(1)

INFLATION FROM AXION MONODROMY

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INTRO inflation : $\ddot{a} > 0 \Leftrightarrow \frac{d}{dt}\left(\frac{\lambda_{pert}}{\lambda_{Hubble}}\right) > 0$

- Many vanilla models compatible w/ WMAP. How to distinguish?

Exciting signatures: NON-GAUSSIANITY & TENSORS

$f_{NL} < \mathcal{O}(100)$ — 1% accuracy; $r < .2$ — upper bound

Lyth bound: $\frac{d\phi}{M_P} \sim dN\sqrt{2\epsilon} \sim dN\sqrt{r/8}$ (slow roll)

Superplanckian range $\Rightarrow \frac{\Delta\phi}{M_p} > \sqrt{\frac{r}{0.01}}\ \frac{N_{CMB}}{30}$

EFT approach : study UV-sensitive observables.

Inflaton is UV-sensitive: $V(\phi) = \frac{1}{2}m^2\phi^2 + \sum_n^{\infty} \lambda_n \frac{\phi^n}{M_p^{n-4}}$

- Large field is natural iff $\exists$ symmetry, e.g. shift sym
- Small field requires tuning dim 5 & dim 6 operators.

Axions : $\mathcal{L}[\phi] = \mathcal{L}[\phi + c] \Rightarrow$ only $\partial\phi$ couplings

Beyond p-Theory : $V(\phi) = \text{const} + \Lambda^4 \cos(\phi/f)$

$f \equiv$ AXION DECAY CONST ; $\Lambda \sim e^{-1/g}$ NON PERTURBATIVE

AXION MONODROMY

$V(\phi) = V_{SR}(\phi) + \Lambda^4 \cos(\phi/f)$

- Embedded in ST
- Testable : $r = 0.07$
- Peculiar : f^{res} & $P_\zeta^{modulated}$

OBSERVATIONS

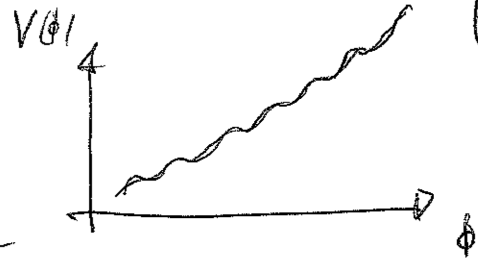
NG ⟷ OBSERVATIONS ⟷ δn_s ; OBSERVATIONS → Tensors

Tensors → GUT scale → $\Delta\phi \gg M_p$ → flat $V(\phi)$

axions w/ shift sym → mp modulations → NG, δn_s

THEORY → axions w/ shift sym ; THEORY → flat $V(\phi)$

The Model



$$\boxed{V = V_{SR}(\phi) + \Lambda^4 \cos(\phi/f)}$$

↖ slow-roll flat potential

- Λ dimension M^1. Non-perturbatively generated
- f axion decay constant. Dimension M^1.
  In string theory $f \simeq \frac{g_s^{\#}}{L^{\#}} M_p$ so always $f \ll M_p$

Trade for other two parameters.

- $b \equiv \frac{\Lambda^4}{V'_{SR} f}$. Then $V(\phi)$ is monotonic iff $\boxed{b<1}$
- $\alpha \equiv \frac{\omega}{H} \equiv \frac{\sqrt{2\epsilon}}{f} = \frac{|\dot\phi|}{fH}$. ω is frequency of $\cos(\phi/f)$

  While H is frequency of dS background.

  $\alpha = \#$ of oscillations in CMB

  To have any interesting effect $\boxed{\alpha \gg 1}$

Background

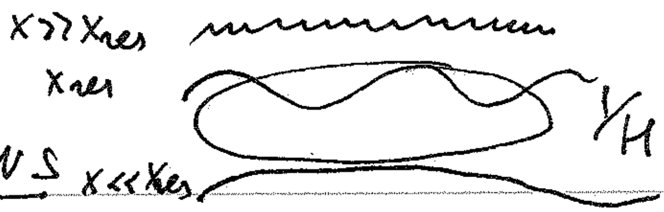
$$\phi(t) = \phi_0(t) + \phi_{osci} \sin\left(\frac{\phi_0(t)}{f}\right)$$

- $\phi_0(t)$ is the slow-roll background. $\mathcal{O}(b^0)$
- Due to $\phi_{osci} \sim \mathcal{O}(b)$ the dynamics violates slow roll

$$\begin{cases} \epsilon = \epsilon_0 + \epsilon_{osci} \\ \eta \simeq \eta_0 + \eta_{osci} \\ \dots \end{cases}$$

