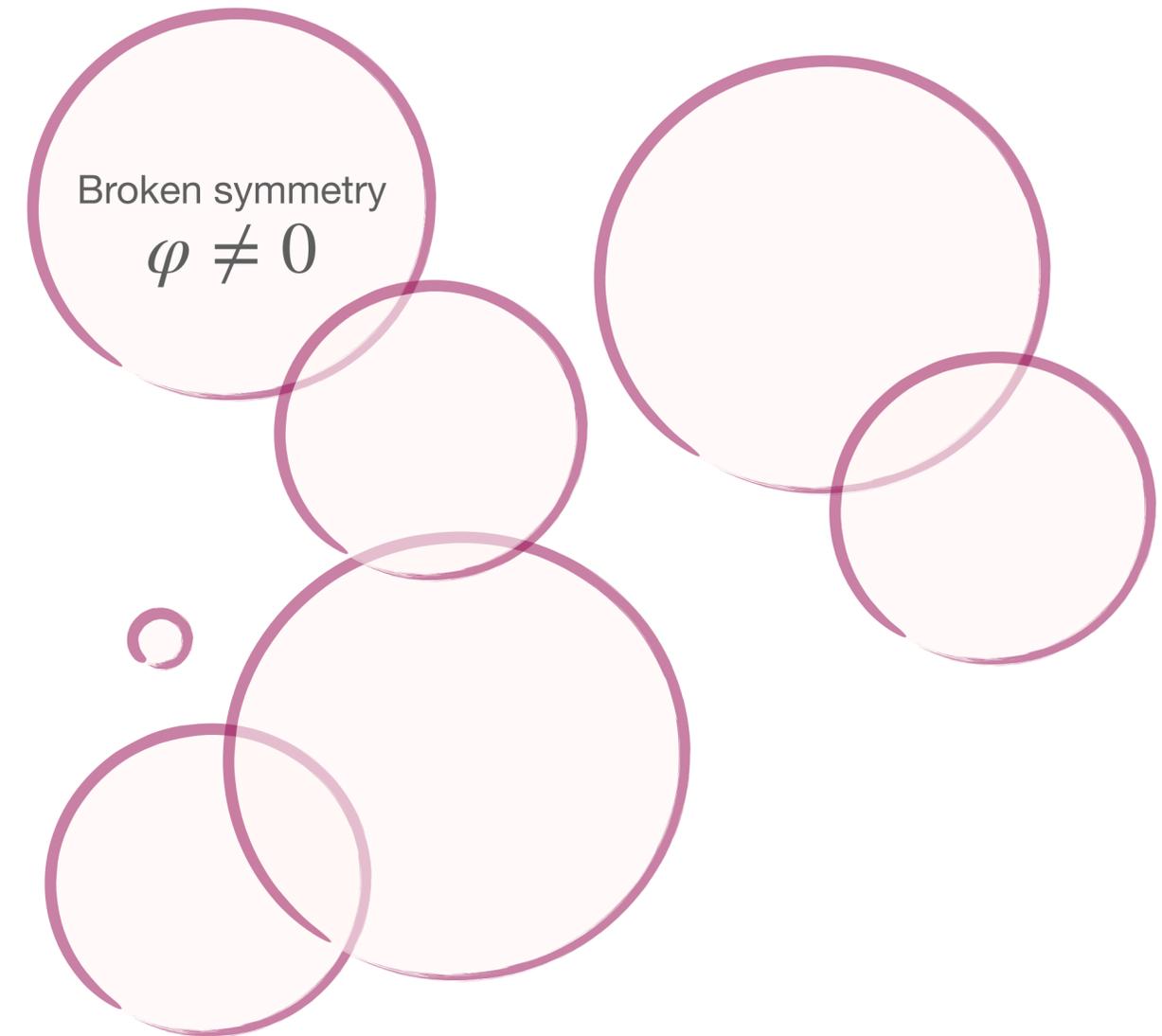Rubakov, 2015
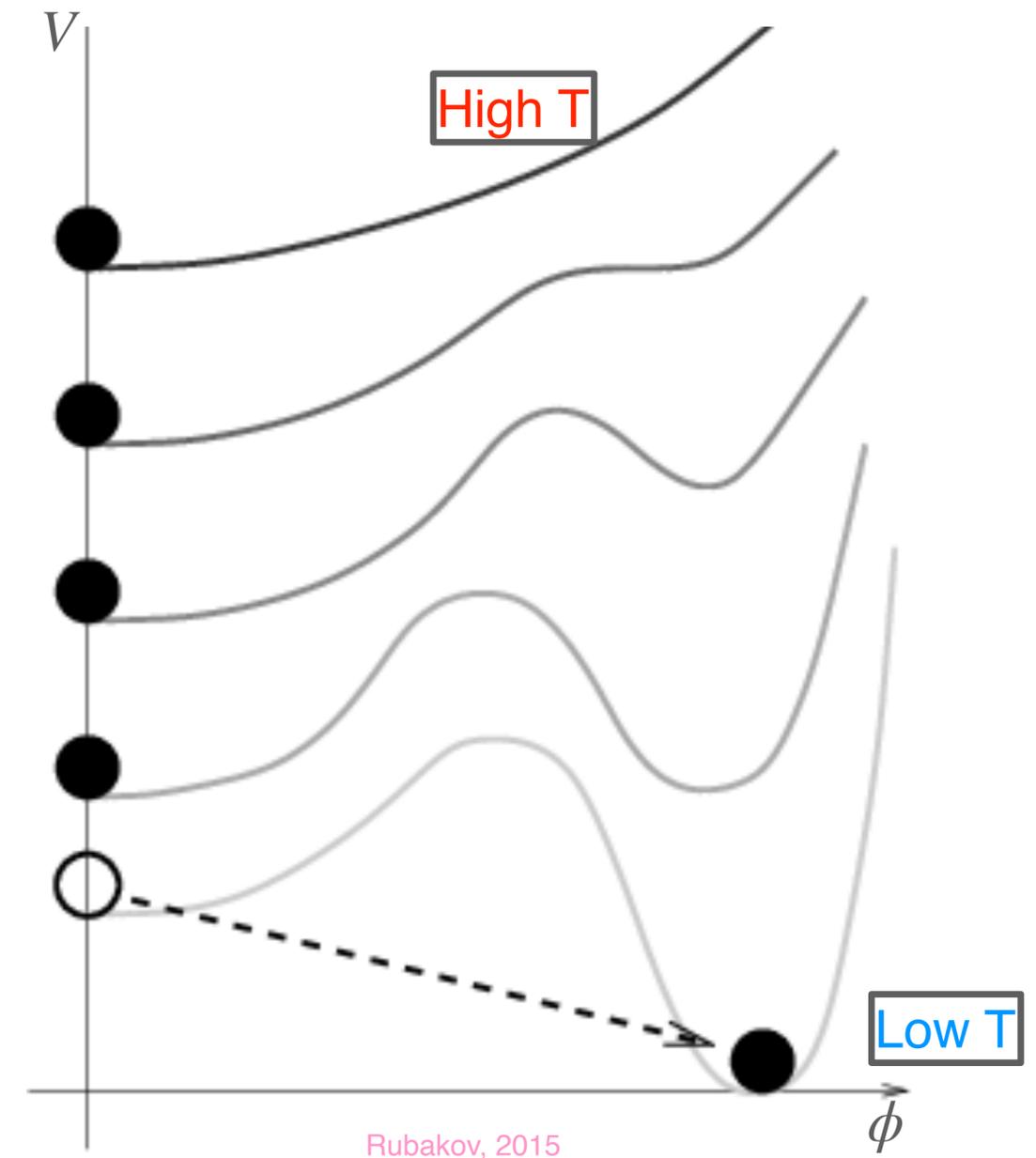
Cosmological first order phase transition

- When the universe cools down, the field transitions

- If a barrier separates the phases, the phase transition is first order

- The phase transition proceeds via nucleation and percolation of bubbles

Broken symmetry
$\varphi \neq 0$

New physics for matter-antimatter generation

- Phase transitions in the Standard Model, electroweak and Quantum Chromodynamics (QCD), are both cross-overs
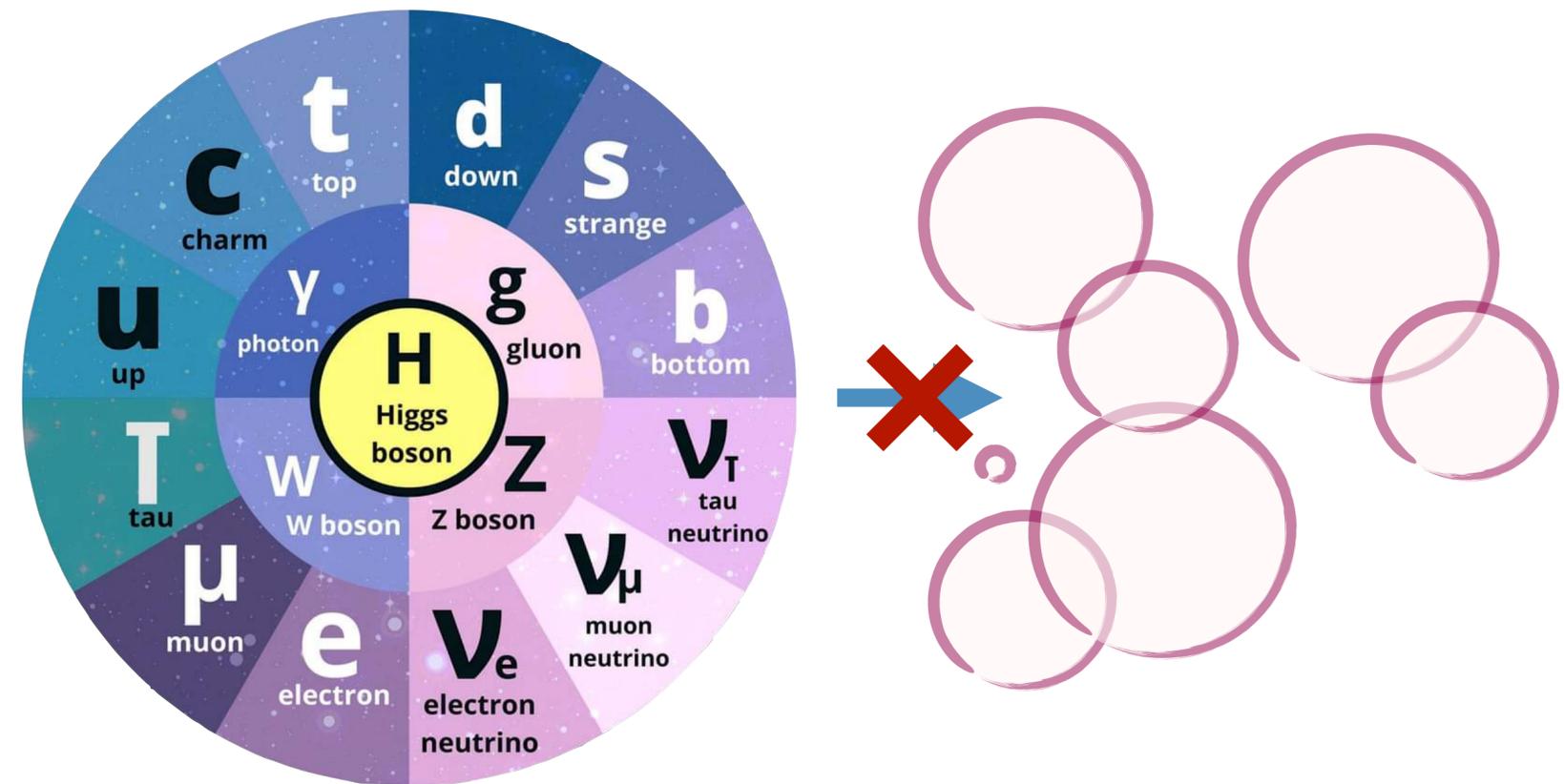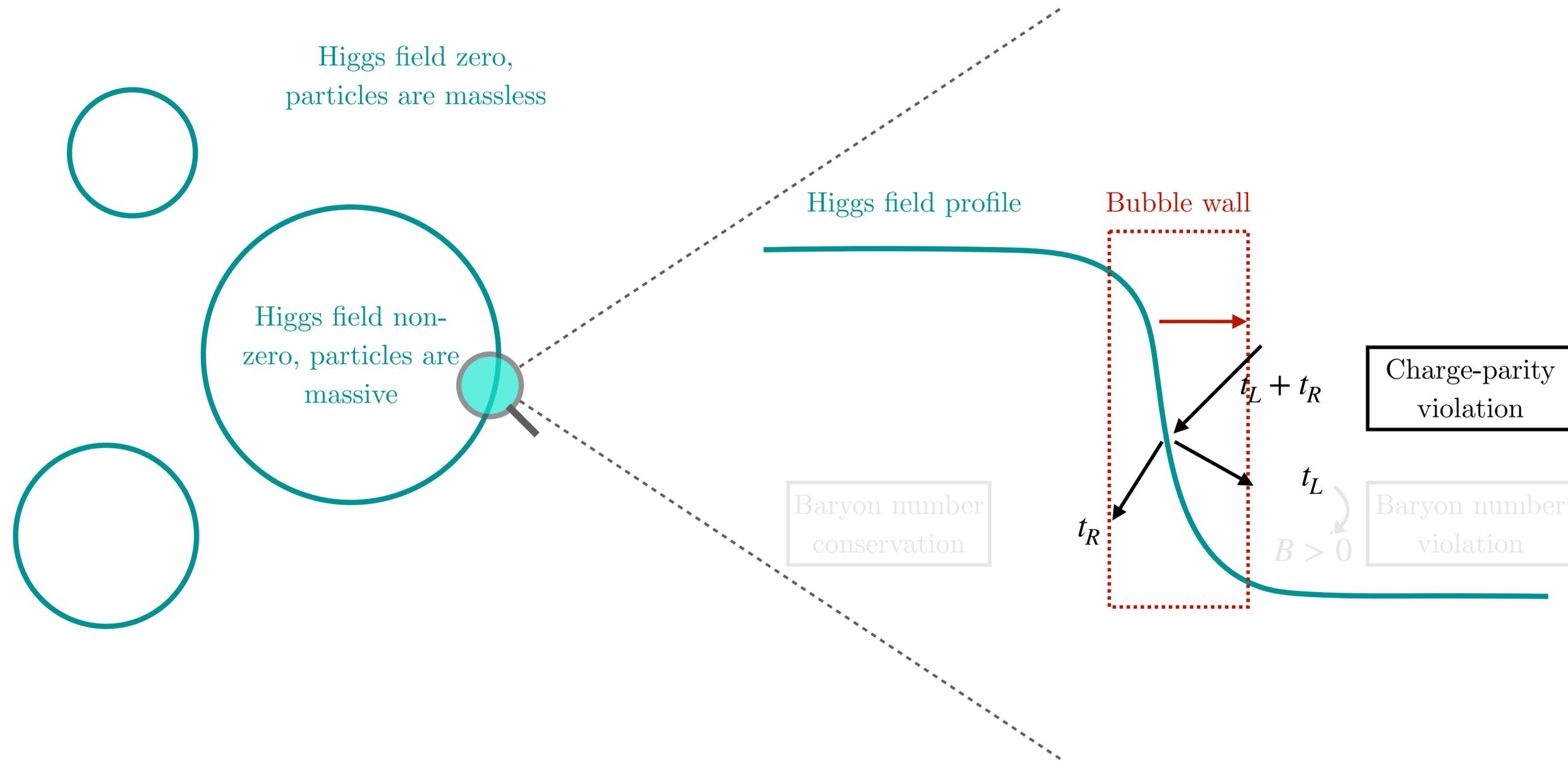
New physics for matter-antimatter generation

