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

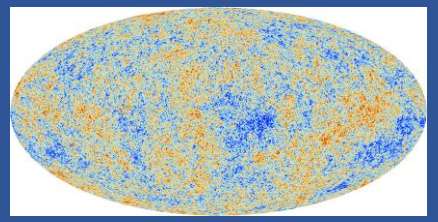
- ❖ Observable signals

  Primordial non-Gaussianities, CMB periodic modulations

- ❖ Conclusions

Introduction

Inflation with axion(s)

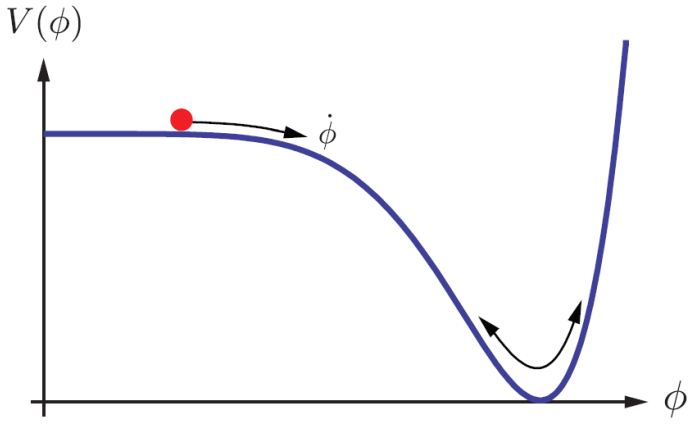


CMB by Planck

❖ Cosmic inflation:

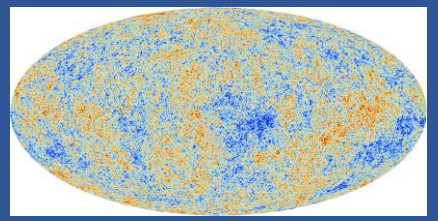
- best known framework to explain early universe
- slowly rolling single real scalar field, inflaton
- $\mathrm{m}_\phi^2 \sim \eta_V \, H_{inf}^2$, "hierarchy problem" for inflaton

  $\sim 10^{-2}$



The Physics of Inflation (Baumann)

Inflation with axion(s)



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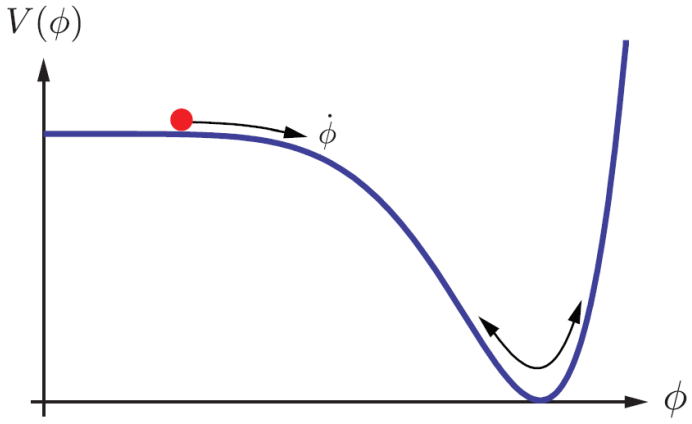

The Physics of Inflation (Baumann)

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

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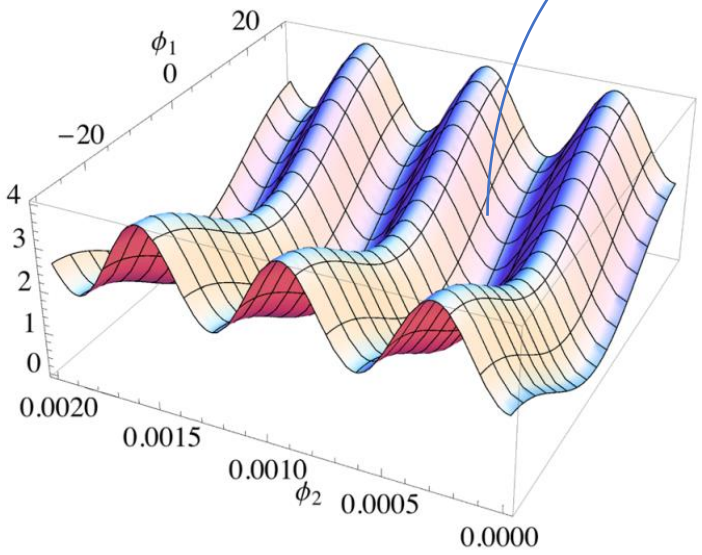
- hierarchical mass eigenstates (ϕ_h, ϕ_l)

