Cosmic Strings from Tribrid Inflation

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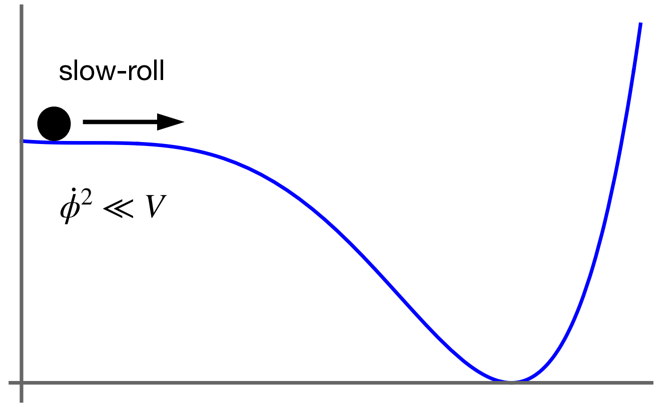
Stefan Antusch, K.T., arXiv: 2406.12521

Introduction

- inflation solves horizon and flatness problems of standard Big Bang cosmology

- further benefit - can dilute away unwanted topological defects:
  -**monopoles**: strong upper bounds on the monopole abundance
  -**domain walls**: dominate universe leading to large inhomogeneities, inconsistent with observations
  -**cosmic strings**: observable signature in stochastic gravitational-wave background, provide valuable window into early universe



- models like Hybrid and Tribrid inflation

- Tribrid inflation embedded in $SO(10)$: metastable cosmic strings, promising explanation of recent PTA results

Standard SUSY Hybrid Inflation

- two types of superfields:
  - inflaton field S, singlet under gauge group G
  -waterfall fields $H, \bar{H}$, in conjugate representation of each other under G
- typical superpotential

$$W = \kappa S(H\bar{H} - M^2)$$

- global SUSY scalar potential

$$V = F^{*i}F_i + \frac{1}{2}D^aD^a$$

$$D^a = -g(\phi^* T^a \phi) \qquad F_i = -\delta W^*/\delta\phi^{*i}$$

Standard SUSY Hybrid Inflation

- For $H = \bar{H} = 0$, F-term of S provides vacuum energy to drive inflation

$$V_0 = |\kappa|^2 M^4$$

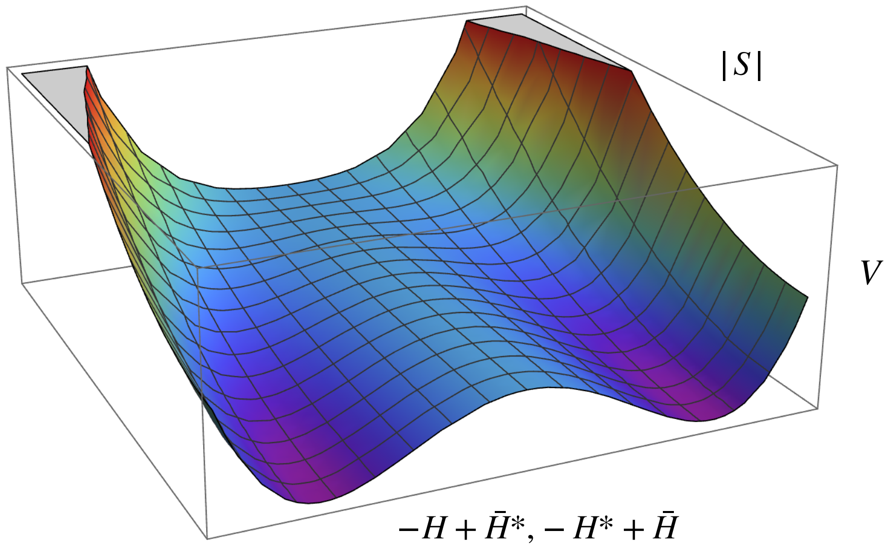
- S field direction exactly flat at tree level, slight slope for example from loop effects

