

# Bubble profile and baryon asymmetry in complex 2HDM

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**OKLAHOMA STATE**  
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1. Matter-antimatter Asymmetry puzzle
2. Electroweak Baryogenesis
  - Electroweak phase transition
  - Bubble profile
  - Semi-classical force approach
3. Complex 2HDM
4. Results
5. Summary

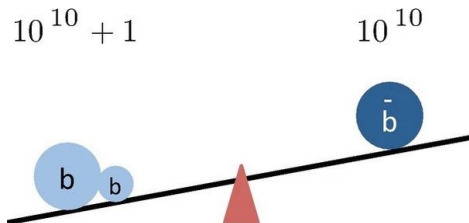
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# Matter-antimatter Asymmetry puzzle



- ▶ Baryon to photon ratio:  $\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = 6 \times 10^{-10} \frac{\text{excess baryons}}{\text{photon}}$

(WMAP data)



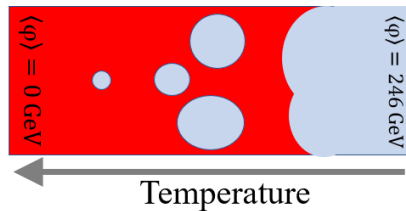
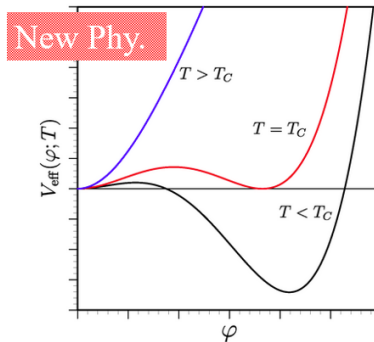
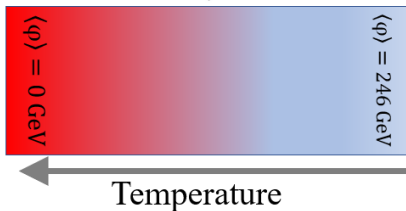
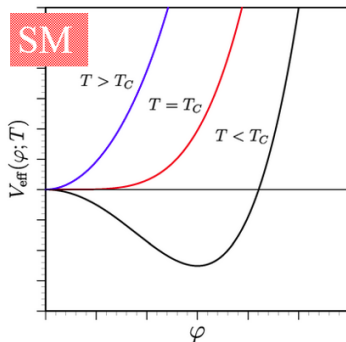
Need physics beyond the standard model!

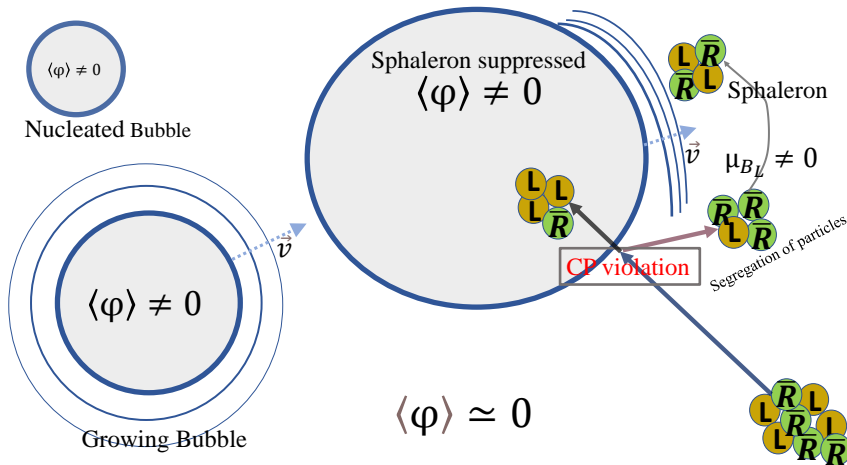
- ▶ The three necessary conditions to dynamically generate baryon asymmetry from none previously existed,
  1. Baryon number violation
  2. C and CP violation
  3. Departure from thermal equilibrium

(A Sakharov 1967)

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# Electroweak phase transition





- Sphaleron to be suppressed inside the bubble, we need a strong first-order phase transition  $\xi \equiv \frac{\langle \varphi \rangle}{T} \gtrsim 1$

- ▶ Key ingredient in estimation of baryon asymmetry during EWBG is bubble profile

$$\frac{d^2\phi}{dr^2} + \frac{2}{r} \frac{d\phi}{dr} = \frac{dV(\phi, T)}{d\phi}, \quad \text{with} \quad \lim_{r \rightarrow \infty} \phi(r) = 0 \quad \text{and} \quad \lim_{r \rightarrow 0} \frac{d\phi(r)}{dr} = 0.$$

(A D Linde 1980)

- ▶ In the literature, it is a customary practice to parameterize tunneling profile  $\theta^i(z)$  by kink profile using tanh function

$$\theta^i(z) = \left( \frac{\theta_{\text{brk}}^i + \theta_{\text{sym}}^i}{2} - \frac{\theta_{\text{brk}}^i - \theta_{\text{sym}}^i}{2} \left( \tanh \left( \frac{z}{L_W} \right) \right) \right).$$