- Phase transitions in the Standard Model, electroweak and Quantum Chromodynamics (QCD), are both cross-overs

- New particles couplings to the Higgs could make the phase transition first order

- This can leave collider signatures, and a stochastic gravitational wave background, potentially observable with LISA
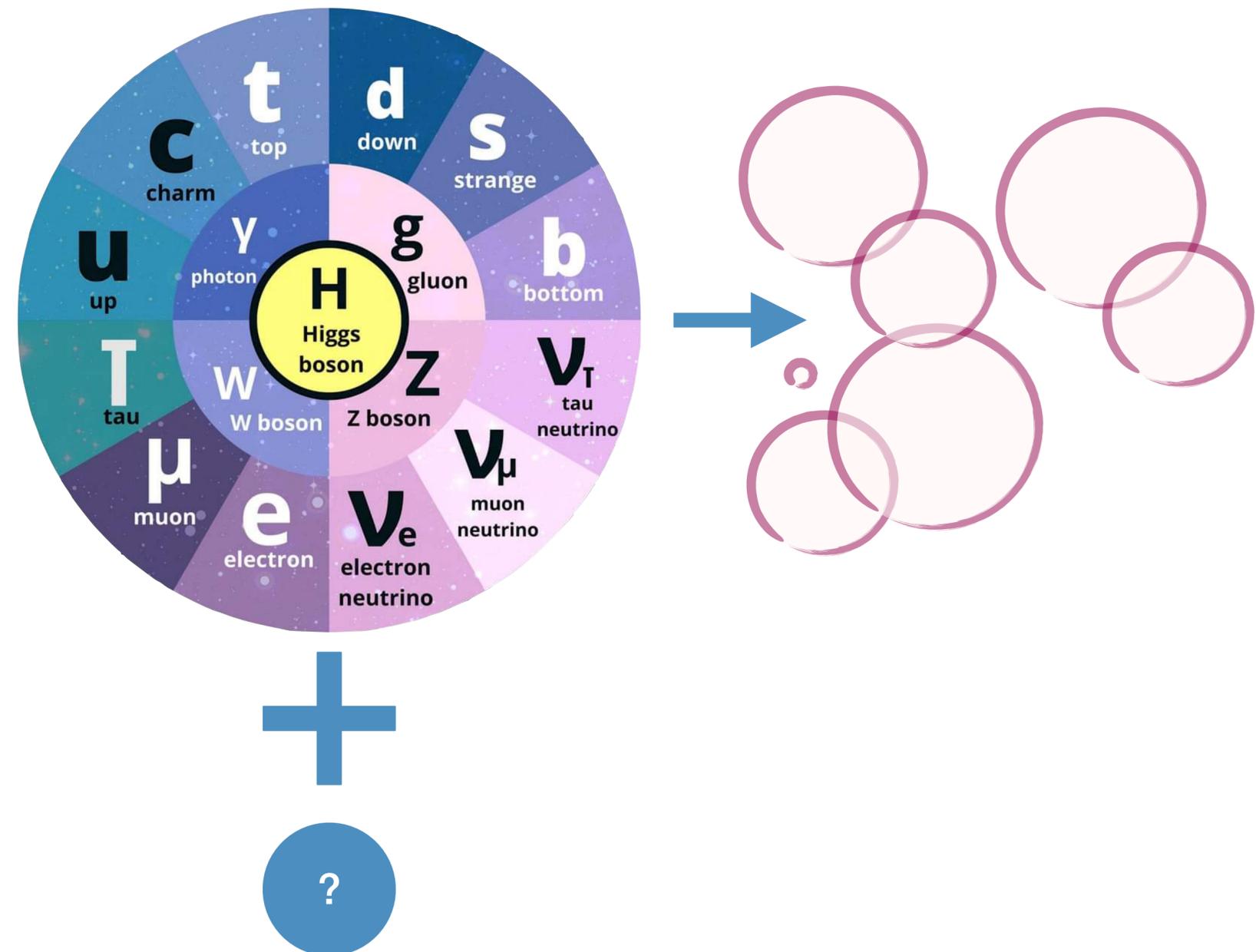
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t_L

t_R

Baryon number conservation

$B > 0$

Baryon number violation

- Recent review: JvdV, Postma, de Vries 2025

New CP-violating operators

- Typically *proportional to the Higgs field* e.g. Higgs-gauge interactions

$$\mathscr{L} = -\, g^2 C_{\varphi\tilde{W}}\varphi^\dagger\varphi\tilde{W}^i_{\mu\nu}W^{\mu\nu}_i - g'^2 C_{\varphi\tilde{B}}\varphi^\dagger\varphi\tilde{B}_{\mu\nu}B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}}\varphi^\dagger\varphi G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$
$$-\, gg' C_{\varphi\tilde{W}B}\varphi^\dagger\tau^i\varphi\tilde{W}^i_{\mu\nu}B^{\mu\nu} + \frac{C_{\tilde{G}}}{3}f_{abc}\tilde{G}^a_{\mu\nu}G^{\nu\rho}_b G^{c\mu}_\rho + \frac{C_{\tilde{W}}}{3}\epsilon_{ijk}\tilde{W}^i_{\mu\nu}W^{\nu\rho}_j G^{k\mu}_\rho$$
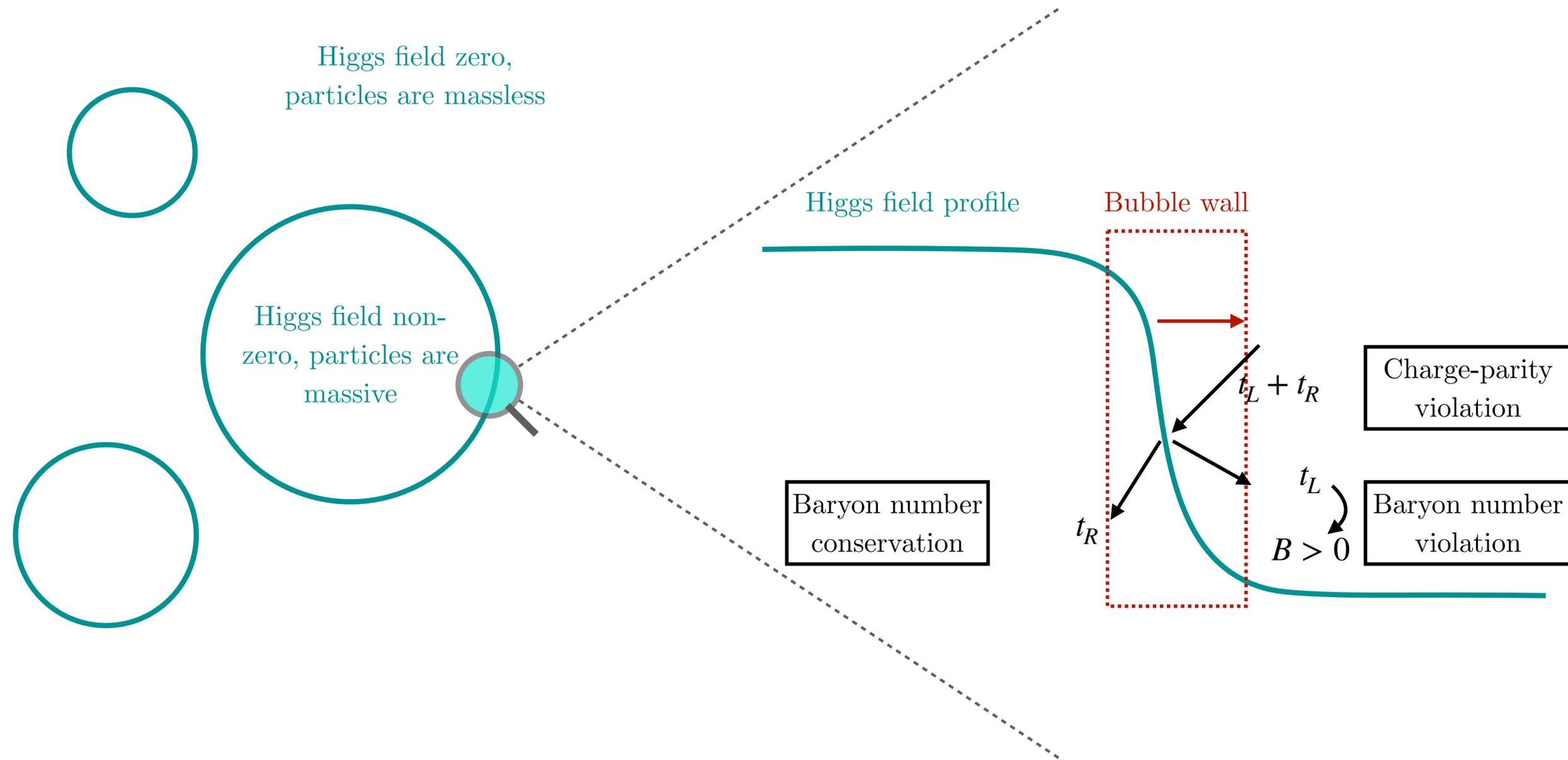
- Or Yukawa-like