- squared mass eigenvalues of waterfall fields

$$m^2_{1,\ldots,2r} = |\kappa|^2(|\langle S\rangle|^2 + M^2)$$

$$m^2_{2r+1,\ldots,4r} = |\kappa|^2(|\langle S\rangle|^2 - M^2)$$

- during inflation, $|\langle S\rangle| > |S_{\text{crit}}| = M$:
  $H = \bar{H} = 0$, S slowly rolling inflaton



Tribrid Inflation: an Example

- three types of superfields:
  - singlet S
  -inflaton fields $\phi, \bar{\phi}$, non-singlets in conjugate representation of each other
  -waterfall fields $H, \bar{H}$, in conjugate representation of each other

- example of superpotential

$$W = \kappa S(H\bar{H} - M^2) + \frac{\zeta}{\Lambda}(\phi\bar{\phi})(H\bar{H})$$

- squared mass eigenvalues of waterfall fields

$$m^2_{1,\ldots,2r} = \frac{|\zeta|^2}{\Lambda^2}|\langle\phi\bar{\phi}\rangle|^2 + |\kappa|^2 M^2 \qquad m^2_{2r+1,\ldots,4r} = \frac{|\zeta|^2}{\Lambda^2}|\langle\phi\bar{\phi}\rangle|^2 - |\kappa|^2 M^2$$

- D-flat direction to realize slow-roll

Topological Defects

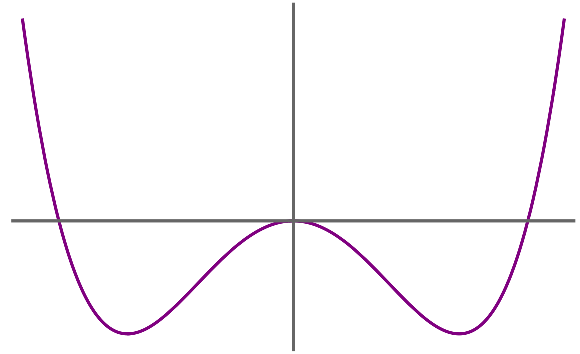
- **Domain walls:** two dimensional, form when vacuum manifold (manifold of equivalent vacua) $\mathscr{M} = G/K$ disconnected

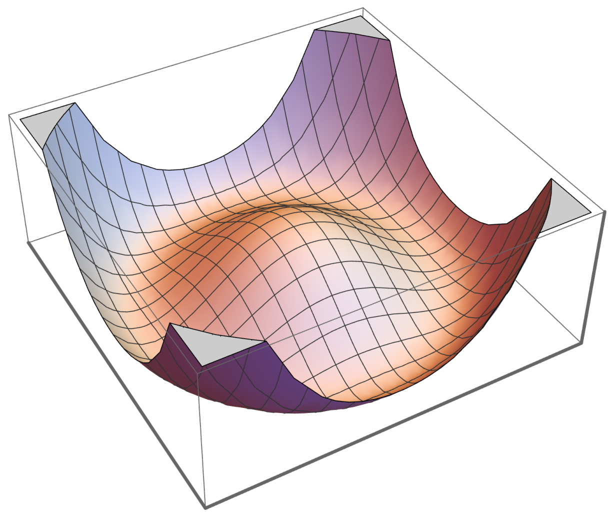
- **Cosmic Strings:** one dimensional, form when $\mathscr{M}$ contains unshrinkable loops

- **Monopoles:** point-like, form when $\mathscr{M}$ contains unshrinkable surfaces

- **Hybrid inflation:** inflaton singlet, symmetry breaking after inflation

- **Tribrid inflation:** inflaton non-singlet, G broken during inflation→defects from after inflation?





Topological Defect Formation in $U(1)$ Tribrid Inflation

$$W = \kappa S\left(H\bar{H} - M^2\right) + \frac{\zeta}{\Lambda}(\phi\bar{\phi})(H\bar{H}) + \frac{\lambda}{\Lambda}(\phi\bar{H})(\phi\bar{H}) + \frac{\gamma}{\Lambda}(\bar{\phi}H)(\bar{\phi}H)$$