$V(\langle\phi_h\rangle, \phi_l) \approx V_0\left(1 - \cos\frac{\phi_l}{f_{eff}}\right)$

; $f_{eff} = Nf > M_{Pl}$ with $f < M_{Pl}$

$V(\phi_l, \phi_h)$

inflationary trajectory



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

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

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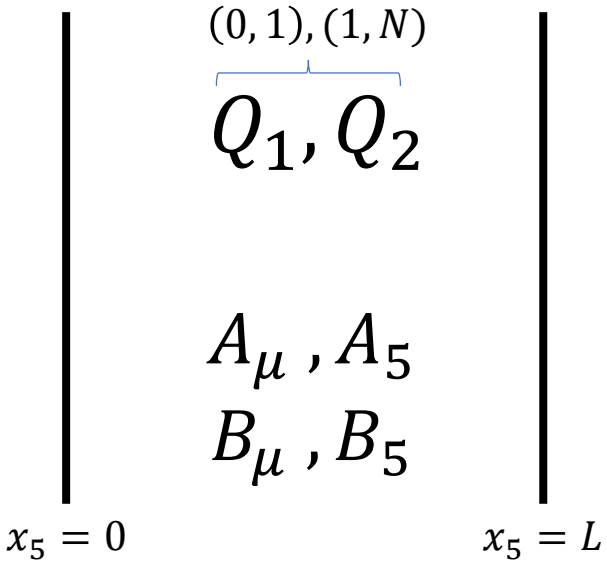

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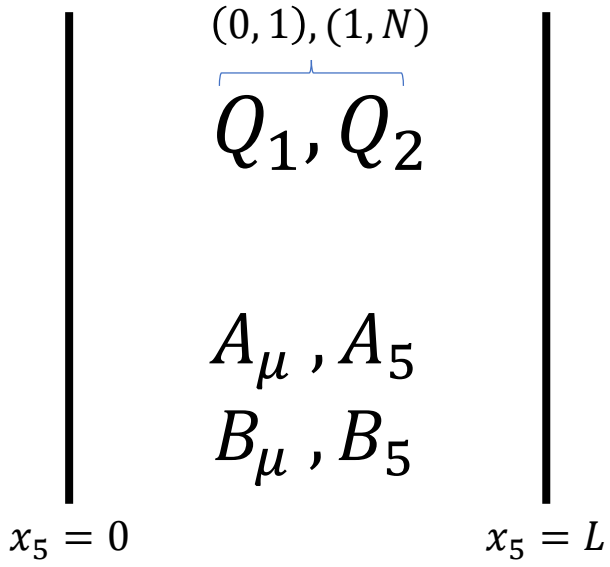

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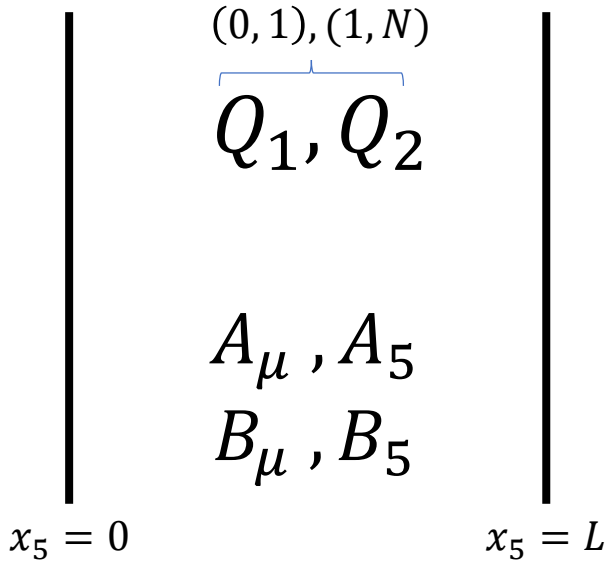

Compatibility with low-scale SUSY?

