Baryogenesis in the 2HDM+a

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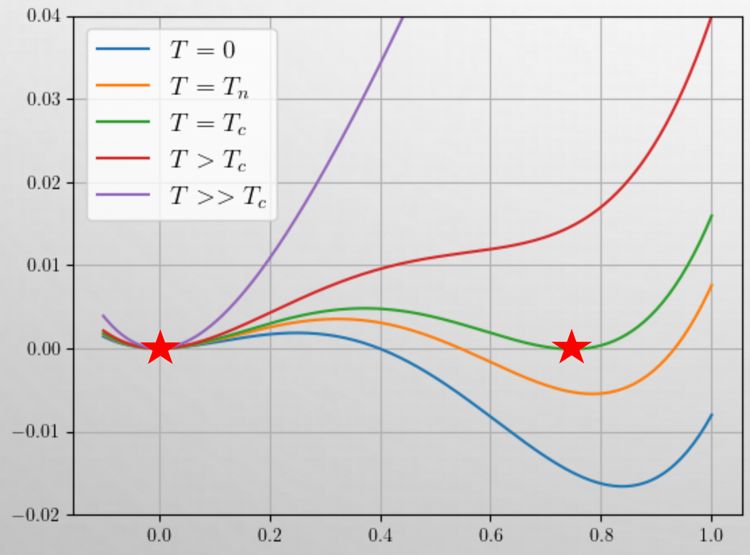
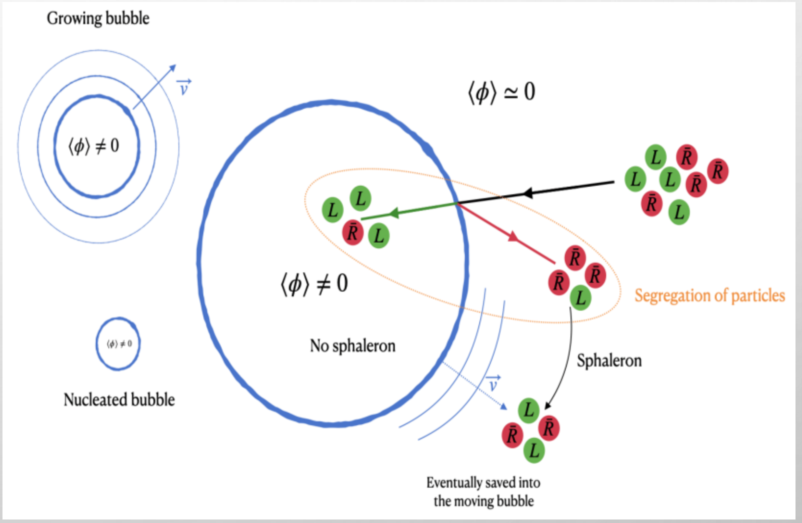
Baryogenesis Checklist

A. Sakharov 1967

1) C & CP-violation
2) Departure from thermal equilibrium
3) Baryon number violation

1) Complex parameters in model
2) Electroweak first-order phase transition
3) B+L number violation via sphalerons





R. Gannouji 2022

Baryogenesis in the SM

1) Complex parameters in model
2) Electroweak first-order phase transition
3) B+L number violation via sphalerons

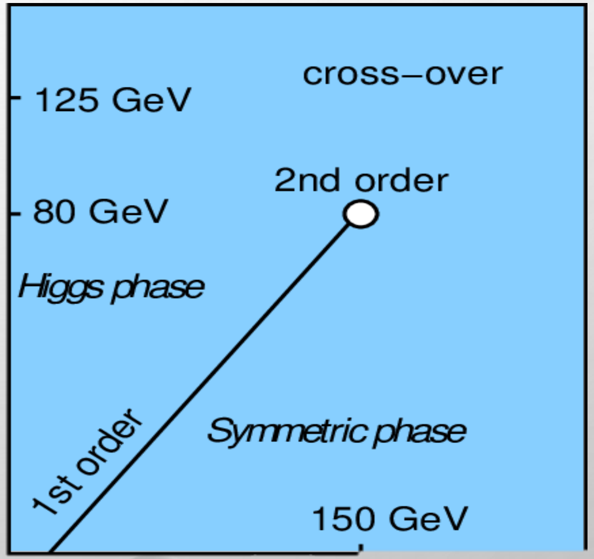
→

1) CKM phase
2) Perturbation theory at finite temperature
3) Non-perturbative $SU(2)_L$ sphalerons

So, what's the problem?