- waterfall field squared mass during inflation, using D-flatness $|\langle\phi\rangle| = |\langle\bar{\phi}\rangle|$

$$m^2_{1,2,3,4} = \left(2\frac{|\gamma|^2}{\Lambda^2} + 2\frac{|\lambda|^2}{\Lambda^2} + \frac{|\zeta|^2}{\Lambda^2}\right)|\phi|^4 \pm \sqrt{4\left(\frac{|\gamma|^2}{\Lambda^2} - \frac{|\lambda|^2}{\Lambda^2}\right)^2|\phi|^8 + \left(2\frac{|\zeta\gamma^* + \lambda\zeta^*|}{\Lambda^2}|\phi|^4 \pm M^2|\kappa|^2\right)^2}$$

$$m_1^2 \sim (+,+), \quad m_2^2 \sim (+,-), \quad m_3^2 \sim (-,+), \quad m_4^2 \sim (-,-)$$

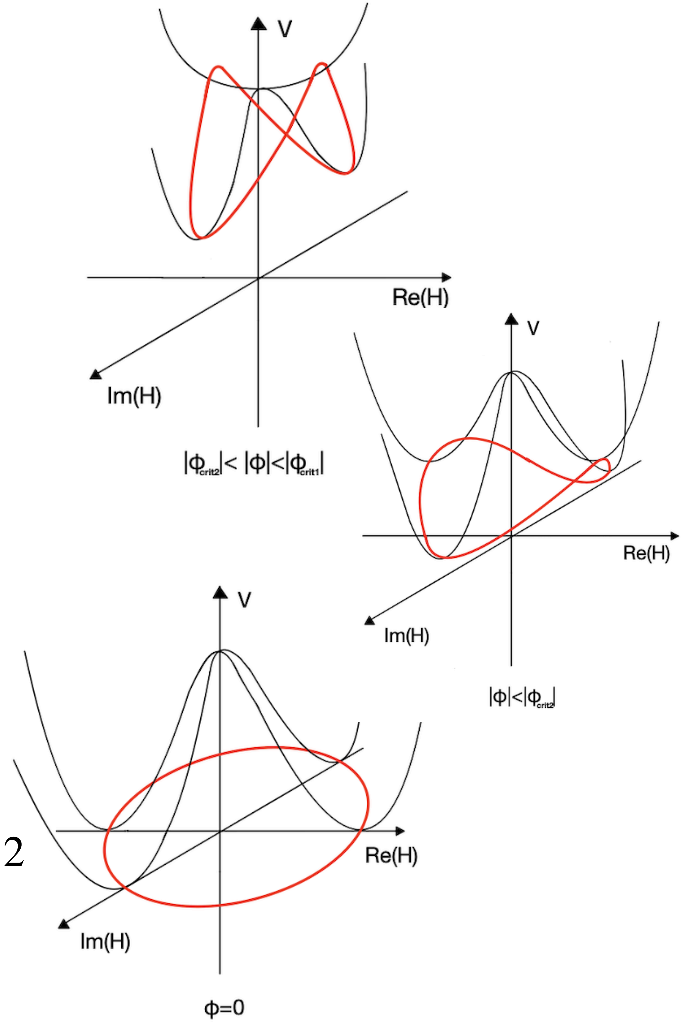
- $m^2_{1,2} > 0$ for any $\langle\phi\rangle$ while $m_3^2 < 0$ for $|\phi| < |\phi_{\text{crit1}}|$ and $m_4^2 < 0$ for $|\phi| < |\phi_{\text{crit2}}|$

Topological Defect Formation in $U(1)$ Tribrid Inflation

- topological defect formation:
  - $|\phi| > |\phi_{\text{crit}1}|$: both waterfall fields stabilized at zero
  - $|\phi_{\text{crit}2}| < |\langle\phi\rangle| < |\phi_{\text{crit}1}|$: one waterfall field direction gets destabilized, domain walls form
  - $|\langle\phi\rangle| < |\phi_{\text{crit}2}|$: on domain wall still $\langle H\rangle = \langle\bar{H}\rangle = 0$, only two waterfall field direction stabilized, from $\langle H\rangle = 0$ on top of domain wall, H can fall into any direction in complex plane, i.e. arg$(H) \in [0,2\pi)$ can take any value

    $\Longrightarrow$ cosmic strings form on top of the domain wall

- judge by considering which symmetries survive during inflation? →No! no global $U(1)$ symmetry unbroken, only a $\mathbb{Z}_2$ symmetry