$$\mathscr{L}_Y = -\,\bar{Q}_L Y_d \varphi d_R(\varphi^\dagger\varphi) - \bar{Q}_L Y_u \tilde{\varphi}u_R(\varphi^\dagger\varphi) - \bar{L}_L Y_e \varphi e_R(\varphi^\dagger\varphi)$$
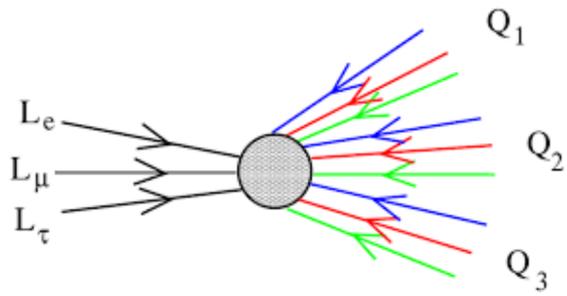
- Effective, dimension-six operators: $C_i, Y_j \propto \dfrac{1}{\Lambda^2}$, with $\Lambda \gg \Lambda_{\text{EW}} \sim 200\,\text{GeV}$
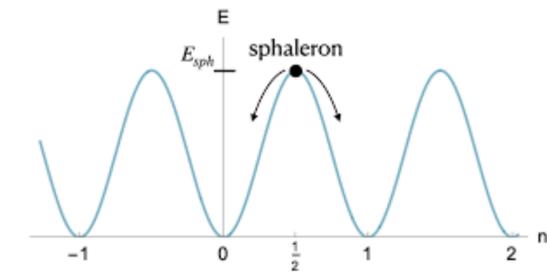
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Baryon number violation

- Recent review: JvdV, Postma, de Vries 2025

Electroweak sphaleron

Conversion of chiral asymmetry to baryon number

- Non-perturbative Standard Model process that violates $B + L$ but preserves $B - L$

- Suppressed at zero temperature as $\Gamma_{\text{sph,b}} \sim T^4 e^{-E_{\text{sph}}/T}$, with $E_{\text{sph}} \sim 2.8 \dfrac{4\pi v}{g}$

- Efficient at high temperature, especially when $v = 0$, in the symmetric phase

- Sourced by chiral asymmetry (generated by the CP-violating interactions)

- Baryon number generated in front of the bubbles, and then absorbed by the expanding bubble

- To avoid *washout* inside of the bubbles, the phase transition needs to be sufficiently strong

CP-violating operators for electroweak baryogenesis and EDMs
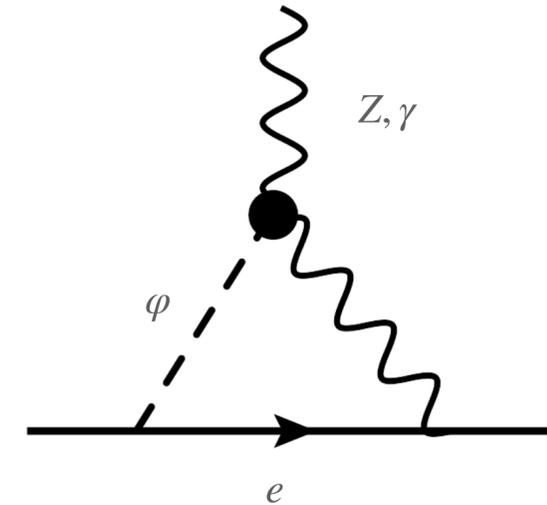
EDMs from new CP-violating operators

- Higgs-gauge interaction

$$\mathscr{L}_{\varphi\varphi WW} = - g^2 C_{\varphi\tilde{W}} \varphi^\dagger \varphi \tilde{W}^i_{\mu\nu} W^{\mu\nu}_i$$

- Contributes to electron EDM

- Strong limit from $\mathrm{HfF^+}$ JILA $d_e < 4.1 \times 10^{-30} e\,\mathrm{cm}$
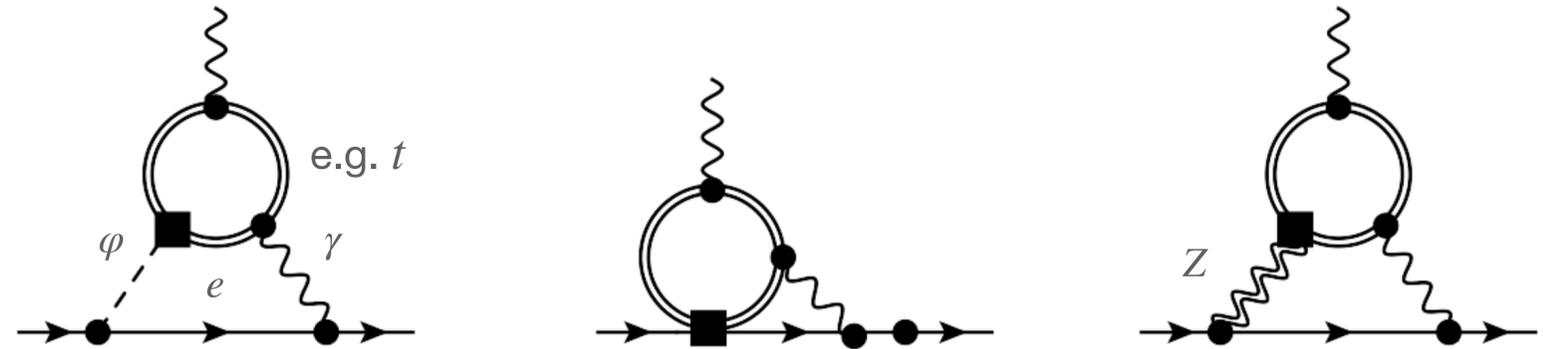
- Used for EWBG in Dine, Huet, Singleton, Susskind 1990, but required scale of new physics is much too low

EDMs from new CP-violating operators

- Yukawa-like

$$\mathcal{L}_{Y,u} = -\bar{Q}_L Y_u \tilde{\varphi} u_R (\varphi^\dagger \varphi)$$
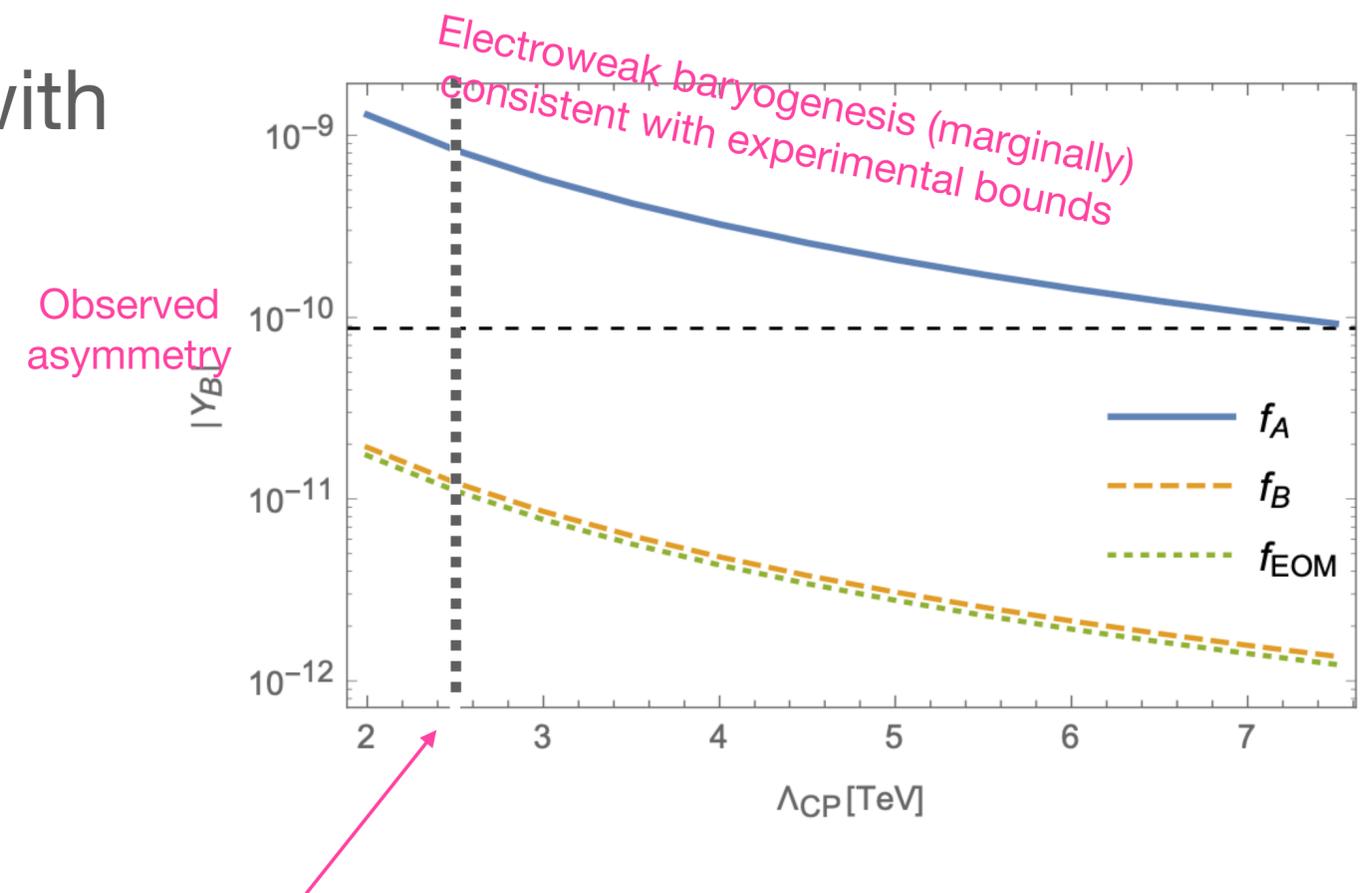

- Top quark contribution to electron-EDM

$$\frac{d_e}{e} = -m_e \frac{8 n_c Q_t^2 \alpha_{\text{em}}}{(4\pi)^3} g(x_t) \times \text{Im}(Y_t), \text{ with } n_3 = 3, Q_t = \frac{2}{3}, g(x_t) \approx 1.4$$

- Limit most severe for largest Y_u (third generation), but source of chiral asymmetry in baryogenesis also proportional to $S^{\text{CPV}} \propto Y_u^2$