SUSY during inflation

❖ Motivation:

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- role of SUSY in fine-tuning (EW, CC, and inflation)
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broken during inflation, still need Goldstone boson shift symmetry for Φ_{inf}, $K(\Phi + \bar{\Phi})$

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❖ Charged matter loops in extranatural inflation cancel with SUSY!

but, we show $V_{eff}^{tree}(A_5)$ possible from boundary VEVs of charged matter

SUSY bi-axion inflation model

KD, Sundrum (2019)

First for single axion…

Hypermultiplet $\ni Q$

$\langle H \rangle = v'$ | H, H^c | $\langle H \rangle = v$

V, Φ

Gauge multiplet $\ni A_M$
$\Phi \ni iA_5$

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

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

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

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

Bi-axion generalization

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

$\phi_l \rightarrow$ inflaton

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

from charged matter

$(Q_A, Q_B) = (1, N)$ and $(0,1)$

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

$\Rightarrow \; W(\Phi_A, \Phi_B) = W\left(N\Phi_h, \frac{\Phi_l}{N}\right) \quad \Rightarrow \quad \boxed{V_{eff}(\phi_l) = V_{eff}\left(\frac{\phi_l}{Nf}\right)}$

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

- 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…

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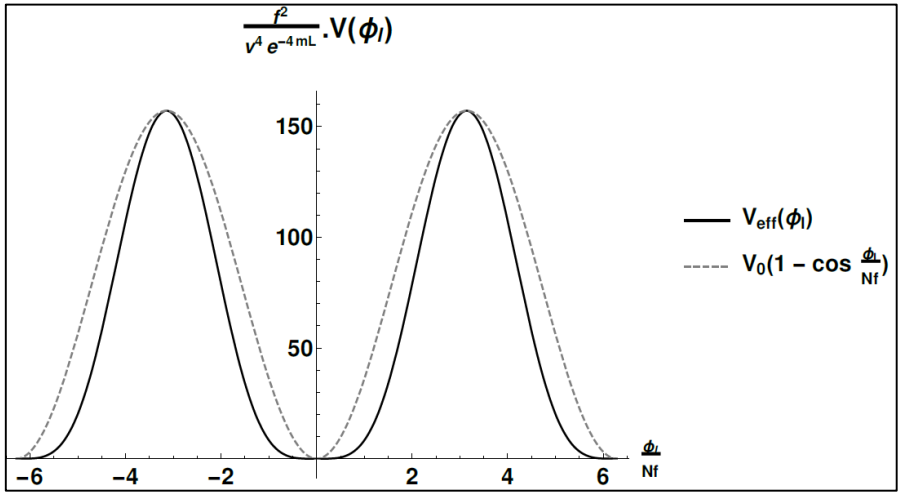
- Inflationary trajectory: heavy fields stabilized, $m_{\eta_h, \phi_h} \sim H_{inf}\, e^{2mL} \frac{N^2}{f}$, $m_{\eta_l} \gtrsim \mathcal{O}(H_{inf})$

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



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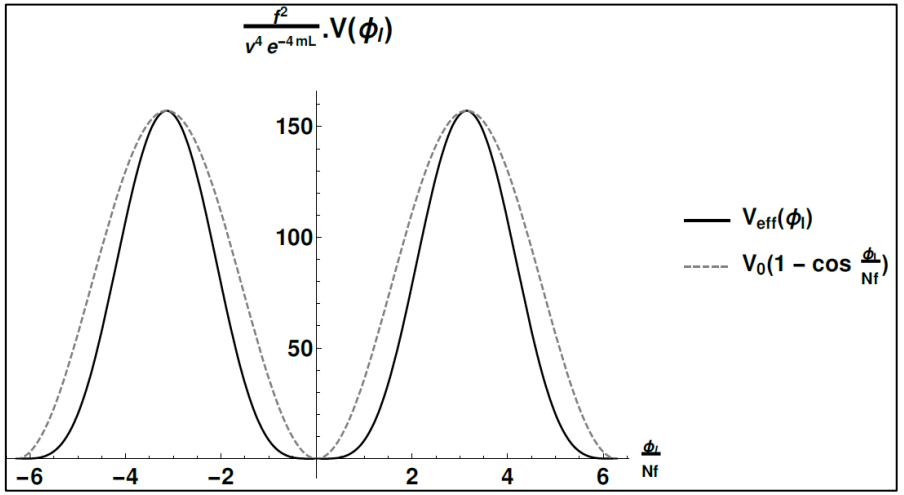

