Supersymmetric Inflation from the Fifth Dimension

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  Primordial non-Gaussianities, CMB modulations

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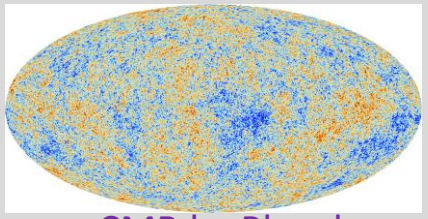
Introduction

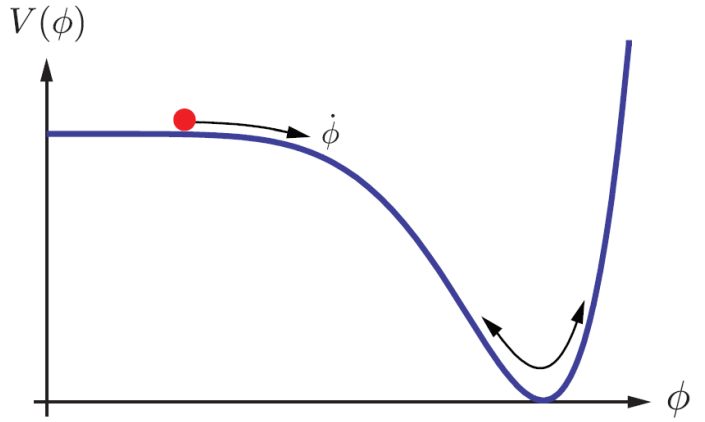
Inflation with axion(s)



CMB by Planck

❖ Cosmic inflation:

- best known framework to explain early universe
- slowly rolling single real scalar field, inflaton
- $\mathrm{m}_\phi^2 \sim \eta_V \, H_{inf}^2$, "hierarchy problem" for inflaton
  - $\eta_V \sim 10^{-2}$



The Physics of Inflation (Baumann)

❖ 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)

Inflation with multiple axions

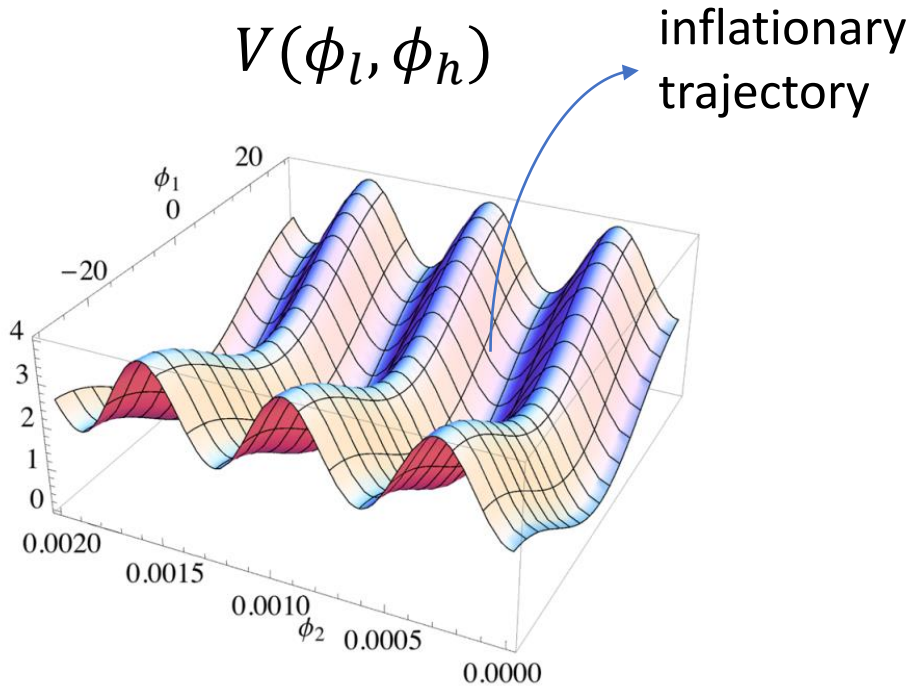
❖ Bi-axion inflation: Kim, Nilles, Peloso (2005)

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

- hierarchical mass eigenstates (ϕ_h, ϕ_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)