Baryogenesis predicted orders of magnitudes too small! ✖

SM perturbation theory unreliable near critical temperature! ✖



M. Hindmarsh et al 2021

BSM Extension – 2HDM+a

$$V_{\text{2HDM}} = \mu_{11}^2|\Phi_1|^2 + \mu_{22}^2|\Phi_2|^2 - \mu_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4$$
$$+\lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right)$$

Two $SU(2)_L$ doublets

$$V_{\text{a}} = \frac{1}{2}\mu_a^2 a^2 + \frac{1}{4}\lambda_a a^4 + i\kappa a\left(\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\lambda_{a,\Phi_1}a^2|\Phi_1|^2 + \frac{1}{2}\lambda_{a,\Phi_2}a^2|\Phi_2|^2$$

Pseudoscalar SM singlet couples to the two Higgs fields

S. Ipek, D. McKeen, A. E. Nelson, 2014

Not the most general potential. Assumptions?

1) Soft $\mathbb{Z}_2$ symmetry, $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$

2) All parameters are real… so no extra CP-violation?

Spectrum and Parameters

V_{2HDM}

- 1 Charged Higgs $H^{\pm}$
- 2 CP-even Higgs h, H
- 1 CP-odd Higgs A^0
- 1 CP-odd scalar a

$\rightarrow$

$V_{\text{2HDM}} + V_{\text{a}}$

- Unchanged
- 2 CP-odd like scalars a_1, a_2

$$\Phi_1 \to H_1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} h \end{bmatrix}$$

$$\Phi_2 \to H_2 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} (H + iA^0) \end{bmatrix}$$

$$V \to V_T(h, H, A^0, a)$$

$$\{\mu_{11}^2\,,\ \mu_{22}^2\,,\ \mu_{12}^2\,,\ \lambda_1\,,\ \lambda_2\,,\ \lambda_3\,,\ \lambda_4\,,\ \lambda_5\,,\ \mu_a^2\,,\ \lambda_a\,,\ \kappa\,,\ \lambda_{a,\Phi_1}\,,\ \lambda_{a,\Phi_2}\}$$