- SUSY breaking *during* inflation…

$\langle D_{\Phi_l} W \rangle_{inf} \approx \frac{1}{N} \langle D_{\Phi_h} W \rangle_{inf}$: order parameter

Goldstino $\propto \langle D_{\Phi_i} W \rangle \chi_i \approx$ heavy axino

… dominantly by heavy sector!

Fine-tunings

… tied to the CC problem!

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

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

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

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

$$\sim \underbrace{\frac{v_w^2 M_{Pl}^2}{V_{\cancel{SUSY}}} \times \frac{meV^4}{V_{\cancel{SUSY}}}}_{\text{low-scale}} \times \underbrace{\frac{V_{\cancel{SUSY}}^{1/2} M_{Pl}}{v^2}}_{\text{high-scale}}$$

prefers $\cancel{SUSY}$ at:

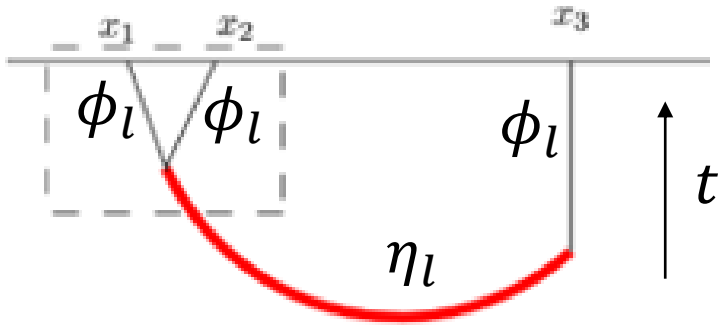
net preference to low-scale $\cancel{SUSY}$!

Observable signals

Primordial non-Gaussianities from sinflaton

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

Chen, Wang (2010), …



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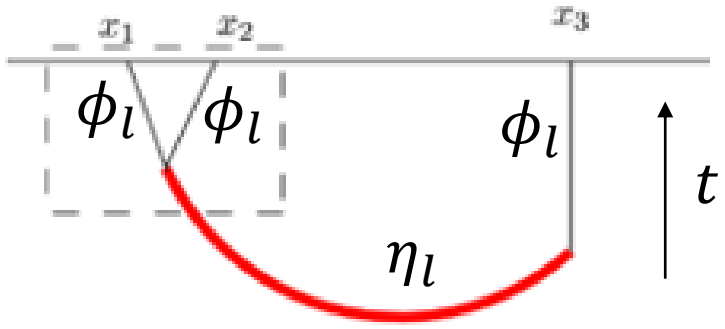

reheating

❖ sinflaton (η_l):

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

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

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

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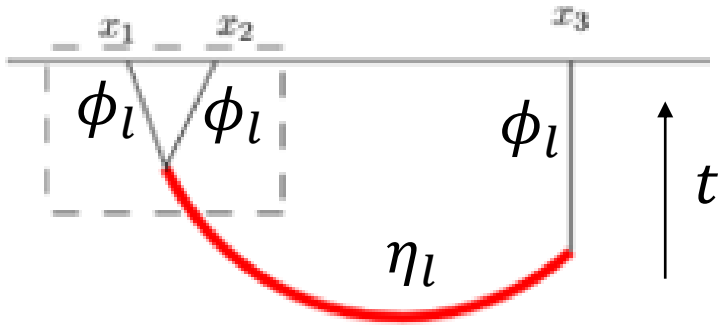

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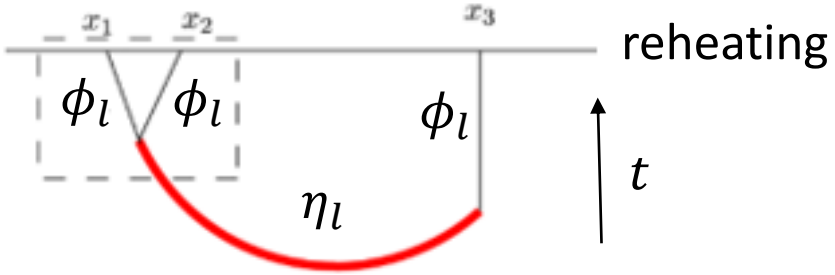