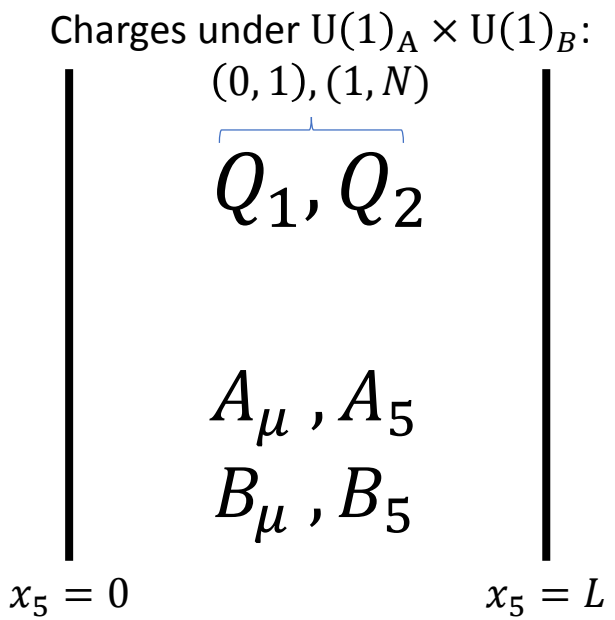
- axions from 5D gauge bosons

$$\phi_A \equiv \int_0^L A_5 \, dx_5 \, , \phi_B \equiv \int_0^L B_5 \, dx_5$$

- integrating out charged matter loops in the bulk…

$$V_{eff}(\phi_A, \phi_B) = V_0^{(1)} \left(1 - \cos\frac{\phi_B}{f_B}\right) + V_0^{(2)} \left[1 - \cos\left(\frac{\phi_A}{f_A} + \frac{N\phi_B}{f_B}\right)\right]$$

$$; V_0^{loop} \sim \frac{e^{-mL}}{L^4} \, , f \sim \frac{1}{gL}$$



Can this picture be supersymmetrized?

SUSY during inflation

❖ 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 (extra fields in super-multiplets)

❖ SUSY by itself can't make inflaton light enough during inflation!

broken during inflation, still need Goldstone boson shift symmetry for Φ_{inf}, $K(\Phi + \overline{\Phi})$

Kawasaki et al. (2000)

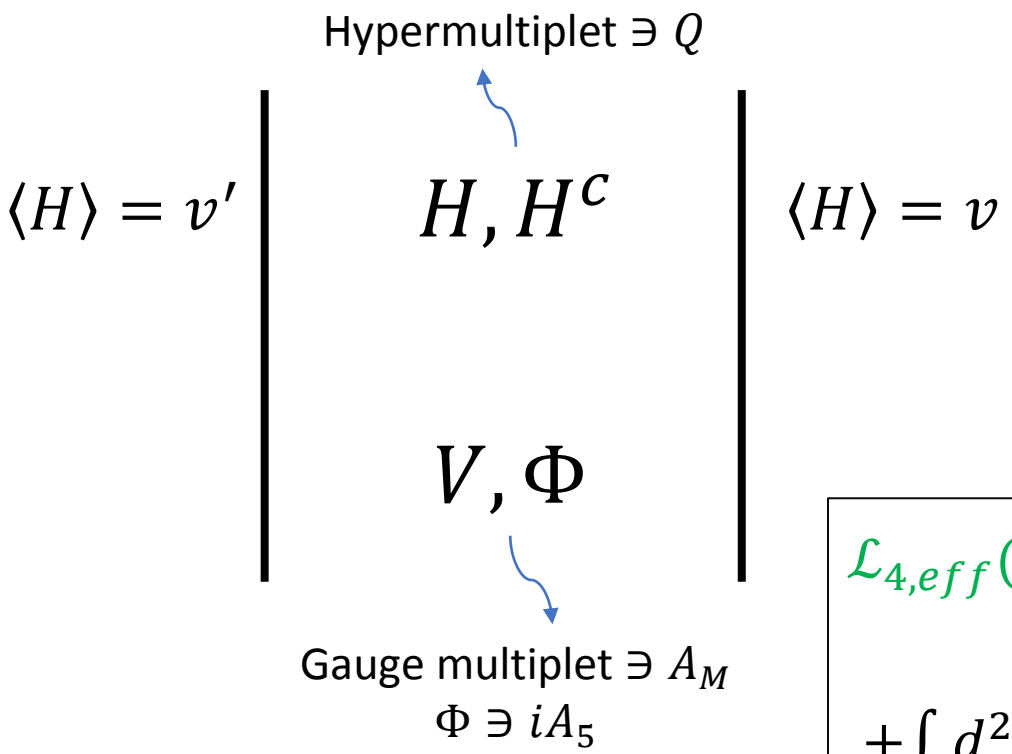
❖ Charged matter loops cancel with SUSY!