$$\Downarrow$$

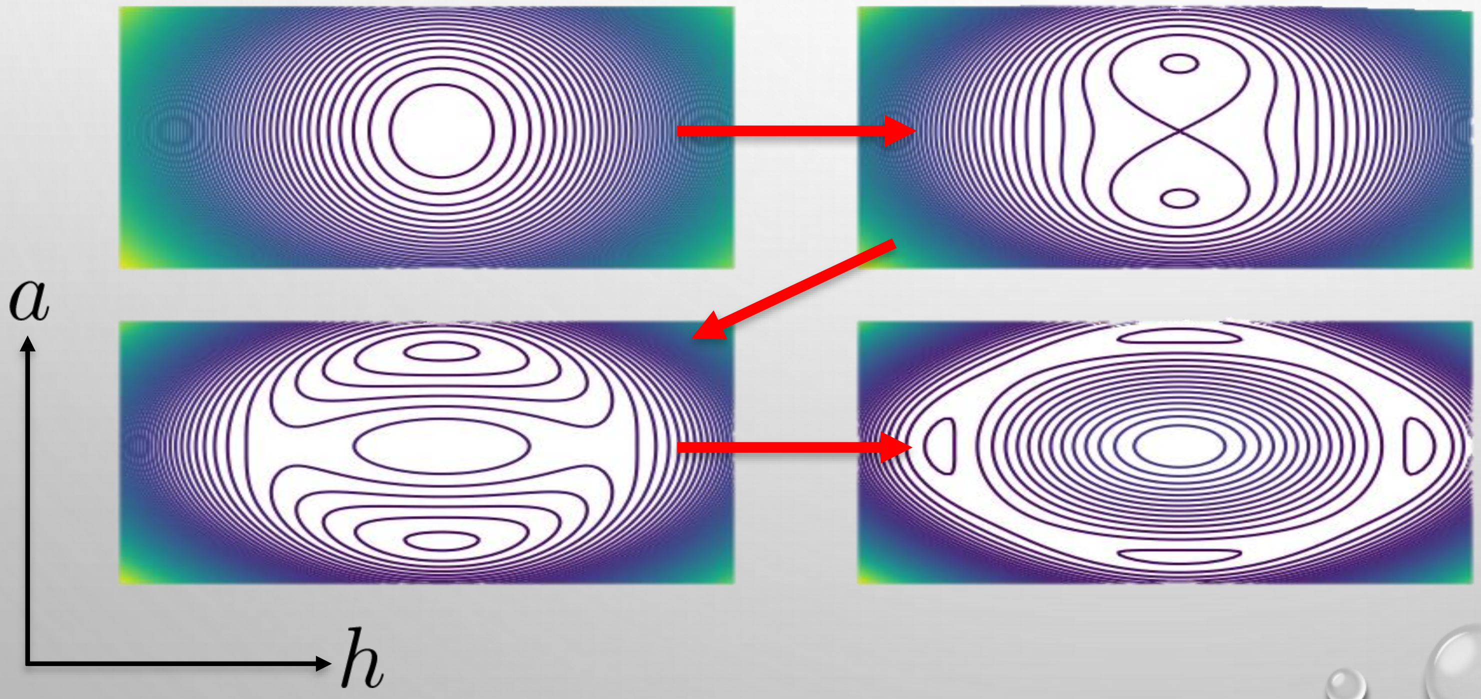
$$\{\beta\,,\ \theta\,,\ v_s\,,\ M\,,\ m_H\,,\ m_{H^\pm}\,,\ m_{a_1}\,,\ m_{a_2}\,,\ \lambda_{a,\Phi_1}\,,\ \lambda_{a,\Phi_2}\}$$

CP-Violation?

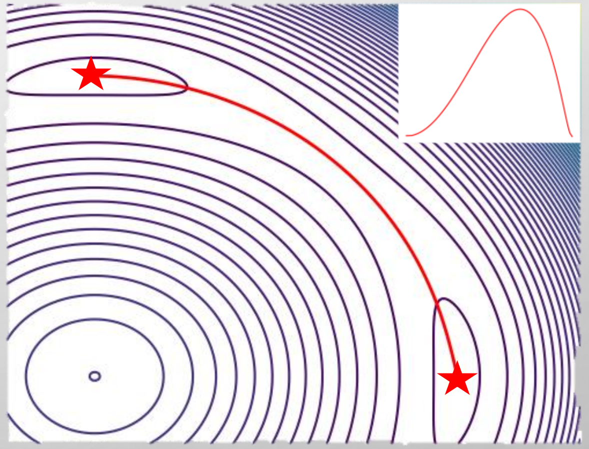
All parameters real $\Longrightarrow$ No extra CP-violation at zero-temperature, avoids tight EDM constraints!

What if pseudoscalar a takes a vacuum expectation value $v_s(T)$?

$$V \supset -\mu_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + i\kappa a(\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1)\,, \quad \delta = \mathrm{Arg}\left(\mu_{12}^2(T)^*\,\mu_{12}^2\right)$$



Potential FOPT from CP-violating to EW minima!



