Supersymmetric Inflation from the Fifth Dimension

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Outline

❖ Introduction
  Inflation with axion(s), SUSY during inflation

❖ SUSY bi-axion inflation model
  Inflationary history, Fine-tunings

❖ Observable signals
  Primordial non-Gaussianities, CMB periodic modulations

❖ Conclusions
Introduction
Cosmic inflation:

- best known framework to explain early universe
- slowly rolling single real scalar field, inflaton
- $m_\phi^2 \sim \eta_V H_{inf}^2$, "hierarchy problem" for inflaton
  $\sim 10^{-2}$
Inflation with axion(s)

❖ Cosmic inflation:
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  \[ \sim 10^{-2} \]

❖ Natural inflation: inflaton as Goldstone boson of global symmetry [Freese et al. (1990)]
  • \( V(\phi) = V_0 \left(1 - \cos\frac{\phi}{f}\right) \)
  • but requires \( f \gtrsim M_{Pl} \)!
  • no dynamical scale \( \gtrsim M_{Pl} \)
  • no fund. global symmetries in QG

Kallosh et al. (1995); Banks, Seiberg (2011); Harlow, Ooguri (2018)
**Bi-axion inflation:** Kim, Nilles, Peloso (2005)

- two Goldstone bosons \((\phi_A, \phi_B)\)
- multiple sources of explicit breaking below \(M_{Pl}\)

\[
V(\phi_A, \phi_B) = V_0^{(1)} \left(1 - \cos \frac{\phi_B}{f_B}\right) \\
+ V_0^{(2)} \left[1 - \cos \left(\frac{\phi_A}{f_A} + \frac{N\phi_B}{f_B}\right)\right]
\]
Inflation with multiple axions

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- two Goldstone bosons ($\phi_A, \phi_B$)
- multiple sources of explicit breaking below $M_{Pl}$
- $V(\phi_A, \phi_B) = V_0^{(1)} \left(1 - \cos \frac{\phi_B}{f_B} \right)$
  $+ V_0^{(2)} \left[1 - \cos \left(\frac{\phi_A}{f_A} + N\frac{\phi_B}{f_B}\right)\right]$

- hierarchical mass eigenstates ($\phi_h, \phi_l$)
  $V(\langle \phi_h \rangle, \phi_l) \approx V_0 \left(1 - \cos \frac{\phi_l}{f_{eff}}\right)$
  ; $f_{eff} = Nf > M_{Pl}$ with $f < M_{Pl}$

Ben-Dayan, Pedro, Westphal (2014)
4D accidental Goldstone bosons from 5D gauge symmetry

- Bi-axion extranatural inflation: Arkani-Hamed et al. (2003); Bai et al. (2015), de la Fuente et al. (2015)

  • axions from 5D gauge bosons

  \[ \phi_A \equiv \int_0^L A_5 \, dx_5, \quad \phi_B \equiv \int_0^L B_5 \, dx_5 \]

  Charges under \( U(1)_A \times U(1)_B \):

  \[ (0,1), (1,N) \]

  \[ Q_1, Q_2 \]

  \[ A_\mu, A_5 \]

  \[ B_\mu, B_5 \]

  \[ x_5 = 0 \]

  \[ x_5 = L \]
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- integrating out charged matter loops in the bulk...
  \[
  V_{\text{eff}}(\phi_A, \phi_B) = V_0^{(1)} \left( 1 - \cos \frac{\phi_B}{f_B} \right) \\
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  \]

; \[ V_0^{\text{loop}} \sim \frac{e^{-mL}}{L^4}, \quad f \sim \frac{1}{gL} \]

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  \[ V_0^{\text{loop}} \sim \frac{e^{-m L}}{L^4}, \quad f \sim \frac{1}{g L} \]

Charges under \( U(1)_A \times U(1)_B \):

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- \(Q_1, Q_2\)
- \(A_\mu, A_5\)
- \(B_\mu, B_5\)

\( x_5 = 0 \) \quad \( x_5 = L \)

Compatibility with low-scale SUSY?
Motivation:

• compatibility of high-scale inflation with low-scale SUSY solution to EW hierarchy problem
• role of SUSY in fine-tuning (EW, CC, and inflation)
• new cosmological observables
SUSY during inflation

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❖ SUSY by itself can’t make inflaton light enough during inflation!
  broken during inflation, still need Goldstone boson shift symmetry for $\Phi_{inf}$, $K(\Phi + \bar{\Phi})$