Because $\frac{1}{H}\frac{\partial}{\partial t} \sim \alpha \gg 1$

$$\epsilon_{osci} \ll \eta_{osci} \ll \frac{\dot\eta}{H} \ll \dots$$



PERTURBATIONS

Comoving gauge $\quad g_{ij} = \delta_{ij}\, a^2 (1+2R) \qquad \delta\phi = 0$

M-S eq: $\quad R_K'' - \dfrac{2(1+2\varepsilon+\delta)}{x} R_K' + R_K = 0 \qquad$ w/ $x = -k\tau$

$\varepsilon(x), \delta(x)$ oscillate very fast. Slow-roll is violated!

$\left(\varepsilon \equiv -\dfrac{\dot H}{H^2} \,;\; \delta \equiv \dfrac{\ddot H}{2H\dot H} \right) \quad \varepsilon_{osc} \ll \delta_{osc} \simeq -3b \sin(\phi/f)$

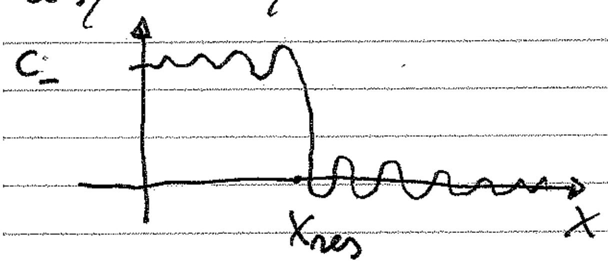
$$\phi/f = \phi_K/f + \alpha \log x$$

• $R_K \sim e^{ix} \Rightarrow R_K$ & $\delta(x)$ RESONATE for $x = x_{res} = \alpha/2$

$x \gg x_{res} \qquad R_K(x) = R_K^{(0)}\, i\sqrt{\tfrac{\pi}{2}}\, x^{\nu} H_\nu^{(1)}(x) \simeq R_K^{(0)} e^{ix}(1-ix)$

$x \ll x_{res} \qquad R_K(x) = R_K^{(0)}\, i\sqrt{\tfrac{\pi}{2}}\, x^{\nu} \left[C_K^{+} H_\nu^{(1)}(x) - C_K^{-} H_\nu^{(2)}(x) \right]$

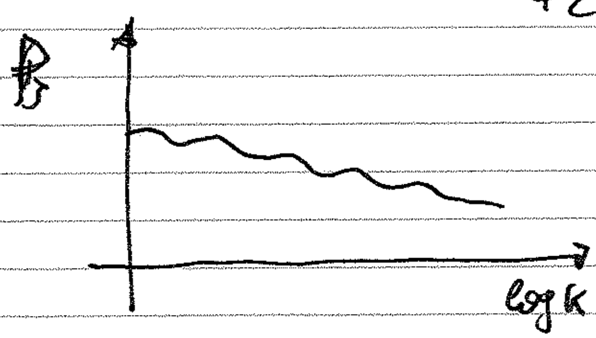
Easy analytic solution. $\qquad C_K \to 3b \sqrt{\dfrac{\pi}{2\alpha}}\, e^{-i\phi_K/f}$



RESONANCE! $\qquad$ inside horizon $\Downarrow$ neglect gravity

POWER SPECTRUM

$$\langle R_K^2 \rangle = (2\pi)^3 \delta^3 \frac{H^2}{4\varepsilon} \left[1 + 3b \sqrt{\frac{2\pi}{\alpha}} \cos\left(\alpha \log \frac{K}{K_*} + \theta\right) \right]$$



Period $\dfrac{2\pi}{\alpha} \Rightarrow \alpha$ in CMB scales

Amplitude $\quad 3b\sqrt{\dfrac{2\pi}{\alpha}}$.

(small w/ b, large w/ $\alpha \gg 1$)

Constraints from WMAP 5 $\quad f b < 10^{-4}$

INTERACTIONS.

Interactions come from $\mathcal{L}[\phi]$ $\Rightarrow$ can neglect gravity.

Decoupling (limit) $S = \int \sqrt{-g}\,[R + \mathcal{L}(\phi + \cancel{\delta\phi})]$

- Easier computations, eg. DBI, ghost, EFT of...
- Compute uncomputable quantities, e.g N-point.

BISPECTRUM

$\langle R(k_1)\, R(k_2)\, R(k_3)\rangle$ = 9-3-3 dof.