but, can get $V_{eff}^{tree}(A_5)$ from non-trivial boundary VEVs of charged matter

SUSY bi-axion inflation model

KD, Sundrum (2019)

First for single axion…



$$\mathcal{L}_5^{SUSY} + \delta\mathcal{L}_5^{boundary}$$

$$\int d^2\theta\, \delta(x_5)\, \lambda\, (H - v)^2 + \cdots$$

Integrating out H, H^c

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

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

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

Bi-axion generalization

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

contributions from charged matter $(1, N), (0,1)$

- Changing basis: $\Phi_h = \Phi_B + \frac{1}{N}\Phi_A, \Phi_l = \Phi_A - \frac{1}{N}\Phi_B$

  $\Rightarrow W(\Phi_A, \Phi_B) = W\left(N\Phi_h, \frac{\Phi_l}{N}\right) \rightarrow W_{eff}\left(e^{\Phi_l/Nf}\right) \Rightarrow \boxed{V_{eff}(\phi_l) = V_{eff}\left(\cos\frac{\phi_l}{Nf}\right)}$

$f_{eff} > M_{Pl}$

- $V_{SUGRA} = e^{K/M_{Pl}^2}\left[\left|D_{\Phi_A}W\right|^2 + \left|D_{\Phi_B}W\right|^2 - \frac{3|W|^2}{M_{Pl}^2}\right] \; ; D_{\Phi_i}W = \partial_{\Phi_i}W + \frac{\partial_{\Phi_i}K}{M_{Pl}^2}W$

  - consistent with EFT, possibly missing only M_{Pl} suppressed terms, e.g. $K \ni (\Phi + \bar{\Phi})^4$

Inflationary history

neglect sub-dominant SUSY breaking needed today…

$$\Phi_a^{scalar} = \frac{1}{\sqrt{2}}(\eta_a + i\phi_a)$$

- Inflation end @ SUSY vacuum ($D_{\Phi_i} W = 0$) with ~zero CC ($W = 0$)

ϕ_l = inflaton

- Inflationary trajectory: $\boxed{V_{eff}(\phi_l) \approx \frac{3\, H_{inf}^2\, M_{Pl}^2}{2}\left(1 - \cos\frac{\phi_l}{Nf}\right)}$; $H_{inf} \sim \frac{v^2}{f M_{Pl}} e^{-2mL}$

$$m_{\eta_h}, m_{\phi_h} \sim H_{inf}\, e^{2mL}\frac{N^2}{f} \quad ; \quad m_{\eta_l} \gtrsim \mathcal{O}\left(H_{inf}\right)$$

heavy fields stabilized

- SUSY breaking *during* inflation:

order parameter for SUSY breaking

$\langle D_{\Phi_l} W \rangle_{inf} \approx \frac{1}{N}\langle D_{\Phi_h} W \rangle_{inf}$, Goldstino $\propto \langle D_{\Phi_i} W \rangle\, \chi_i \approx$ heavy axino

⇒ heavy sector: dominant source of super-Higgsing *during* inflation!

Fine-tunings

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

$\Delta W_0 \sim \mathcal{O}(v^2)$

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

- $T_{net} = T_{EW} \times T_{CC} \times T_{W_0}$

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

prefers S~~USY~~ at: low-scale high-scale

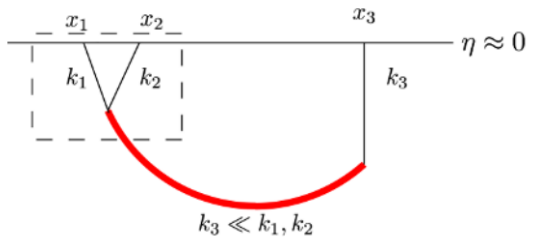
net preference to
low-scale S~~USY~~!

Observable signals

Primordial non-Gaussianities from sinflaton

Chen, Wang (2010), …

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



❖ sinflaton (η_l):

- Mass: $m_{\eta_l} \approx \sqrt{6}\, H_{inf} \left(1 + \frac{c\, M_{Pl}^2}{\Lambda^2}\right)^{1/2}$

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

  - $\left(\frac{c}{\Lambda^2}\right)_{loop} \sim \frac{g^2 N^2}{16\pi^2 m_{KK}^2} \lesssim \frac{1}{M_{Pl}^2}$ with $g \lesssim 0.1$

- Coupling with inflaton:

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

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

  $\sim \mathcal{O}(1)$ with $\Lambda \sim V_{inf}^{1/4} \lesssim 10^{-2}\, M_{Pl}$

3-point correlation function of curvature perturbations

observable at future 21-cm or possibly even LSS surveys!