Kawasaki et al. (2000)
SUSY during inflation

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❖ Charged matter loops in extranatural inflation cancel with SUSY!
  but, we show \( V_{\text{eff}}^{\text{tree}}(A_5) \) possible from boundary VEVs of charged matter
SUSY bi-axion inflation model

KD, Sundrum (2019)
First for single axion...

\[ \langle H \rangle = v' \quad H, H^c \quad \langle H \rangle = v \]

Hypermultiplet \( \ni Q \)

Gauge multiplet \( \ni A_M \)
\( \Phi \ni iA_5 \)

\[ \mathcal{L}_{5}^{\text{SUSY}} + \delta \mathcal{L}_{5}^{\text{boundary}} \]

\[ \int d^2 \theta \, \delta(x_5) \lambda (H - v)^2 + \ldots \]
First for single axion...

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\[ H, H^c \]

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\[ V, \Phi \]

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SUSY constraints: \( \partial_{H,H^c}W = 0 \)
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Integrating out \( H, H^c \)

SUSY constraints: \( \partial_{H,H^c} W = 0 \)

\[ \mathcal{L}_{4,\text{eff}}(\Phi) = \int d^4 \theta \, \frac{1}{2} (\Phi + \bar{\Phi})^2 \]

\[ + \int d^2 \theta \, \left( W_0 + \lambda \, \frac{v^2 e^{-mL}}{e^{\sqrt{2} \Phi}} + v' \, e^{mL} \, e^{-\frac{gL}{\sqrt{2}} \Phi} - 2vv' \right) + \text{h.c.} \]
Bi-axion generalization

\[ K = \frac{1}{2} (\Phi_A + \bar{\Phi}_A)^2 + \frac{1}{2} (\Phi_B + \bar{\Phi}_B)^2 \quad ; \quad W = W_0 + W_1 (\Phi_A + N \Phi_B) + W_2 (\Phi_B) \]

\[ \Phi^{scalar} = \frac{1}{\sqrt{2}} (\eta + i\phi) \]

\[ \phi_l \to \text{inflaton} \]

from charged matter

\((Q_A, Q_B) = (1, N) \text{ and } (0, 1)\)
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- Changing basis: \( \Phi_h = \Phi_B + \frac{1}{N} \Phi_A, \Phi_l = \Phi_A - \frac{1}{N} \Phi_B \)
  \[ W(\Phi_A, \Phi_B) = W(N \Phi_h, \frac{\Phi_l}{N}) \]
  \[ V_{\text{eff}}(\phi_l) = V_{\text{eff}}(\frac{\phi_l}{Nf}) \]

\( \Phi_{\text{scalar}} = \frac{1}{\sqrt{2}} (\eta + i\phi) \)

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from charged matter \( (Q_A, Q_B) = (1, N) \) and \((0,1)\)

\( (f_{\text{eff}} = Nf) > M_{Pl} \)
Bi-axion generalization

- \( K = \frac{1}{2} (\Phi_A + \overline{\Phi}_A)^2 + \frac{1}{2} (\Phi_B + \overline{\Phi}_B)^2 \); \( W = W_0 + W_1 (\Phi_A + N \Phi_B) + W_2 (\Phi_B) \)

- Changing basis: \( \Phi_h = \Phi_B + \frac{1}{N} \Phi_A \), \( \Phi_l = \Phi_A - \frac{1}{N} \Phi_B \)
  \( \Rightarrow W(\Phi_A, \Phi_B) = W(N \Phi_h, \frac{\Phi_l}{N}) \Rightarrow V_{\text{eff}}(\phi_l) = V_{\text{eff}}(\frac{\phi_l}{Nf}) \)

- \( V_{\text{SUGRA}} = e^{K/M_{Pl}^2} \left[ |D_{\Phi_A} W|^2 + |D_{\Phi_B} W|^2 - \frac{3|W|^2}{M_{Pl}^2} \right] ; D_{\Phi_i} W = \partial_{\Phi_i} W + \frac{\partial_{\Phi_i} K}{M_{Pl}^2} W \)
  - consistent with EFT, possibly missing only \( M_{Pl} \)-suppressed terms, e.g. \( K \ni (\Phi + \overline{\Phi})^4 \)
Inflationary history