Summary and Conclusions

- **Hybrid and Trbirid inflation:** end of inflation reached when waterfall field, which was stabilised at zero during inflation, starts rapidly rolling towards its minimum where the symmetry group G is spontaneously broken

- **SUSY Hybrid inflation:** inflaton is gauge singlet, evaluate topological defects from homotopy group

- **Tribrid inflation:** inflaton gauge non-singlet, its VEV already breaks symmetry during inflation
  $\longrightarrow$ raises question whether topological defects can form after inflation

- arrive at correct conclusion carefully study dynamics of waterfall transition, evaluating topological defect formation solely on symmetry arguments can be misleading

- results can be used to analyse Tribrid inflation associated with final step of multi-stage $SO(10)$ breaking, cosmic strings can be metastable and provide promising explanation of recent PTA results

Thank you!

Topological Defect Formation in $U(1)$ Tribrid Inflation

- general superpotential form for Tribrid inflation with local $U(1)$

$$W = \kappa S(H\bar{H} - M^2) + f(H, \bar{H}, \phi, \bar{\phi})$$

	S	ϕ	$\bar{\phi}$	H	$\bar{H}$
$U(1)$	0	1	-1	1	-1

- realize Tribird inflation: flat direction of scalar potential with dominating vacuum energy, s.t. slow roll can take place for sufficient number of e-folds

⟶ F-term of S large vacuum energy density drive inflation: $V_0 = |\kappa|^2 M^2$

⟶ D-flatness condition $V_D = 0$ provides flat direction,

$$D = -g\left(|\phi|^2 - |\bar{\phi}|^2 + |H|^2 - |\bar{H}|^2\right)$$

⟶ small slope: SUSY breaking, loop and non-canonical Kahler potential terms

- $U(1)$ already broken during inflation: topological defects form after inflation?

Topological Defect Formation in $U(1)$ Tribrid Inflation

- Case 1: $W = \kappa S\left(H\bar{H} - M^2\right) + \frac{\zeta}{\Lambda}(\phi\bar{\phi})(H\bar{H})$

- waterfall field squared mass during inflation, using D-flatness $|\langle\phi\rangle| = |\langle\bar{\phi}\rangle|$

$$m_{1,2}^2 = \frac{|\zeta|^2}{\Lambda^2}|\langle\phi\rangle|^4 + |\kappa|^2 M^2, \quad m_{3,4}^2 = \frac{|\zeta|^2}{\Lambda^2}|\langle\phi\rangle|^4 - |\kappa|^2 M^2$$

$$v_1 = -H + \bar{H}^*, \quad v_2 = -H^* + \bar{H}, \quad v_3 = H + \bar{H}^*, \quad v_4 = H^* + \bar{H}$$

- $m_{1,2}^2 > 0$ for any $\langle\phi\rangle \implies \langle v_1\rangle = \langle v_2\rangle = 0 \implies \langle\bar{H}\rangle = \langle H^*\rangle$

- at critical point $|\phi_{\text{crit}}|$: arg$(\langle\bar{H}\rangle) \equiv -$ arg$(\langle H\rangle)$(mod 2π) and $|\langle\bar{H}\rangle| = |\langle H\rangle|$ plugging into potential $\implies$ V depends only on $|H|$, i.e. arg$(\langle H\rangle) \in [0,2\pi)$ random

$\implies$ cosmic strings

Topological Defect Formation in $U(1)$ Tribrid Inflation

- Case 2: $W = \kappa S\left(H\bar{H} - M^2\right) + \frac{\lambda}{\Lambda}(\phi\bar{H})(\phi\bar{H}) + \frac{\gamma}{\Lambda}(\bar{\phi}H)(\bar{\phi}H)$
- waterfall field squared mass during inflation, using D-flatness $|\langle\phi\rangle| = |\langle\bar{\phi}\rangle|$

$$m^2_{1,2,3,4} = 2\left(\frac{|\lambda|^2}{\Lambda^2} + \frac{|\gamma|^2}{\Lambda^2}\right)|\langle\phi\rangle|^4 \pm \sqrt{4\left(\frac{|\lambda|^2}{\Lambda^2} - \frac{|\gamma|^2}{\Lambda^2}\right)^2|\langle\phi\rangle|^8 + M^4|\kappa|^4}$$

$$v_1 = \alpha_- H + \bar{H}^*, \quad v_2 = \alpha_- H^* + \bar{H}, \quad v_3 = \alpha_+ H + \bar{H}^*, \quad v_4 = \alpha_+ H^* + \bar{H}$$