- Strong limit from HfF^+ JILA $d_e < 4.1 \times 10^{-30} e$ cm

Tightening bounds on CP-violating operators

- De Vries, Postma, JvdV, White 2017: EWBG with

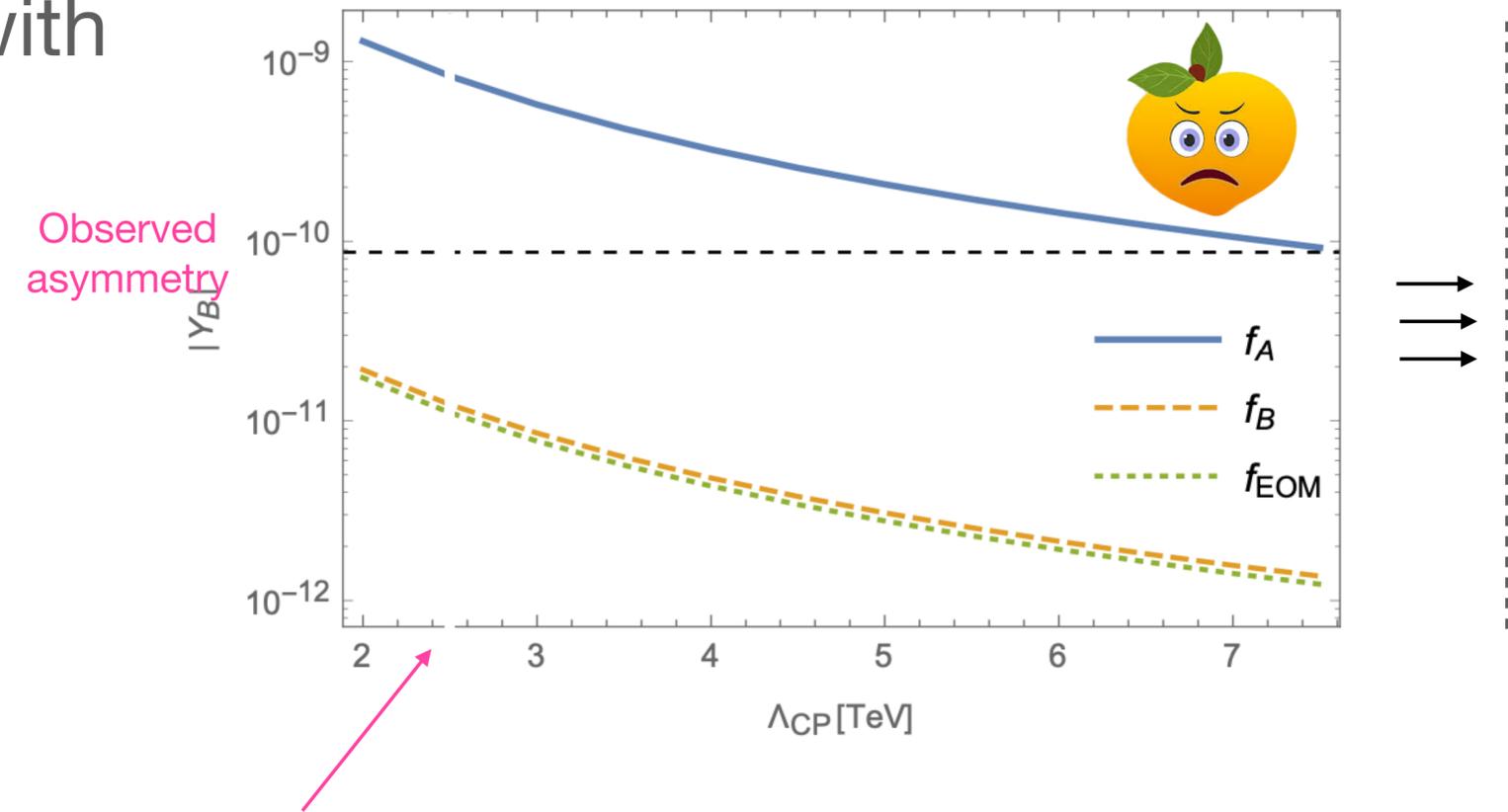$$-\frac{y_t}{\Lambda^2_{CPV}}\bar{Q}_L\tilde{\varphi}t_R\varphi^\dagger\varphi$$

- Best limit in 2017: ACME 2013 $\Lambda_{CPV} > 2.5\,\text{TeV}$

- Current best limit: JILA 2022 $\Lambda_{CPV} > 12\,\text{TeV}$

Tightening bounds on CP-violating operators

- De Vries, Postma, JvdV, White 2017: EWBG with

$$-\frac{y_t}{\Lambda_{\mathrm{CPV}}^2}\bar{Q}_L\tilde{\varphi}t_R\varphi^\dagger\varphi$$

Observed asymmetry

- Best limit in 2017: ACME 2013 $\Lambda_{\mathrm{CPV}} > 2.5\,\mathrm{TeV}$

- Current best limit: JILA 2022 $\Lambda_{\mathrm{CPV}} > 12\,\mathrm{TeV}$

Bottom and tau contributions

- De Vries, Postma, JvdV 2018: baryogenesis with top, bottom and tau

- Bottoms can not have enough CP-violation to explain the baryon asymmetry

- Tau-leptons can, with $\Lambda_{\mathrm{CPV}} \sim 1\,\mathrm{TeV}$ — but this result was ruled out later
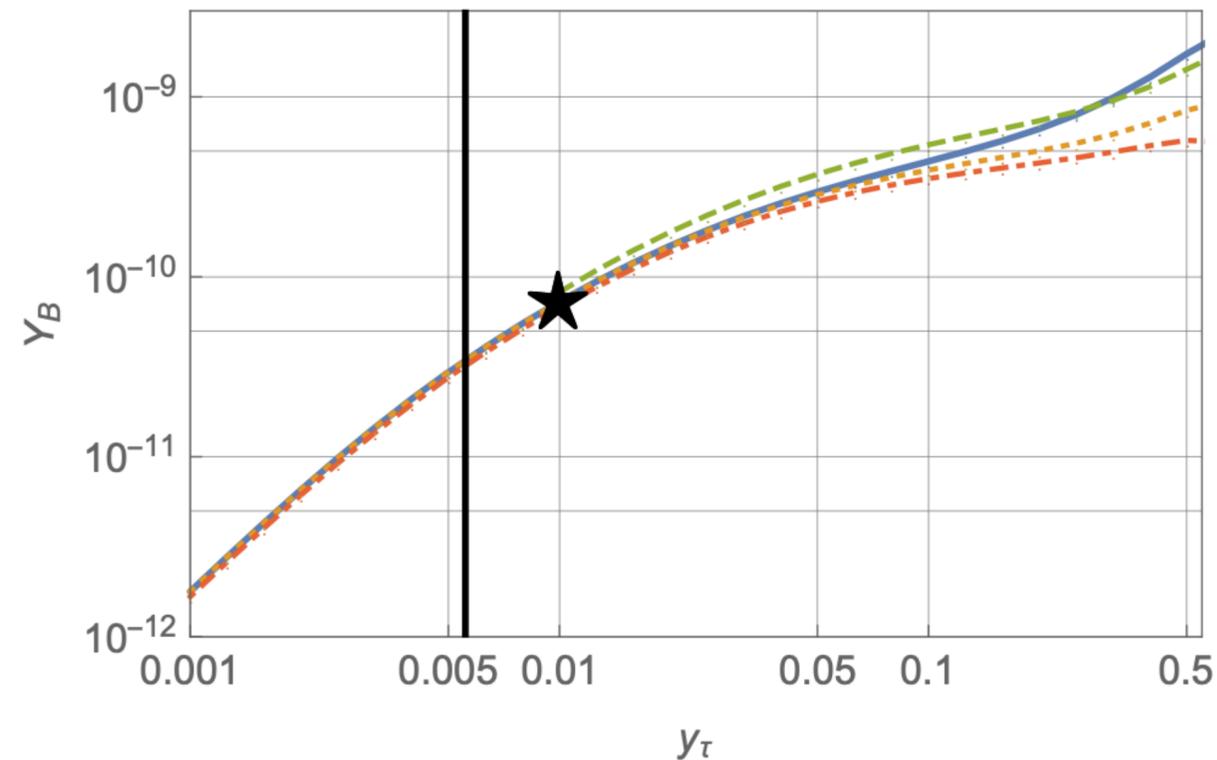
EDMs put strong constraints on EWBG models

Models and mechanisms consistent with EDM constraints

- Flavor-changing CPV operators Liu, Ramsey-Musolf, Shu 2011
  Requires additional CKM suppression to create a (flavor-conserving) EDM

- Two-step electroweak baryogenesis Laurent et al. 2021
  CP-violation proportional to some new field s

$$\mathcal{L}_{\varphi s} = -y_t \bar{Q}_L \tilde{\varphi} t_R \frac{is}{\Lambda_{\text{CPV}}}$$

Works if $s \neq 0$ during the phase transition, but $s = 0$ at present. CP-violation is proportional to the singlet vev, which vanishes at zero temperature

- Models with temperature-dependent CKM matrix Brugisser, Konstandin, Servant 2017

- Cancellations between different contributions to the dominant EDM

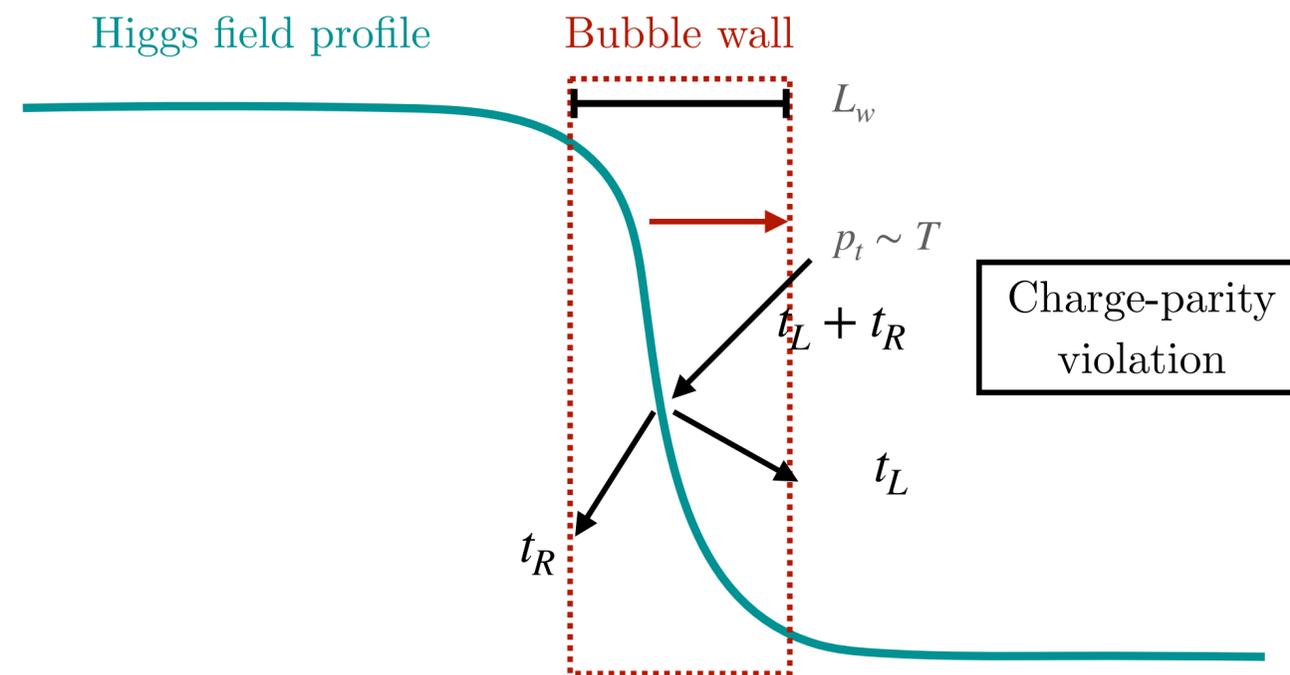# Recent developments in the transport equations

Transport equations

- Boltzmann-like equations for the chiral asymmetry

- Interactions are faster than the baryon number-violating ones: solve system in two steps