• Inflation end @ SUSY vacuum \( (D_{\phi_i} W = 0) \) with \( \sim \)zero CC \( (W = 0) \)
Inflationary history

- Inflation end @ SUSY vacuum \( (D\phi_i W = 0) \) with \( \sim \)zero CC \( (W = 0) \)

- Inflationary trajectory: heavy fields stabilized, \( m_{\eta_h, \phi_h} \sim H_{inf} e^{2mL} \frac{N^2}{f} \), \( m_{\eta_l} \gtrsim \mathcal{O}(H_{inf}) \)

\[
V_{eff}(\phi_I) \sim \frac{3 H_{inf}^2 M_{Pl}^2}{2} \left(1 - \cos \frac{\phi_I}{Nf}\right) \quad ; \quad H_{inf} \sim \frac{v^2}{fM_{Pl}} e^{-2mL}
\]

neglect sub-dominant SUSY breaking needed today…
Inflationary history

• Inflation end @ SUSY vacuum \((D\phi_i W = 0)\) with \(\sim\) zero CC \((W = 0)\)

• Inflationary trajectory: heavy fields stabilized, \(m_{\eta h, \phi h} \sim H_{inf} e^{2mL} \frac{N^2}{f}, \frac{m_{\eta_l}}{v} \gtrsim O(H_{inf})\)

\[ V_{eff}(\phi_l) \sim \frac{3}{2} \frac{H_{inf}^2 M_{Pl}^2}{2} \left(1 - \cos \frac{\phi_l}{Nf} \right) ; \quad H_{inf} \sim \frac{v^2}{f M_{Pl}} e^{-2mL} \]

• SUSY breaking *during* inflation...

\[ \langle D_{\phi_l} W \rangle_{inf} \approx \frac{1}{N} \langle D_{\phi h} W \rangle_{inf} : \text{order parameter} \]

Goldstino \(\propto \langle D_{\phi_l} W \rangle \chi_i \approx \) heavy axino

... dominantly by heavy sector!
Fine-tunings

\[ CC = -3 \frac{\Delta W_0^2}{M_{Pl}^2} + V_{SUSY}^{today} \approx m e V^4 \]

\[ \Delta W_0 \sim O(v^2) \]

• Consider gravity-mediation to SM

\[ i.e. \frac{V_{SUSY}^{today}}{M_{Pl}^2} \sim v_w^2 \]
Fine-tunings

... tied to the CC problem!

\[ CC = -3 \frac{\Delta W_0^2}{M_{Pl}^2} + V_{SUSY}^{today} \approx meV^4 \]

\[ \Delta W_0 \sim O(v^2) \]

consider gravity-mediation to SM
i.e. \( V_{SUSY}^{today} / M_{Pl}^2 \sim v_w^2 \)

\[ T_{net} = T_{EW} \times T_{CC} \times T_{W_0} \]

\[ \sim \frac{v_w^2 M_{Pl}^2}{V_{SUSY}} \times \frac{meV^4}{V_{SUSY}} \times \frac{V_{SUSY}^{1/2} M_{Pl}}{v^2} \]

net preference to low-scale SUSY!

prefers SUSY at: low-scale  high-scale

SUSY Inflation from the 5th Dimension: Kaustubh Deshpande (UMD)
Observable signals
Primordial non-Gaussianities from sinflaton

need $m_X \approx H_{inf}$, tree-level contributions, $X(\partial \phi)^2$ coupling

Chen, Wang (2010), ...
Primordial non-Gaussianities from sinflaton

need $m_X \approx H_{inf}$, tree-level contributions, $X(\partial \phi)^2$ coupling

Chen, Wang (2010), ...

- sinflaton ($\eta_l$):

  \[ m_{\eta_l} \approx \sqrt{6} H_{inf} \left(1 + \frac{c M_{Pl}^2}{\Lambda^2}\right) \frac{1}{2} \]

  \[ K_5 \ni \delta(x_5) \frac{c}{\Lambda^2} (\Phi_A + \Phi_A)^2 (\Phi_B + \Phi_B)^2 \]

  loops of (1, N) charged matter $\Rightarrow \frac{c}{\Lambda^2} \sim \frac{g^2 N}{16\pi^2 m_{KK}^2}$
Primordial non-Gaussianities from sinflaton

need \( m_X \approx H_{inf} \), tree-level contributions, \( X(\partial \phi)^2 \) coupling