- $m^2_{1,2} > 0$ for any $\langle\phi\rangle \implies \langle v_1\rangle = \langle v_2\rangle = 0 \implies \langle\bar{H}\rangle = (-\alpha_-)\langle H^*\rangle$
- at critical point $|\phi_{\text{crit}}|$: $\arg(\langle\bar{H}\rangle) \equiv -\arg(\langle H\rangle) (\text{mod } 2\pi)$ and $|\langle\bar{H}\rangle| = (-\alpha_-)|\langle H\rangle|$ plugging into potential $\implies$ V depends only on $|H|$, i.e. $\arg(\langle H\rangle) \in [0,2\pi)$ random

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Topological Defect Formation in $U(1)$ Tribrid Inflation

- topological defect formation:
  - $|\phi| > |\phi_{\text{crit}1}|$: both waterfall fields stabilized at zero
  - $|\phi_{\text{crit}2}| < |\langle\phi\rangle| < |\phi_{\text{crit}1}|$: one waterfall field direction gets destabilized, eigenstates corresponding to $m^2_{1,2,4} > 0$ still zero vevs

$$\Longrightarrow \langle H \rangle = \pm |\langle H \rangle| e^{i\frac{\varphi}{2}}, \quad \langle \bar{H} \rangle = \mp \alpha |\langle H \rangle| e^{-i\frac{\varphi}{2}}$$

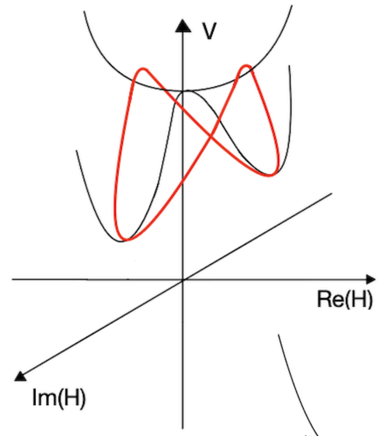
domain walls form

- $|\langle\phi\rangle| < |\phi_{\text{crit}2}|$: on domain wall still $\langle H \rangle = \langle \bar{H} \rangle = 0$, only two waterfall field direction stabilized

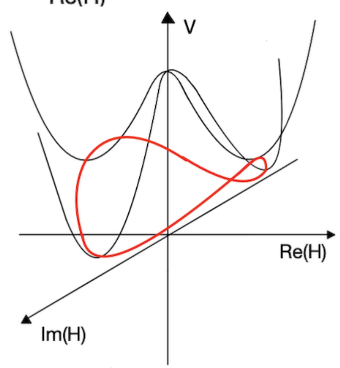
$$\Longrightarrow \quad \langle \bar{H} \rangle = \frac{1}{2}\left[(\beta - \alpha)e^{-i\varphi}\langle H \rangle - (\beta + \alpha)\langle H^* \rangle\right]$$

from $\langle H \rangle = 0$ on top of domain wall, H can fall into any direction in complex plane, i.e. $\arg(H)$ can take any value

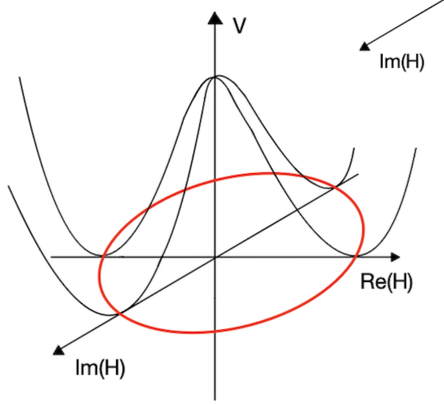
$\Longrightarrow$ cosmic strings form on top of the domain wall