Periodic modulations in CMB

Flauger et al. (2017)
de la Fuente et al. (2015)

- Generic heavy hypermultiplet: mass M, charges (n_A, n_B)

$$\Rightarrow \frac{\delta V}{V_{inf}} \approx \underbrace{n_B\, e^{2mL}\, e^{-ML}} \cos\left[(Nn_B - n_A)\frac{\phi_l}{f_{eff}}\right]$$: "higher harmonics"

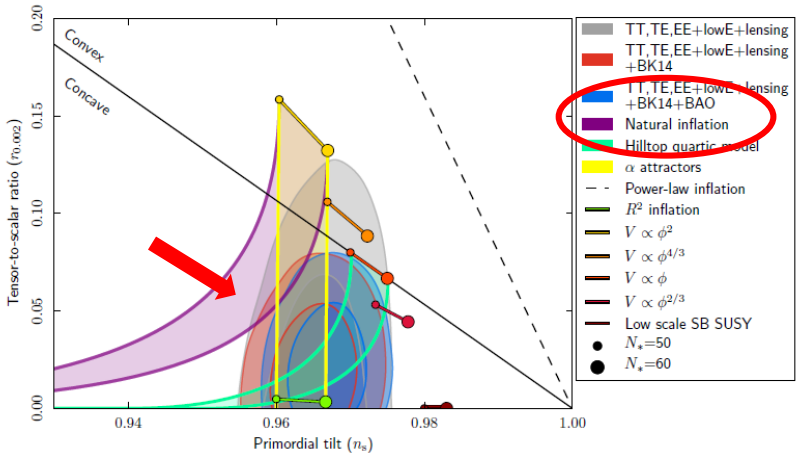
- Observational constraint: $\left|\frac{\delta V}{V_{inf}}\right| \lesssim 10^{-5}$ (also depending upon the frequency)

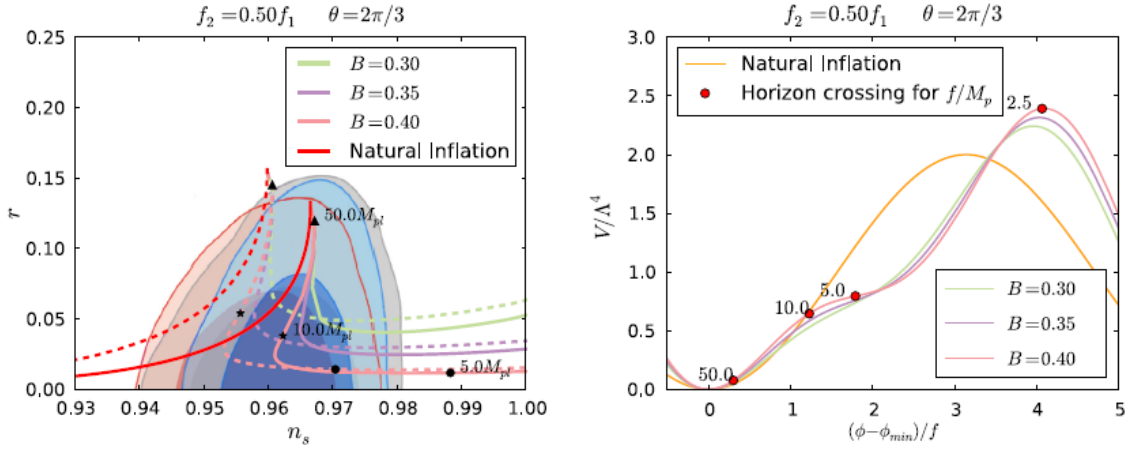
  Choi, Kim (2016)

- Charged matter with $M \lesssim \frac{1}{5}\Lambda_{5D}$ lies within sensitivity! ; $\Lambda_{5D} \approx \frac{c}{g^2}\frac{1}{L}$

Tension with Planck data and a way out…

Planck (2018)





But…
generically ∃ higher harmonics
in axionic inflation!

Multi-natural inflation

Czerny, Takahashi (2014)

multiple cosine terms with comparable size,
plausibly no fine-tuning of parameters
(work in progress)

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!