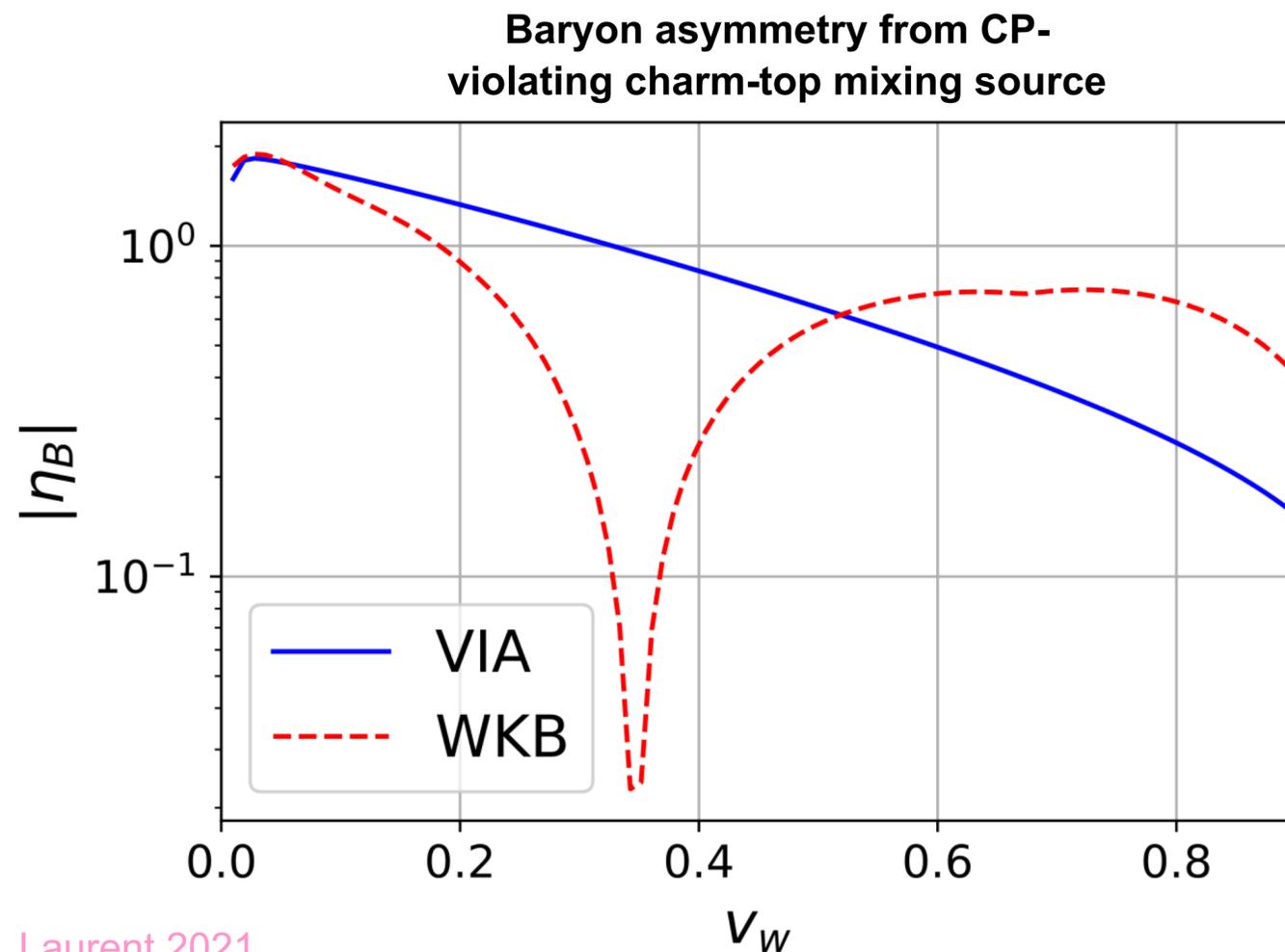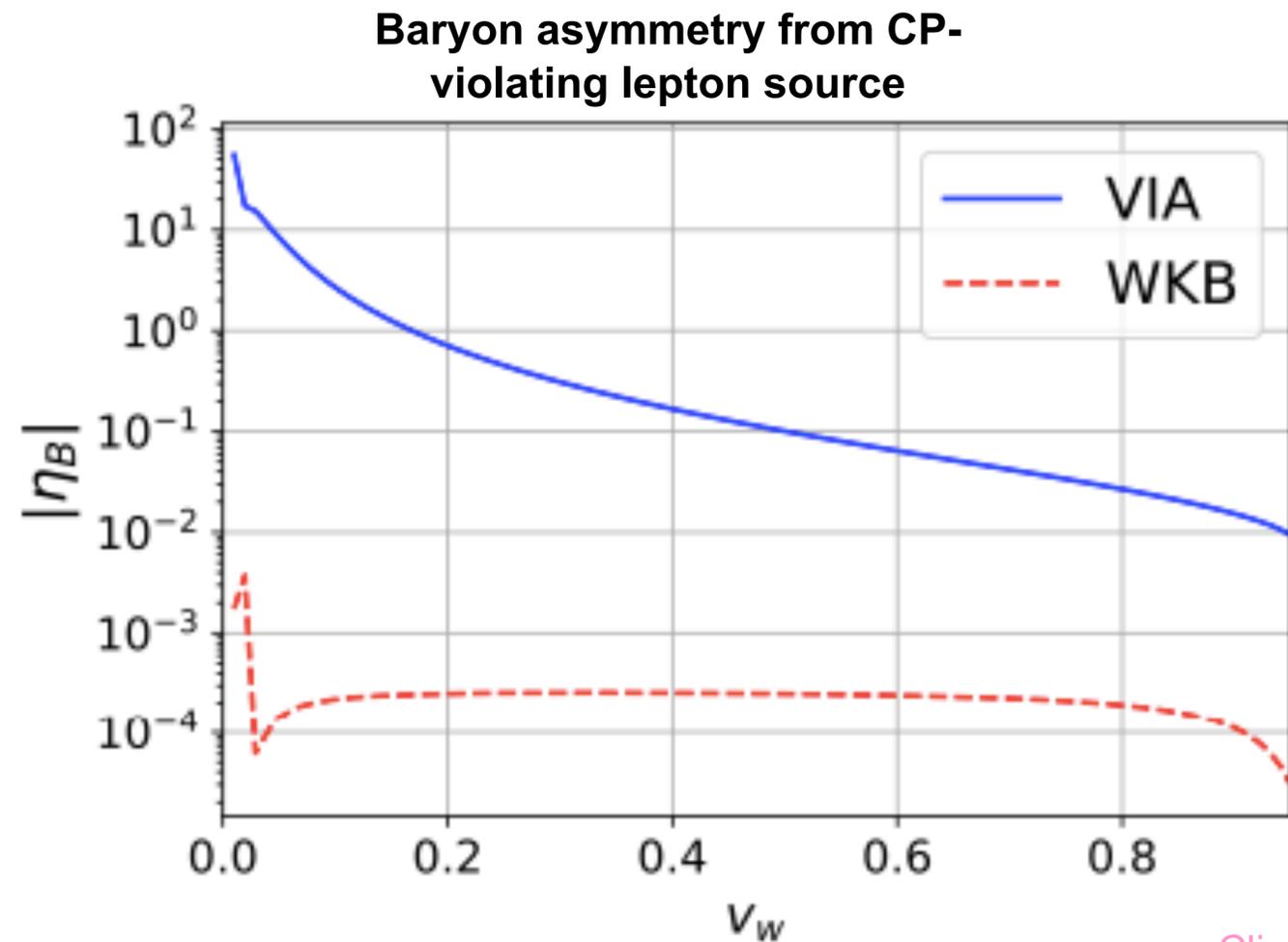- Difficulty: particles have space-time dependent masses
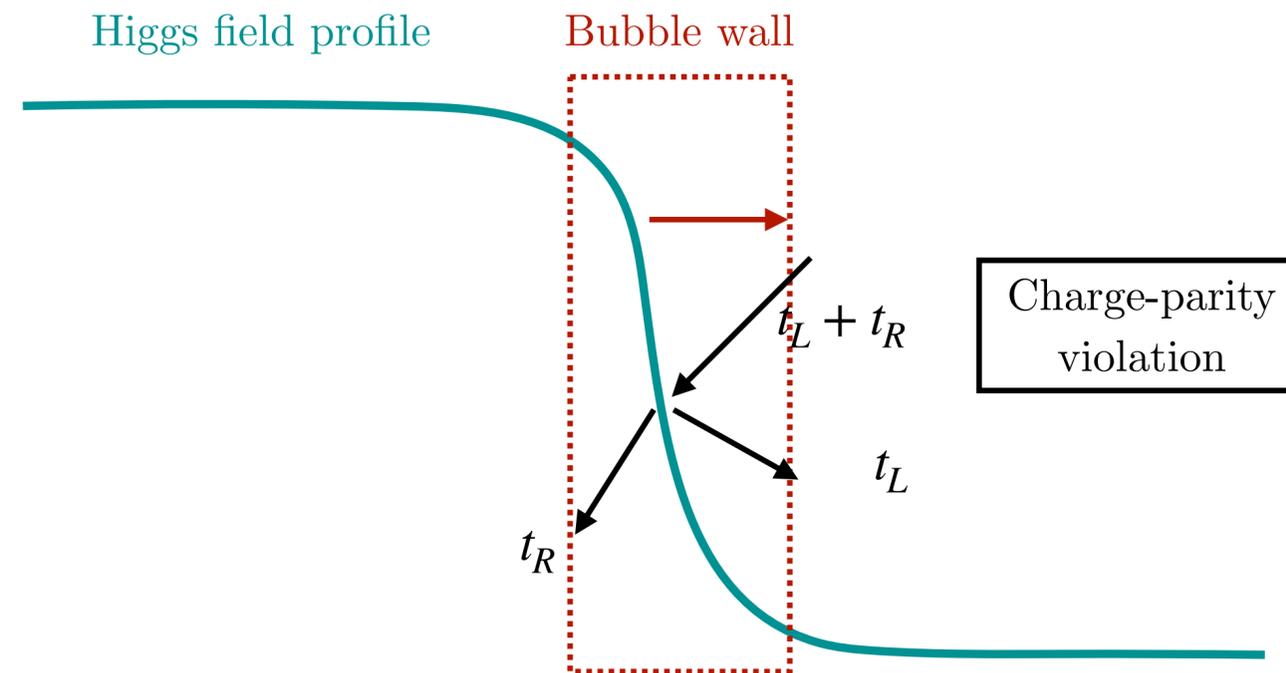
Approximation schemes to derive transport equations

- Starting point: equations of motion for the propagators

- WKB/semi-classical approach: gradient expansion in $1/(L_w T)$

- Vev-insertion approximation (VIA): expansion in m_t/T (used in the 2017 plot)