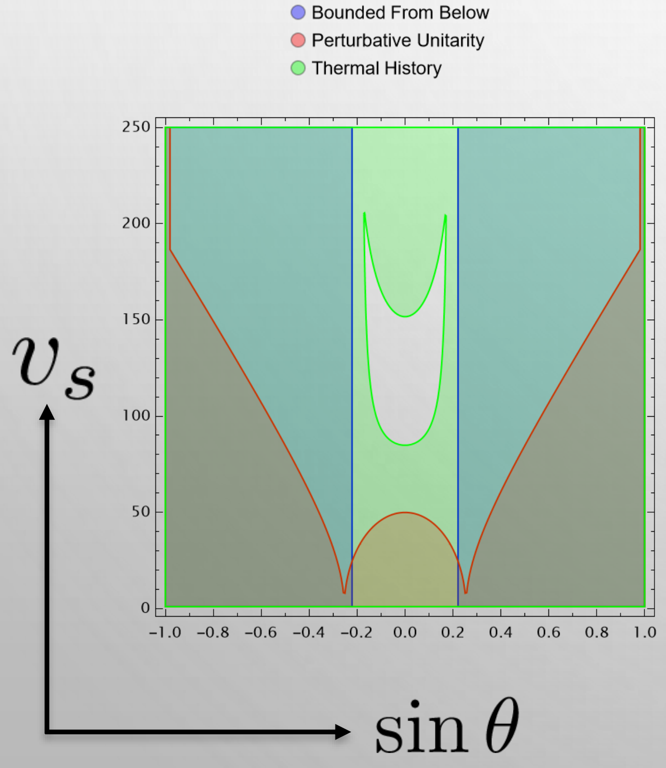
Parameter Space Constraints

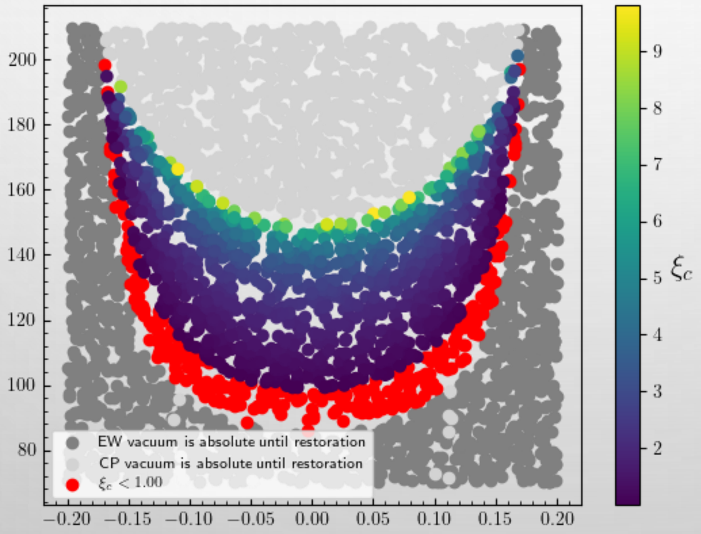
Theoretical

- Thermal History
- Perturbative Unitarity
- Bounded from Below

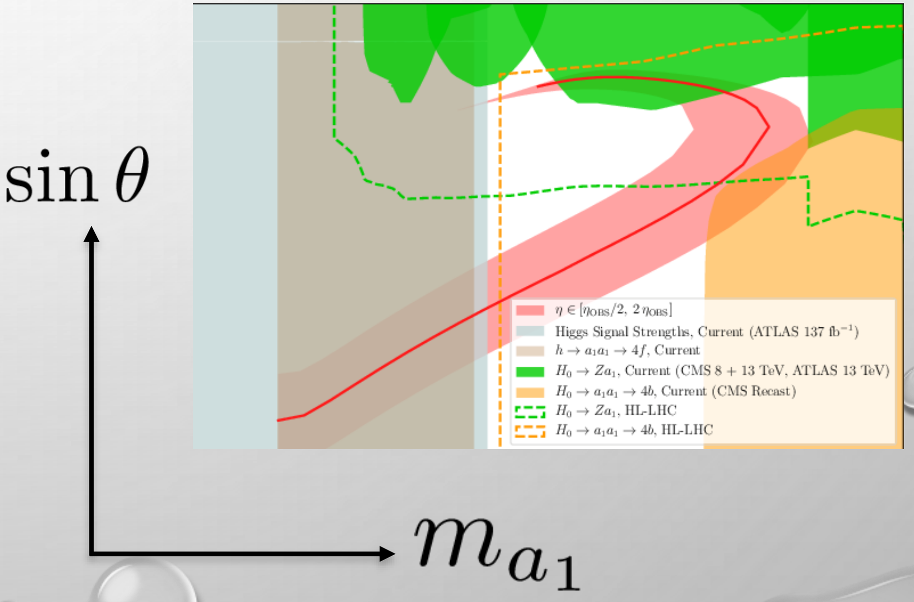
Experimental

- Direct Searches
- Flavour Physics
- EW Precision





S.J. Huber, K. Mimasu, J. M. No 2023