Test of NG: $\langle R^3 \rangle_c = f_{NL}^{shape} \cdot F(k_1, k_2, k_3) \cdot (2\pi)^3 \delta^3$

$H_I = \int d^3x \, \frac{V^{(N)}}{N!} \delta\phi^N$ + mixing w/ gravity

Explicit inspection shows that mixing is subleading.

$\langle R^3 \rangle = -i \int_{-\infty}^{t} dt' \, \langle [R^3, H_I] \rangle$ w/ $R_k = R_k^{(0)} x^{3/2} H^{(1)}_{3/2}(\ldots$

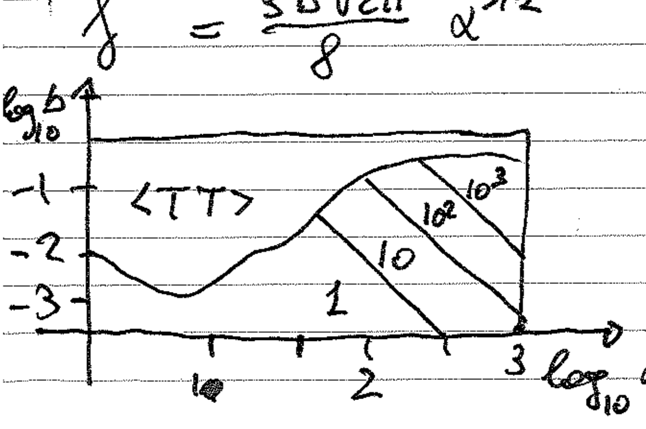
Schematically: $\int dx \, e^{-ix} \sin(\phi_k/f + \alpha \log x)$

b/c $V^{(3)} \simeq \frac{3\alpha b}{f} \sin(\phi/f)$

Analytic exact solution or stationary phase approx:

$$\langle R^3 \rangle = \frac{(2\pi)^7 \Delta^4 \delta^3}{\prod_i k_i^2} f^{res} \left[\sin\left(\alpha \log K/k_*\right) + \frac{K}{\alpha} \sum \frac{1}{k_i} \cos(\alpha \log \ldots \right.$$

$f^{res} = \frac{3b\sqrt{2\pi}}{8} \alpha^{3/2}$



- linear in $b \ll 1$ & $\alpha^{3/2} \gg 1$
- $\delta n_s \sim b/\sqrt{\alpha}$ complementary
- $F^{res}(k_i)$ is not scale-invariant
- $F^{res} \perp$ any other known shape

$\cos < \pi/\alpha \ll 1$

N-POINT

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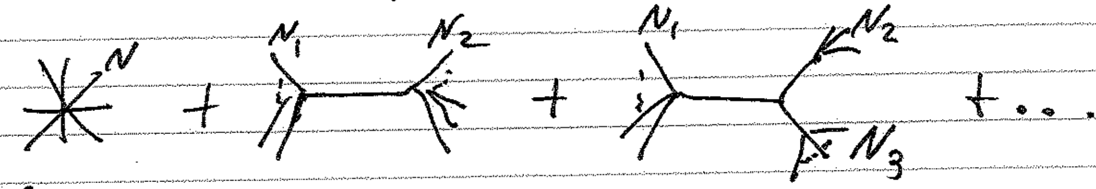
The simplest model! Computable!

$\langle \delta\phi^N \rangle =$ 

at tree level

 $: \quad = (2\pi)^3 \delta^3 \dfrac{A_N}{K^{N-3} \prod_i k_i^2} \left[\sin\left(\phi K/f\right) - \dfrac{K}{\alpha} \sum \dfrac{1}{k_i} \cos(\phi/f) \right]$

$$A_N = (-)^N \frac{3b\sqrt{2\pi}}{2} \alpha^{2N-9/2} \left(2\pi^2 \Delta_R^2\right)^{N-1}$$

- Linear in b & α^{2N}
- Multi-vertex gets $b\sqrt{\alpha} \sum_{m=1}^{3} \left(\dfrac{K}{9\alpha}\right)^m$ for each vertex plus a combinatoric factor $C(N)$.
- Estimate $C(N) \Rightarrow$ Multi-v. suppressed to $N = 15-20$
- Computed (first time) $\langle \delta\phi^N \rangle$ w/ $N \gg 3$. (e.g. $N=4$)
- Can check a large number of consistency relations.

OUTLOOK

- Inflation is UV sensitive. Large field even more.
- Axion monodromy provides a UV embedding in ST.
- $r = 0.07$ & potentially f_{NL}^{res}. Testable.
- New NG, $\perp$ to the others.
- The simplest model, $\langle \delta\phi^N \rangle$ w/ $N \gg 3$!