24

Poor agreement between approximation schemes

Baryon asymmetry from CP-violating lepton source

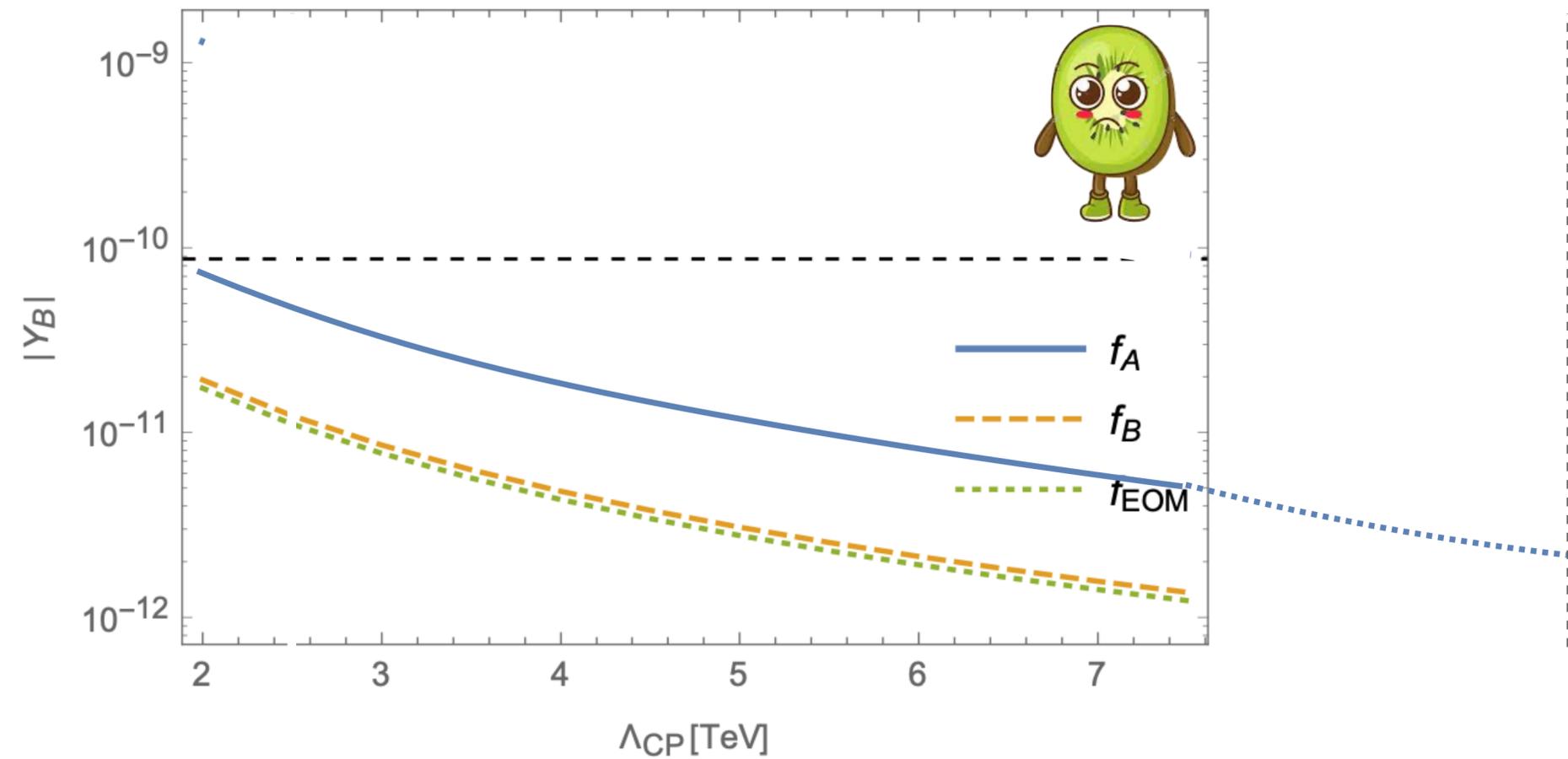Baryon asymmetry from CP-violating charm-top mixing source

Cline, Laurent 2021

- WKB source $\propto m''$, VIA source $\propto m'$

- But actually VIA source vanishes in gradient expansion Kainulainen 2021, Postma, JvdV, White 2022

Poor agreement between approximation schemes
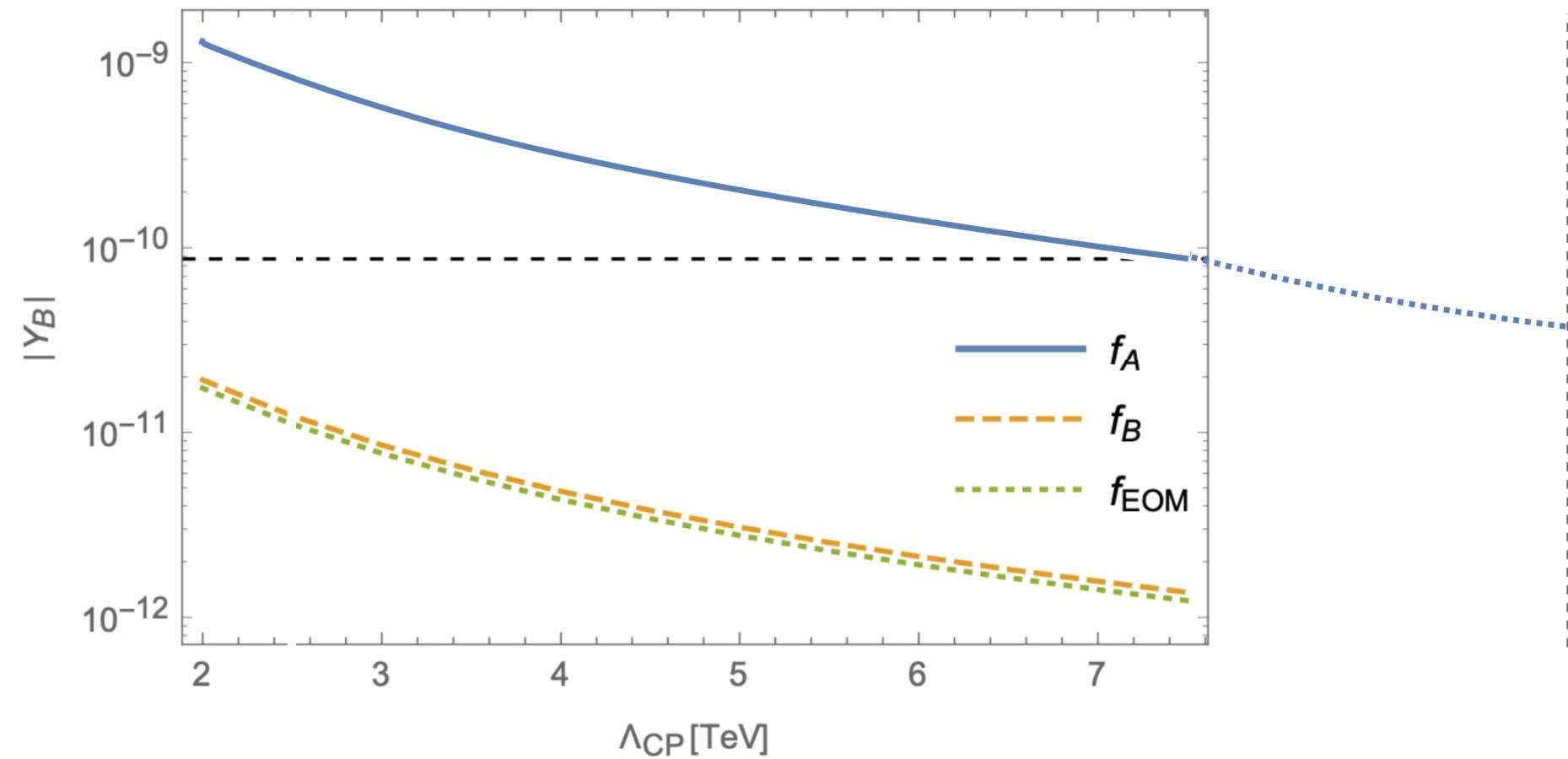
# Poor agreement between approximation schemes

Are there any sources at lower orders in gradients?

- *Flavor source* for systems with non-diagonal mass matrix, e.g.
  Cirigliano, Lee, Tulin 2011

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \phi^\dagger M^2 \phi, \quad \phi = \frac{1}{\sqrt{2}}(\phi_L \ \phi_R)^T, \quad M^2 = \begin{pmatrix} m_L^2 & e^{-i\alpha}v \\ e^{i\alpha}v & m_R^2 \end{pmatrix}$$

- Source appears at *first order* in gradients, larger CP-violating source, EWBG feasible within EDM bounds?

- Difficult to derive the Boltzmann equation, not many studies have been done

**Baryon asymmetry in 2HDM with CP-violating portal**

= Flavor source

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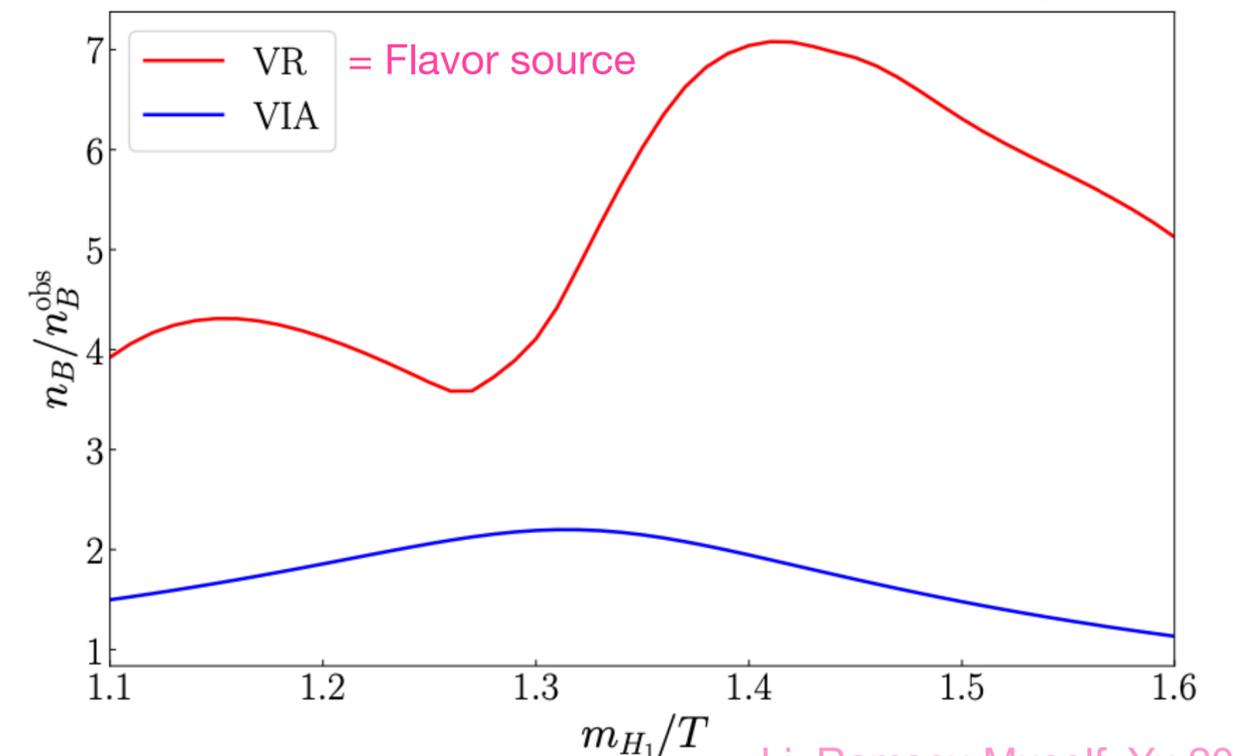
Bubble expansion velocity

- Wall velocity was often set to some favorable value, without dedicated computation

- Public code **(wa(go** Ekstedt, Gould, Hirvonen, Laurent, Niemi, Schicho, JvdV 2024 computes the velocity for any model

- BAU can be non-zero for larger wall velocities than previously thought Cline, Kainulainen 2020