Bubble Nucleation

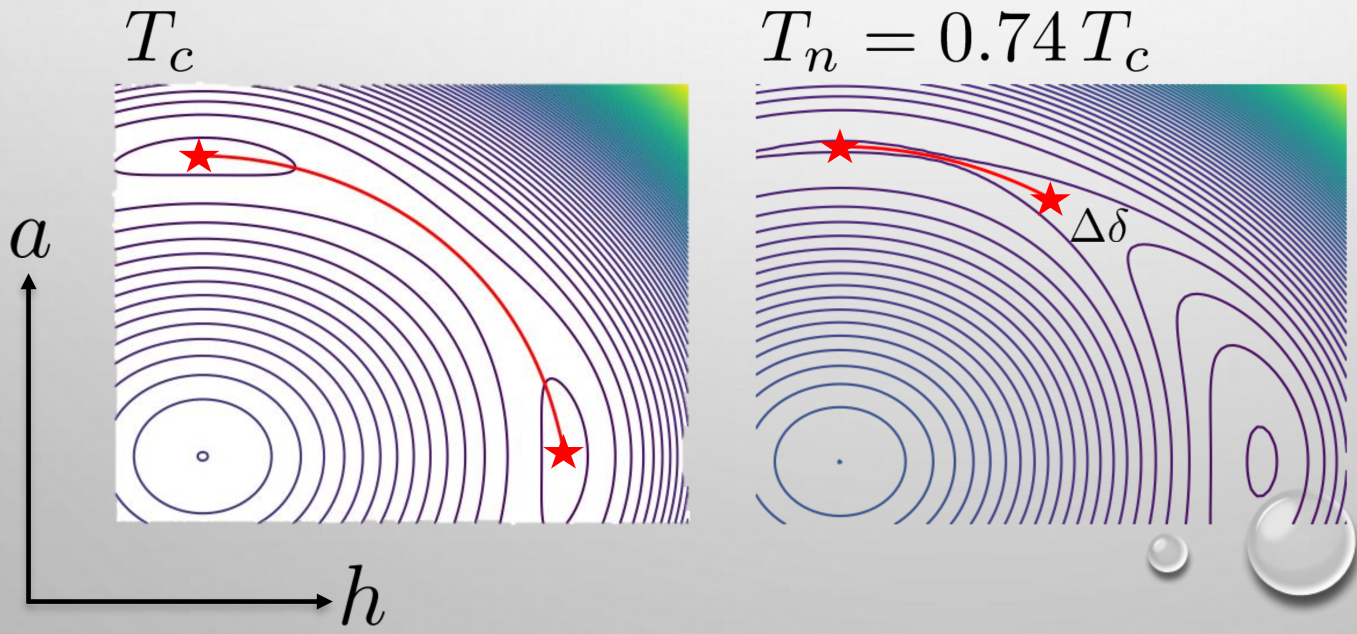
Phase transition happens at $T_n < T_c$, condition required is $S_3/T \approx 140$

Solve EOM's

$$\frac{\partial^2 \phi_i}{\partial \rho^2} + \frac{2}{\rho}\frac{\partial \phi_i}{\partial \rho} = \frac{\partial V_T}{\partial \phi_i}\,, \quad \phi_i(\infty) = 0\,,\ \phi_i'(0) = 0$$