- sinflaton-inflaton coupling:

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

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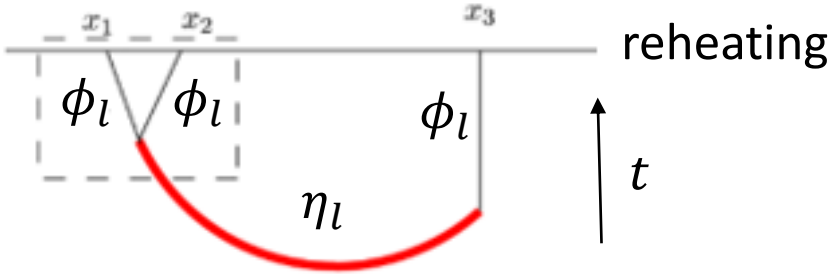

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$$\Rightarrow \quad f_{NL} \sim 10^{-6}\left(\frac{M_{Pl}}{\Lambda}\right)^4 \sim \mathcal{O}(10^{-2}) \quad ; \; \Lambda \sim M_5 \sim 0.1\, M_{Pl}$$

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

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

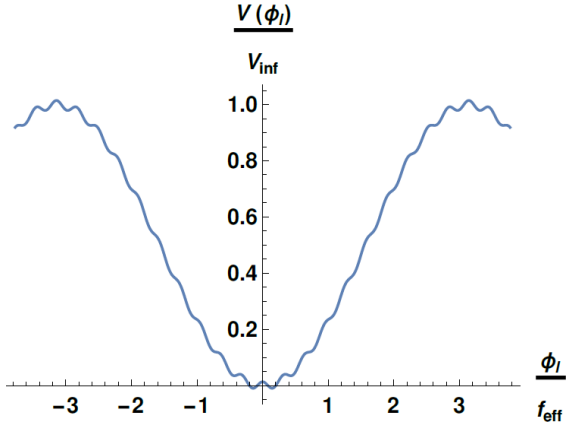
observable at future 21-cm or possibly even earlier LSS surveys!

Periodic modulations in CMB

Flauger et al. (2014)
de la Fuente et al. (2015)

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

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



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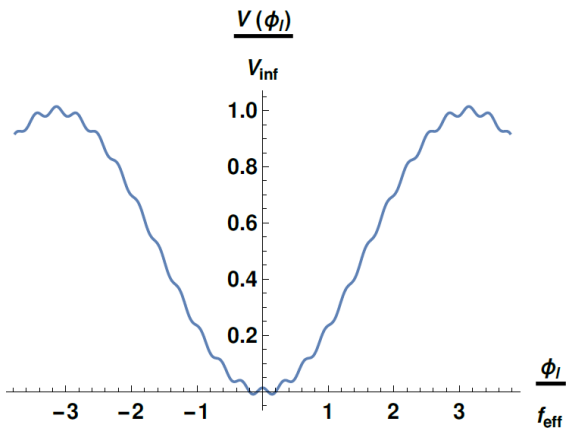

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  Choi, Kim (2016)

(also depending upon the "higher harmonic" frequency)

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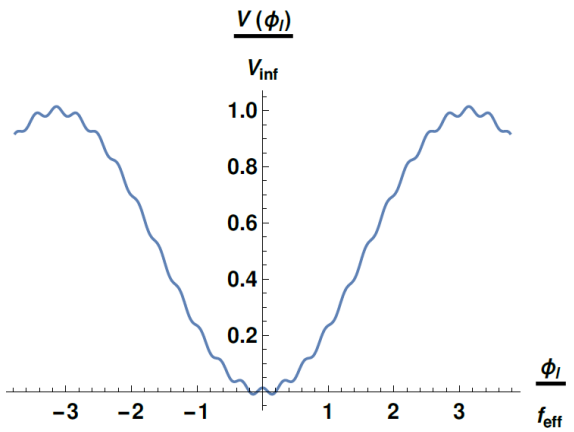