$|\phi_{\text{crit}2}| < |\phi| < |\phi_{\text{crit}1}|$



$|\phi| < |\phi_{\text{crit}2}|$



$\phi = 0$

Topological Defect Formation in $U(1)$ Tribrid Inflation

- $U(1)$ gauge symmetry broken during inflation still cosmic strings + temporary domain walls form at waterfall
- judge by considering symmetries which survive during inflation?

$$V = \left|\kappa\left(H\bar{H} - M^2\right)\right|^2 + \left|\frac{\zeta}{\Lambda}\bar{\phi}(H\bar{H}) + 2\frac{\lambda}{\Lambda}(\phi\bar{H})\bar{H}\right|^2 + \left|\frac{\zeta}{\Lambda}\phi(H\bar{H}) + 2\frac{\gamma}{\Lambda}(\bar{\phi}H)H\right|^2$$

$$+\left|\kappa S\bar{H} + \frac{\zeta}{\Lambda}(\phi\bar{\phi})\bar{H} + 2\frac{\gamma}{\Lambda}(\bar{\phi}H)\bar{\phi}\right|^2 + \left|\kappa SH + \frac{\zeta}{\Lambda}(\phi\bar{\phi})H + 2\frac{\lambda}{\Lambda}(\phi\bar{H})\phi\right|^2 + \frac{g^2}{2}\left(|\phi|^2 - |\bar{\phi}|^2 + |H|^2 - |\bar{H}|^2\right)^2$$

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$$+\left|\kappa S\bar{H} + \frac{\zeta}{\Lambda}(\phi\bar{\phi})\bar{H} + 2\frac{\gamma}{\Lambda}(\bar{\phi}H)\bar{\phi}\right|^2 + \left|\kappa SH + \frac{\zeta}{\Lambda}(\phi\bar{\phi})H + 2\frac{\lambda}{\Lambda}(\phi\bar{H})\phi\right|^2 + \frac{g^2}{2}\left(|\phi|^2 - |\bar{\phi}|^2 + |H|^2 - |\bar{H}|^2\right)^2$$

➡ No!

- no global $U(1)$ symmetry unbroken, only a $\mathbb{Z}_2$ symmetry
$\Longrightarrow$domain walls form but no cosmic strings, this conclusion would be incorrect

	H	$\bar{H}$
$\mathbb{Z}_2$	1	1

,

- arrive at correct answer careful consideration of waterfall dynamics at the two critical points necessary

Embedding into $SO(10)$

- Tribrid inflation possibilities realising inflation in close contact to particle physics models:
  -inflaton can be scalar component of a matter superfield, or a D-flat direction of matter fields
  -phase transition ending inflation can be part of the spontaneous breaking of a larger gauge group to SM

- $SO(10) \to \mathcal{G}_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \to G_{SM}$

- SO(10)-embedding: $F_\alpha \equiv \mathbf{16}_\alpha$ $(\alpha = 1,\ldots,4)$ and $\bar{F} \equiv \overline{\mathbf{16}}$ matter representations, this leads to three light generations of charged fermions of the SM, a vector-like heavy generation and five singlet states (right-handed neutrinos) and the waterfall fields $H \equiv \mathbf{16}$ and $\bar{H} \equiv \overline{\mathbf{16}}$ (which break $\mathcal{G}_{3211} \to G_{SM}$ after inflation)

- at the SO(10)-level, the superpotential may contain the following terms:

$$W_{\text{Tribrid}} = \kappa S\left(H\bar{H} - M^2\right) + \frac{\zeta_\alpha}{\Lambda}(\bar{F}F_\alpha)(H\bar{H}) + \frac{\tilde{\zeta}_\alpha}{\Lambda}(\bar{F}H)(F_\alpha\bar{H}) + \frac{\lambda_{\alpha\beta}}{\Lambda}(\bar{H}F_\alpha)(\bar{H}F_\beta) + \frac{\gamma}{\Lambda}(\bar{F}H)(\bar{F}H),$$

- could be formed by the right-handed sneutrinos, satisfying the D-flatness condition $\sum_{\alpha=1}^{4} |\nu_\alpha^c|^2 = |\bar{\nu}^c|^2$