Evaluate action

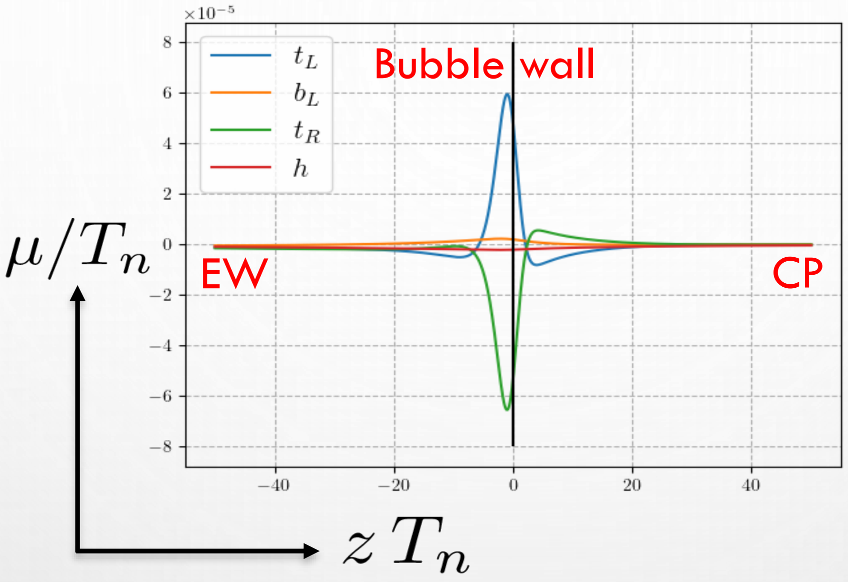
$$S_3 = 4\pi \int_0^\infty d\rho\, \rho^2 \left[\left(\frac{1}{2} \frac{d\phi_i}{d\rho} \right)^2 + V_T(\phi_i) \right]$$

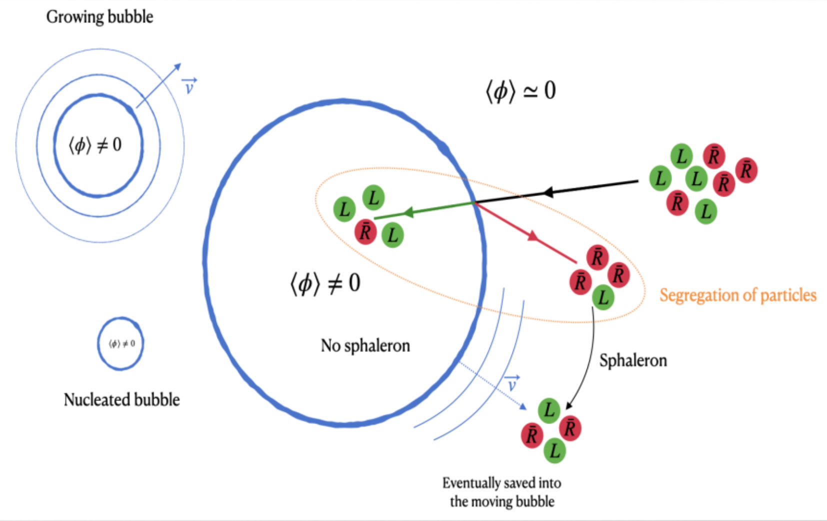


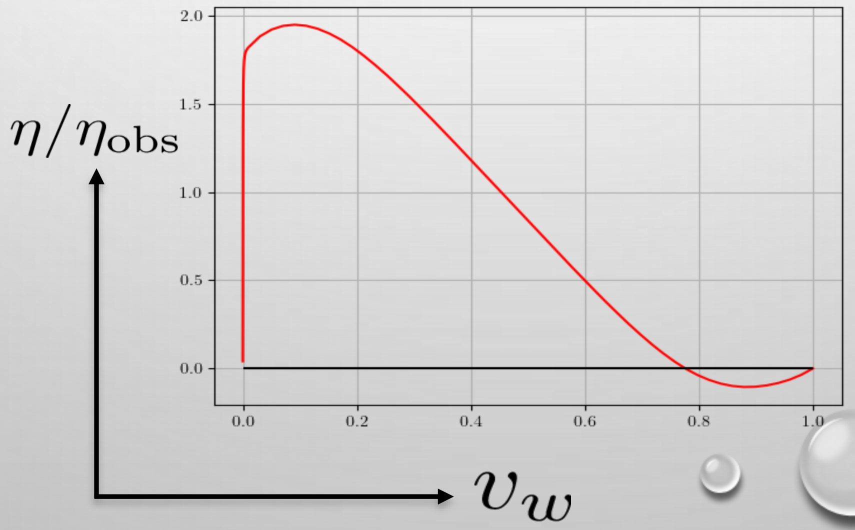
Phase of the complex parameter δ in potential changes across the phase transition!