- Good news for gravitational wave detection?
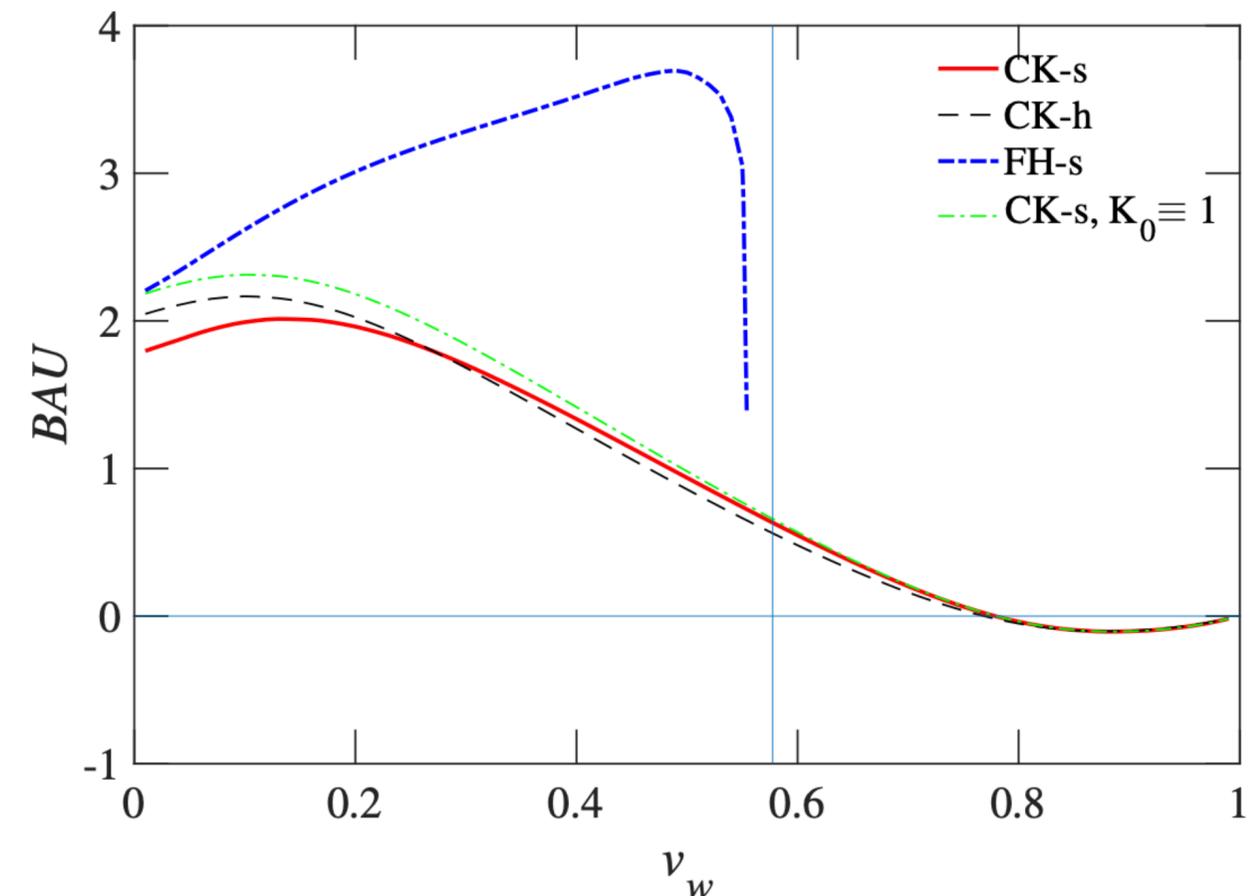
Corrected phase transition temperature and wall velocity
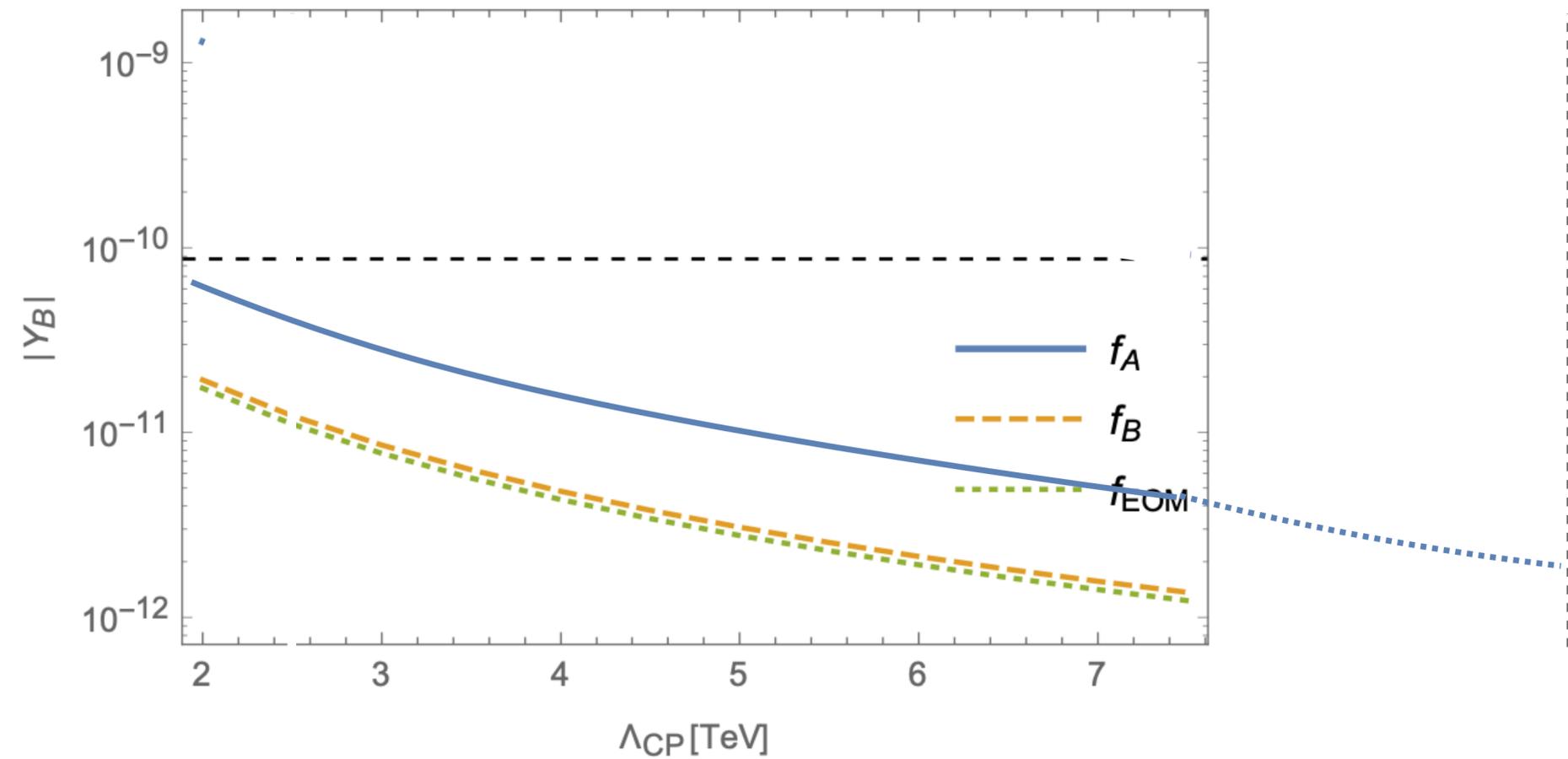
# Corrected phase transition temperature and wall velocity
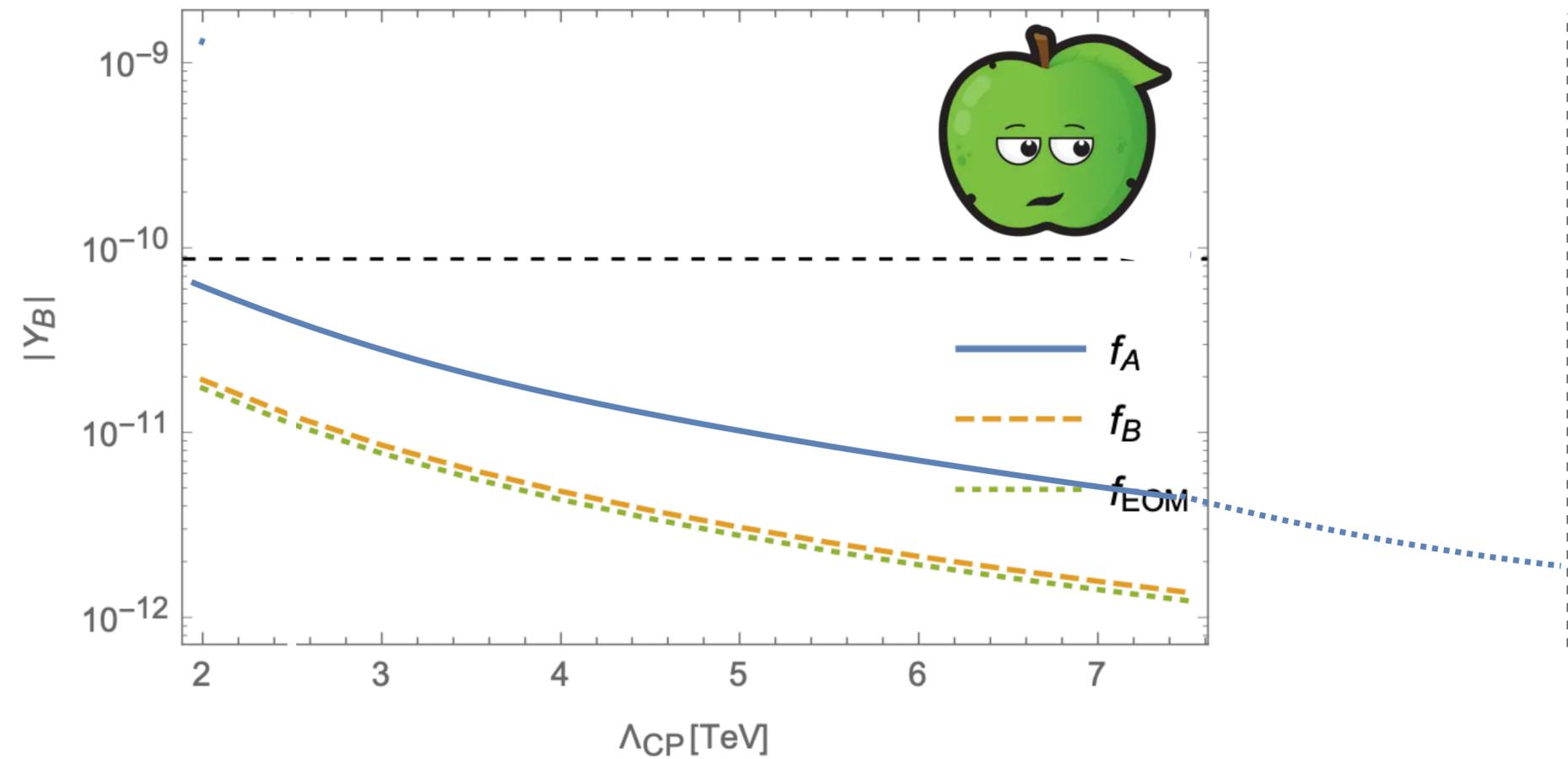
Non-washout criterion

- Baryon diffusion equation in the broken phase:

$$v_w \gamma_w \frac{d\rho_b}{dz} = \mathcal{R}\rho_b \quad \rightarrow \quad \rho_b(z) \sim \rho_b(0)e^{-\frac{\mathcal{R}}{2v_w}z} = \rho_b(0)e^{-\frac{n_f A \Gamma_{\text{sph,b}}}{2v_w T^3}z}$$

- Common approach: $\Gamma_{\text{sph,b}} \sim T^4 e^{-E_{\text{sph}}/T}$, with $E_{\text{sph}} \sim 2.8\frac{4\pi v}{g}$ and demanding that the washout is less than e^{-10} gives $\frac{v}{T} \gtrsim 1$

- Gauge-dependent!