Chen, Wang (2010), ...

\[ m_{\eta_l} \approx \sqrt{6} H_{inf} \left( 1 + \frac{c M_{Pl}^2}{\Lambda^2} \right)^{\frac{1}{2}} \]

\[ \sim H_{inf} \text{ possible with } g \lesssim 0.1 \]

\[ K_5 \ni \delta(x_5) \frac{c}{\Lambda^2} (\Phi_A + \bar{\Phi}_A)^2 (\Phi_B + \bar{\Phi}_B)^2 \]

loops of \((1, N)\) charged matter \( \Rightarrow \frac{c}{\Lambda^2} \sim \frac{g^2 N}{16\pi^2 m_{KK}^2} \)
Primordial non-Gaussianities from sinflaton

- sinflaton-inflaton coupling:

\[ K_5 \equiv \delta(x_5) \frac{c}{\Lambda^2} (\Phi_A + \bar{\Phi}_A)^4 \Rightarrow \mathcal{L}_4 \equiv \frac{c}{\Lambda^2} \eta_l^2 (\partial \phi_l)^2 \]
Primordial non-Gaussianities from sinflaton

- sinflaton-inflaton coupling:

\[ K_5 \ni \delta(x_5) \frac{c}{\Lambda^2} (\Phi_A + \bar{\Phi}_A)^4 \Rightarrow \mathcal{L}_4 \ni \frac{c}{\Lambda^2} \eta_l^2 (\partial \phi_l)^2 \]

\[ \Rightarrow f_{NL} \sim 10^{-6} \left(\frac{M_{Pl}}{\Lambda}\right)^4 \sim \mathcal{O}(10^{-2}) ; \Lambda \sim M_5 \sim 0.1 \, M_{Pl} \]

\[ \sim \mathcal{O}(1) \quad ; \quad \Lambda \sim V_{inf}^{1/4} \lesssim 10^{-2} \, M_{Pl} \]

- Typical size of 3-pt. correlation function of curvature perturbations

- Observable at future 21-cm or possibly even earlier LSS surveys!
Periodic modulations in CMB

• Generic heavy hypermultiplet: $M, (n_A, n_B)$

\[
\Rightarrow \frac{\delta V}{V_{inf}} \approx n_B e^{2mL} e^{-ML} \cos \left[ (Nn_B - n_A) \frac{\phi_l}{f_{eff}} \right]
\]
Periodic modulations in CMB

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• Observational constraint: $\left| \frac{\delta V}{V_{inf}} \right| \lesssim 10^{-5}$ (also depending upon the “higher harmonic” frequency)

Choi, Kim (2016)

Flauger et al. (2014)
de la Fuente et al. (2015)
Periodic modulations in CMB

- Generic heavy hypermultiplet: \( M, (n_A, n_B) \)
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- Observational constraint: \( \left| \frac{\delta V}{V_{\text{inf}}} \right| \lesssim 10^{-5} \) (also depending upon the “higher harmonic” frequency)

- Charged matter with \( M \lesssim \frac{1}{5} \Lambda_{5D} \) lies within sensitivity!

\[ \Lambda_{5D} \approx \frac{c}{g^2 L} \]

(Choi, Kim (2016))

Flauger et al. (2014)
de la Fuente et al. (2015)
Tension with Planck data and way out...

Planck (2018)
Tension with Planck data and way out...

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“Multi-natural inflation”
higher harmonics in axionic inflation

Czerny, Takahashi (2014)
Tension with Planck data and way out...

Planck (2018)

"Multi-natural inflation"  Czerny, Takahashi (2014)
highert harmonics in axionic inflation

work in progress w/ Kumar, Sundrum

“Hybrid axionic inflation”  e.g. Peloso, Unal (2015)
Heavy field becomes tachyonic, i.e. waterfall transition, and ends inflation.
⇒ small-scale hybrid inflation
Conclusions
Conclusions

• **Axionic inflation**: one of the simplest, natural models of high-scale inflation
  - satisfies current CMB constraints

• **Compatible with low-scale SUSY** solution to EW hierarchy problem
  - fine-tuning considerations also prefer low SUSY breaking scale

• **Observable signals**
  - **primordial NG**: sinflaton, boundary-localized gauge singlets
  - **CMB periodic modulations**: charged matter close to 5D EFT cutoff
Thank you!