- Observational constraint: $\left|\frac{\delta V}{V_{inf}}\right| \lesssim 10^{-5}$ (also depending upon the "higher harmonic" frequency)

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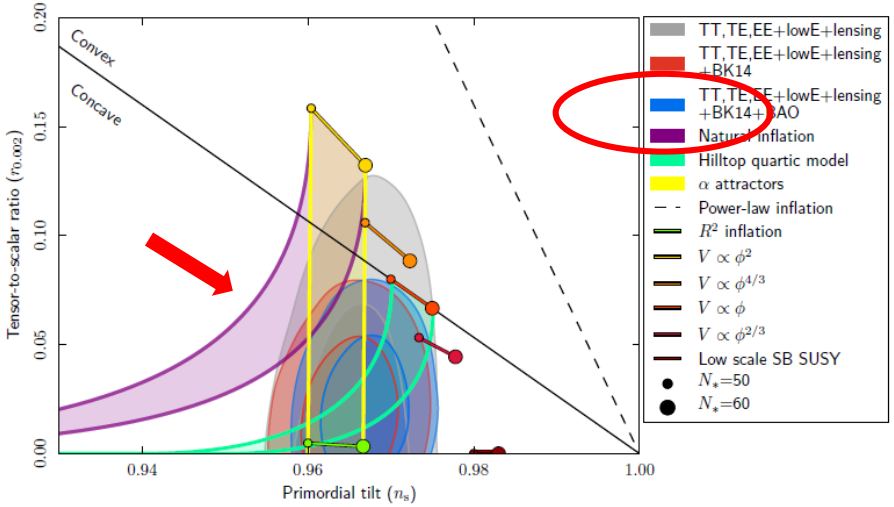
- Charged matter with $M \lesssim \frac{1}{5}\Lambda_{5D}$ lies within sensitivity! ; $\Lambda_{5D} \approx \frac{c}{g^2}\frac{1}{L}$

Tension with Planck data and way out…

Planck (2018)



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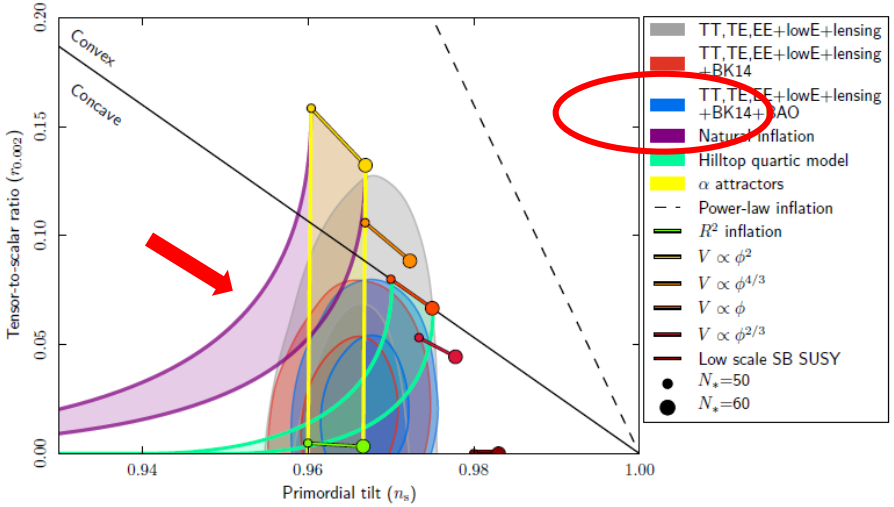
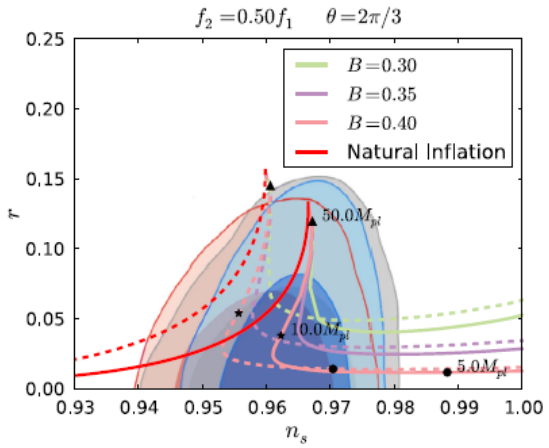
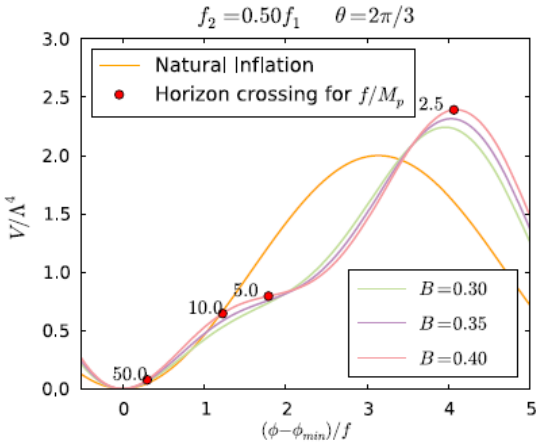