Gauge-independent washout criterion

- Gauge-independent, non-perturbative washout criterion determined by Annala, Rummukainen, Tenkanen 2025

- SM-like effective theory, applicable to models with radiatively generated phase transition
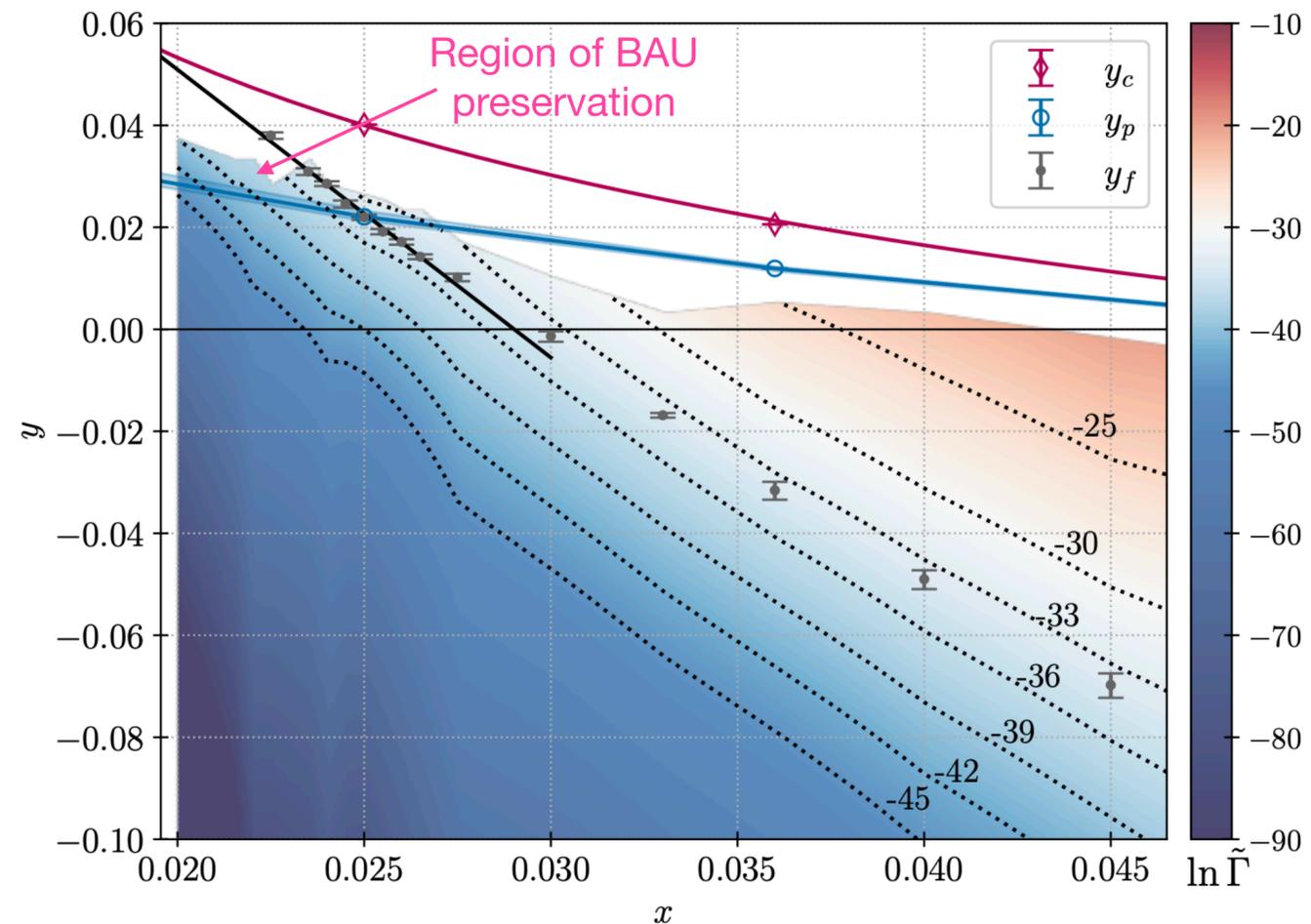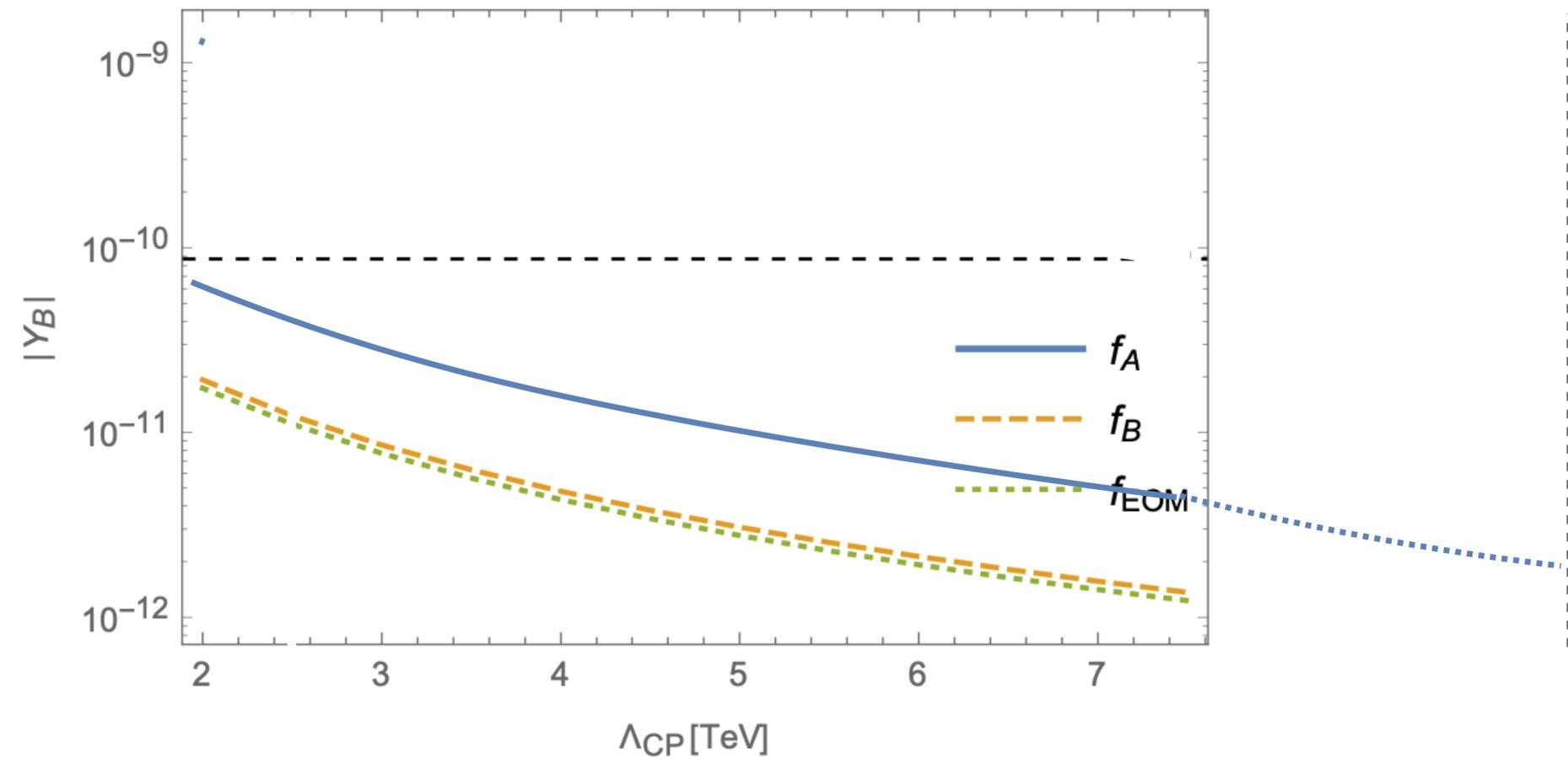
Gauge-independent washout criterion

- Gauge-independent, non-perturbative washout criterion determined by Annala, Rummukainen, Tenkanen 2025

- SM-like effective theory, applicable to models with radiatively generated phase transition

- For different type of phase transitions, the gauge-independent washout criterion is still lacking

Too strong washout?

Too strong washout?
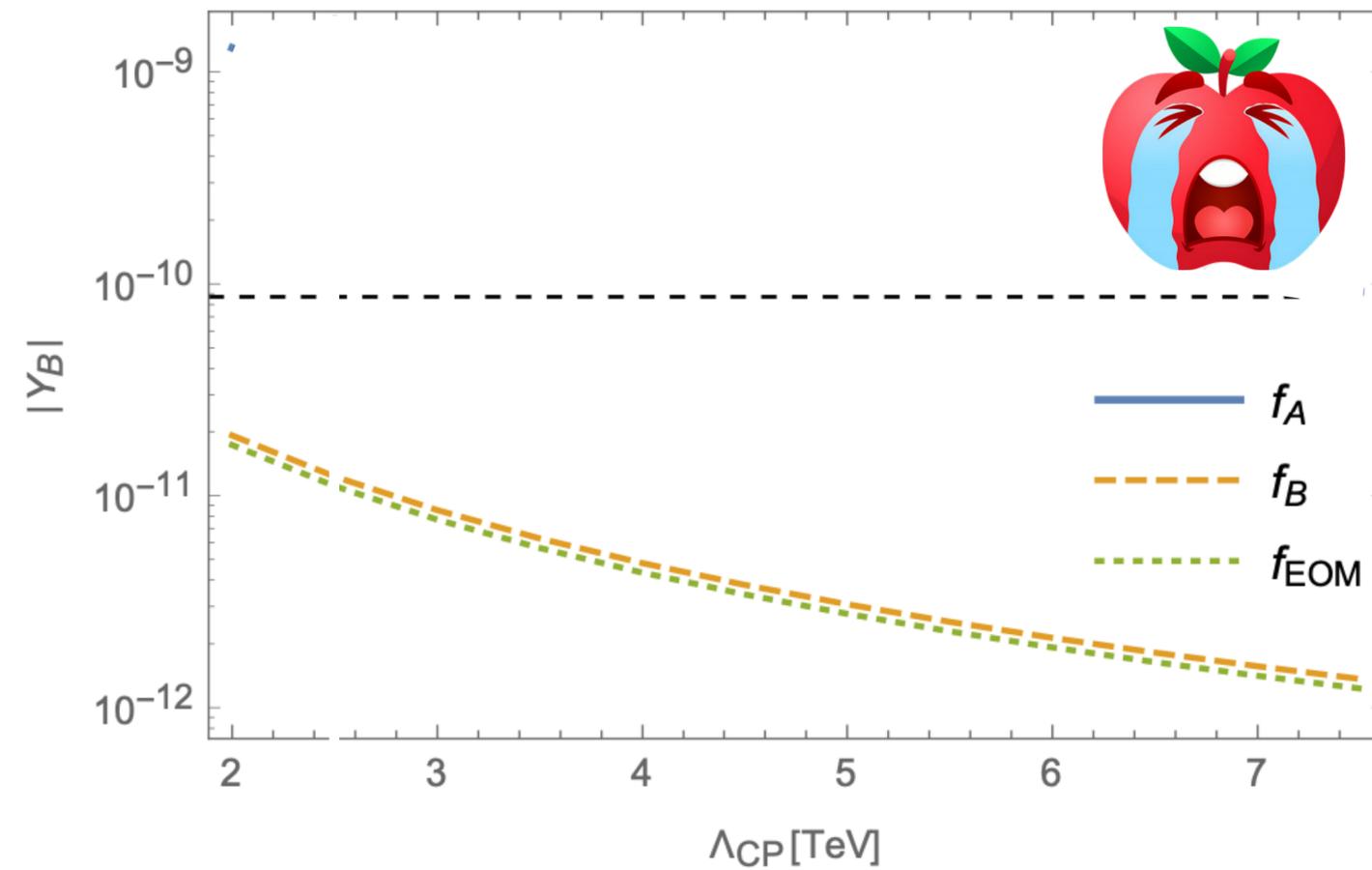
Summary

- Electroweak baryogenesis is an interesting mechanism for the generation of the matter-antimatter asymmetry

- The responsible new physics can leave traces in current and near-future experiments, like colliders and gravitational waves

- EDM experiments are putting stringent constraints on CP-violating operators

- EWBG with CP-violation from the SMEFT is in tension with EDM experiments

- Significant progress in computation of the BAU in recent years, some results need to be re-evaluated