(D Bodeker, L Fromme, S J. Huber, M Seniuch 2004 )

$$\theta^i(z \rightarrow -\infty) = \theta_{\text{brk}}^i$$

$$\theta^i(z \rightarrow \infty) = \theta_{\text{sym}}^i$$

- ▶ Particle interaction with bubble wall can be formalized using the WKB approximation. Force acting on the particle is given by (+particle/-antiparticle)

$$F_z = -\frac{(m^2)'}{2E_0} \pm s \frac{(m^2\theta')'}{2E_0 E_{0z}} \mp \frac{\theta' m^2 (m^2)'}{4E_0^3 E_{0z}}.$$

( L Fromme, S J. Huber, 2006 )

- ▶ Source term of the top quark  $S_t$

$$S_t = -v_W K_{8,t} \partial_z (m_t^2 \partial_z \theta) + v_W K_{9,t} (\partial_z \theta) m_t^2 (\partial_z m_t^2).$$

In front of the bubble wall, the negative value of  $\partial_z \theta$  leads to a positive  $S_t$  and, thereby, in most cases, positive asymmetry.

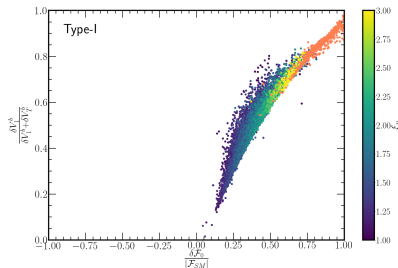
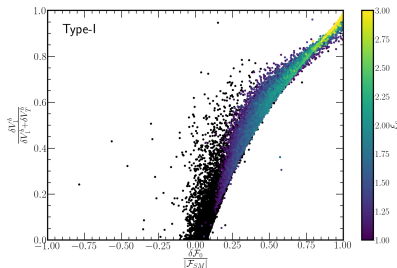
- ▶ Chemical potential for left-handed quarks  $\mu_{BL} = \mu_{q1,2} + \mu_{q2,2} + \frac{1}{2}(\mu_{t,2} + \mu_{b,2})$ .
- ▶ LH quark asymmetry is converted into baryon asymmetry by weak sphalerons,

$$\eta_\beta = \frac{n_B}{s} = \frac{405 \Gamma_{ws}}{4\pi^2 v_w g_\star T} \int_0^\infty dz \mu_{BL} \exp \left( -\frac{45 \Gamma_{ws} z}{4v_w} \right).$$

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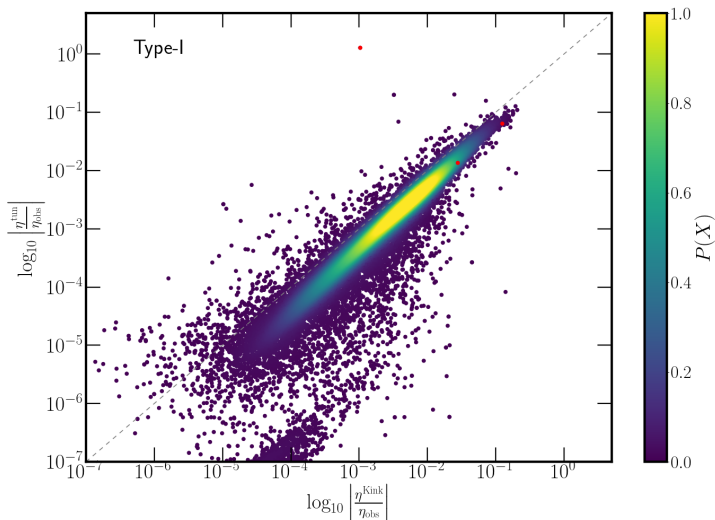
Complex 2HDM with a softly broken  $\mathbb{Z}_2$  symmetry.

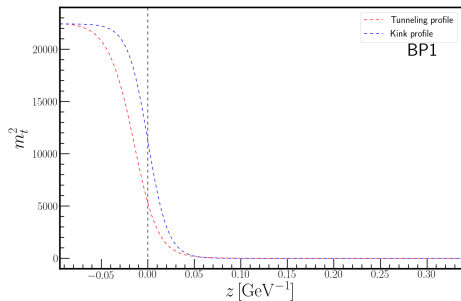
$$V_0(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left( \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. \right).$$



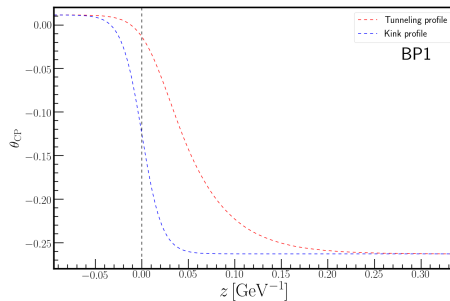
$$\frac{\Delta \mathcal{F}_0}{|\mathcal{F}_{SM}|} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{\text{SM}}}{|\mathcal{F}_{SM}|}, \quad \mathcal{F}_0 \equiv V_{\text{eff}}(v_1, v_2, T = 0) - V_{\text{eff}}(0, 0, T = 0)$$