"Multi-natural inflation"

Czerny, Takahashi (2014)

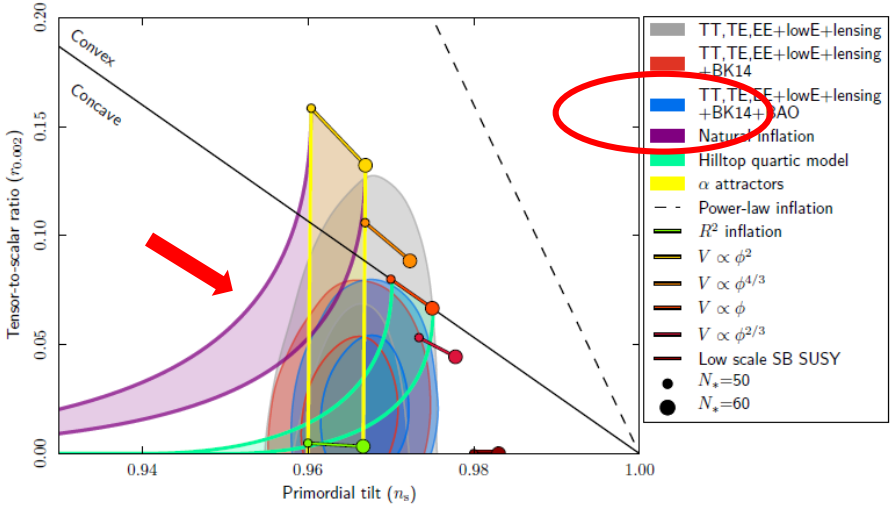
higher harmonics in axionic inflation





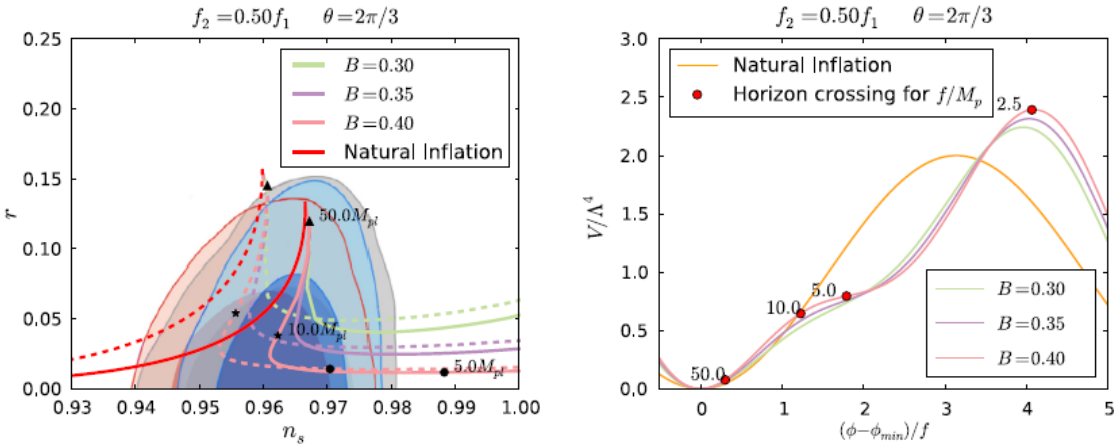
Tension with Planck data and way out…

Planck (2018)



"Multi-natural inflation" Czerny, Takahashi (2014)

higher 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!