Transport Equations

- Due to CP-violation, top quark has mass $m_t(z) = |m_t(z)|e^{i\theta_t(z)}$
- Left and right-handed tops interact differently with bubble wall and chiral asymmetry accumulates.
- Sphalerons convert right to left-handed tops outside the bubble wall, so asymmetry isn't washed out.







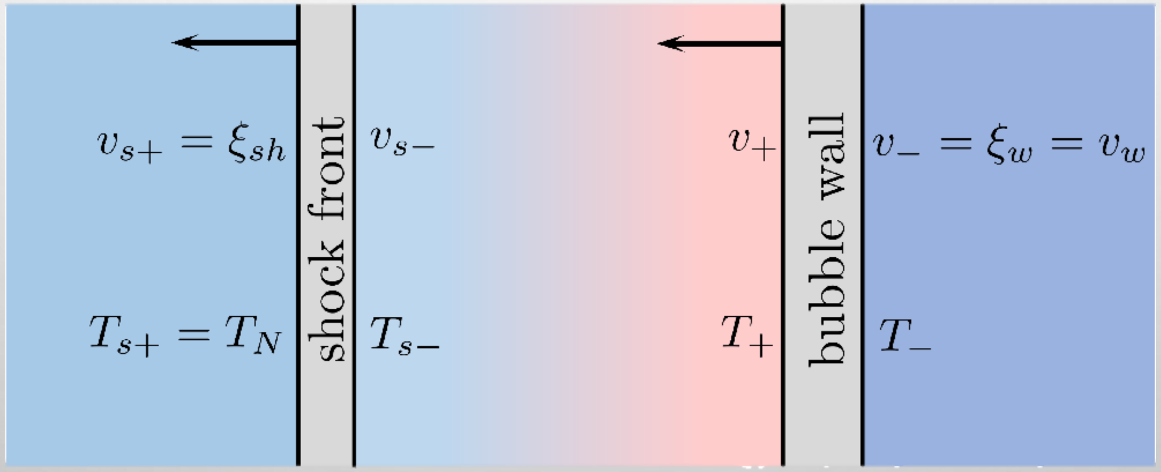
Solved using method from J.M.Cline, K. Kainulainen 2020, v_w is an input.

Wall Velocity

How fast do the bubble walls move after nucleation?
Most difficult part of the problem with many different approaches!

- Needed as an input for the transport equations to calculate baryogenesis
- Use different estimates and hope that it constrains range of velocities

G. C. Dorsch et al 2017
G.C. Dorsch, S. J. Huber, T. Konstandin 2018
W. Ai, B. Laurent, J. Van de Vis 2023



J. Siyu, H. P. Fa, W. Xiao 2023

Summary

Model to Predictions

1. Introduce BSM extension and build phenomenological potential
2. Find spectra and 'physical' parameter set
3. Apply relevant theoretical and experimental constraints
4. Estimate wall velocity and solve transport equations for baryogenesis
5. Scan chosen parameter space

Details

1. 2HDM+a
2. Set $\{\beta\,,\ \theta\,,\ v_s\,,\ M\,,\ m_H\,,\ m_{H^\pm}\,,\ m_{a_1}\,,\ m_{a_2}\,,\ \lambda_{a,\Phi_1}\,,\ \lambda_{a,\Phi_2}\}$
3. Theory - TH, BFB, PU, VT, SNR…
   Experiment - FCNC, DS, EWPO, EDM…
4. Wall velocity difficult to calculate, hopefully estimates are good enough!
5. Well-motivated limits: common heavy mass scale, alignment limit, dark matter…

Thank You!

Questions?