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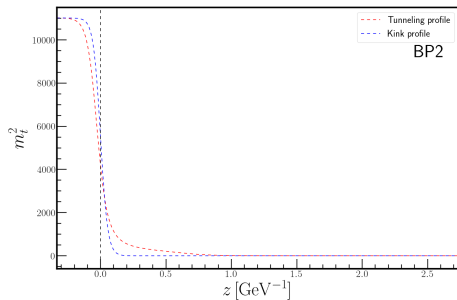




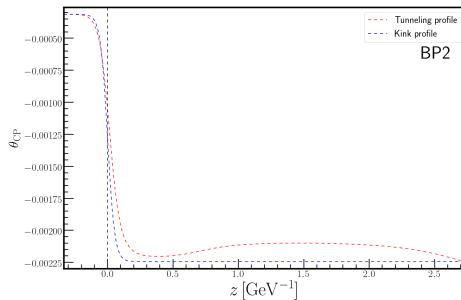
$$\eta_B^{\text{tun}} = 5.51061 \times 10^{-12}$$



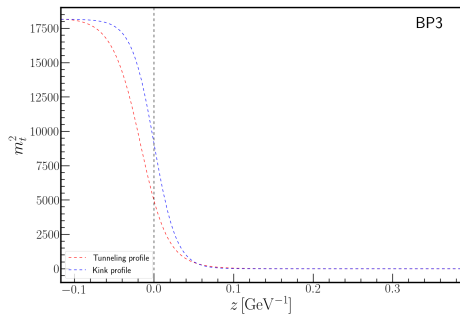
$$\eta_B^{\text{kink}} = 1.05886 \times 10^{-11}$$



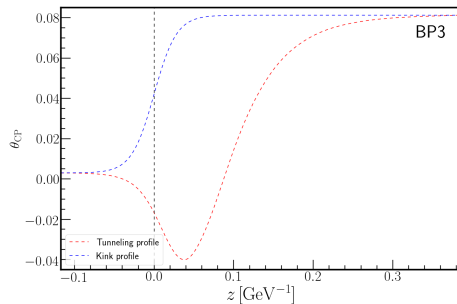
$$\eta_B^{\text{tun}} = 1.08663 \times 10^{-10}$$



$$\eta_B^{\text{kink}} = 8.79358 \times 10^{-14}$$



$$\eta_B^{\text{tun}} = 1.16237 \times 10^{-10}$$



$$\eta_B^{\text{kink}} = -2.33474 \times 10^{-12}$$

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1. For most points, the kink profile can capture baryon asymmetry predicted by the tunneling profile, but there are a small fraction of points where the difference in asymmetry is significant.
2. The kink profile generally gives a slightly larger asymmetry in magnitude than the tunneling profile because it provides a larger top mass near the bubble wall.
3. In some cases, source term can be active in larger regime for the tunnelling profile and could yield two or more orders large asymmetry compared to kink profile.
4. The behavior of the phase of top mass  $\theta_{CP}$  near the bubble wall could differ for kink and tunnelling profiles, and it could lead to the opposite sign of asymmetry.
5. When vacuum upliftment measure  $\Delta\mathcal{F}_0/|\mathcal{F}_0^{\text{SM}}|$  is very large, universe could be trapped in the false vacuum. Vacuum trapping constraint excludes bulk of  $\xi_c > 2$ .

Thank you!



- ▶ Particle interaction with bubble wall can be formalized using the WKB approximation. Force acting on the particle is given by (+particle/-antiparticle)

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( L Fromme, S J. Huber, 2006 )

- ▶ Perturbation from equilibrium density of species  $i$  due to bubble wall movement

$$f_i = \frac{1}{e^{\beta[\gamma_W(E_0 + v_w p_z) - \mu_i]} \pm 1} + \delta f_i$$

- ▶ The evolution of  $f_i$  is described by the Boltzmann equation

$$\mathbf{L}[f_i] \equiv (v_g \partial_z + \dot{p}_z \partial_{p_z}) f_i = C[f_i], \quad v_g = \frac{P_z}{E_0} \left( 1 \pm \frac{\theta' m^2}{2E_0^2 E_{0z}} \right).$$

$$\text{Plasma velocity } u_i \equiv \left\langle \frac{p_z}{E_0} \delta f_i \right\rangle.$$

- ▶ We can separate CP odd and even parts

$$\mu_i \equiv \mu_{i,1e} + \mu_{i,2o} + \mu_{i,2e}, \quad \delta f_i \equiv \delta f_{i,1e} + \delta f_{i,2o} + \delta f_{i,2e}.$$

- ▶ Second-order CP odd chemical potential and plasma velocities

$$\mu_{i,2} \equiv \mu_{i,2o} - \bar{\mu}_{i,2o}, \quad u_{i,2} \equiv u_{i,2o} - \bar{u}_{i,2o}.$$

- ▶ Source term of the top quark  $S_t$

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