Poly-instanton axion inflation

Shohei Uemura (MISC, Kyoto Sangyo University)

based on arXiv:1703.03402 [hep-ph]

With Tatsuo Kobayashi (Hokkaido University), SU, and Junji Yamamoto (Kyoto University),

July 13, 2017, @ KAIST, Daejeon

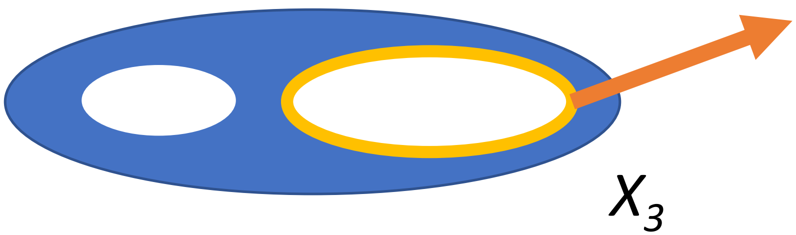
Axion−inflation

- Axion : fields having shift symmetry

$$\phi \sim \phi + \delta$$

- Axion is a good candidate of the inflaton.

   1. $V(\phi) = V(\phi + \delta)$ --> flatness of the potential.
   2. String compactifications provide many axions.



Moduli fields $T_i = \tau_i + i\phi_i$

Axion

e.g. natural inflation

$$V = V_0\left(\cos\left(\frac{\phi}{f}\right) + 1\right)$$

-> We need modulation terms.

e.g. Aligned inflation, Monodromy inflation ....

E. Silverstein and A..Westphal, [2008]

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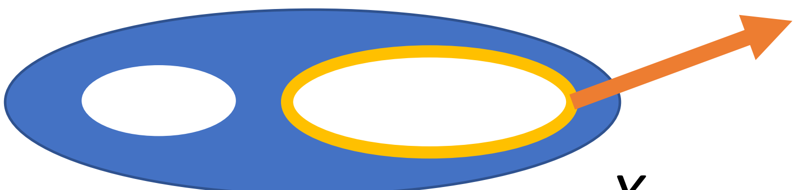


X_3

Moduli fields $T_i = \tau_i + i\phi_i$

Axion

e.g. natural inflation

$V = V_0$ ... ns.

inflation ....

E. Silverstein and A..Westphal, [2008]

Poly-instanton axion inflation

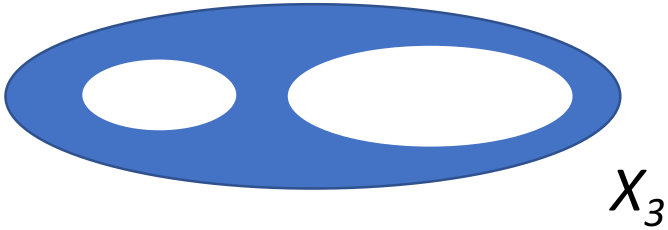
Before talking about poly-instanton, I'd like to talk about D-brane instanton

D–brane instanton effect

- Consider IIB orientifold on CY 3–fold X_3, –> SUGRA
- Dp–brane instanton : instanton like Dp–brane configuration,

non-perturbatively correct the EFT.

$$W = W_0$$



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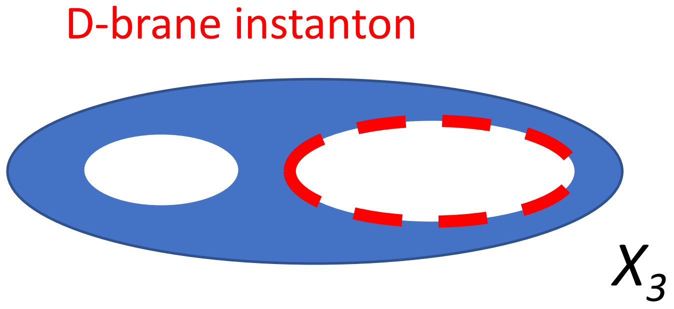

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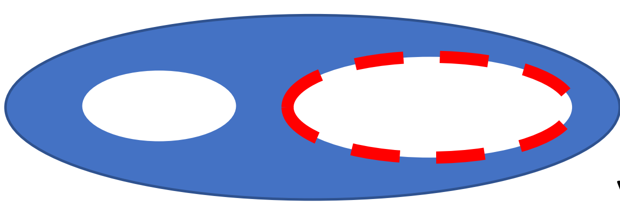
$$W = W_0 + A_1 e^{-S}$$

Single instanton effect

D-brane instanton



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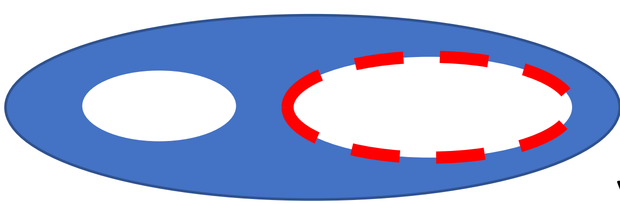
$$W = W_0 + A_1 e^{-a_i T}$$

Single instanton effect



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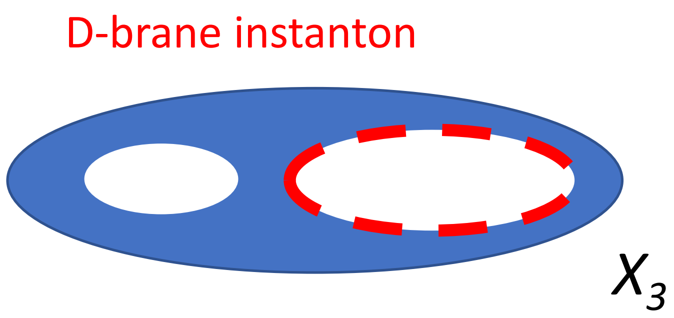

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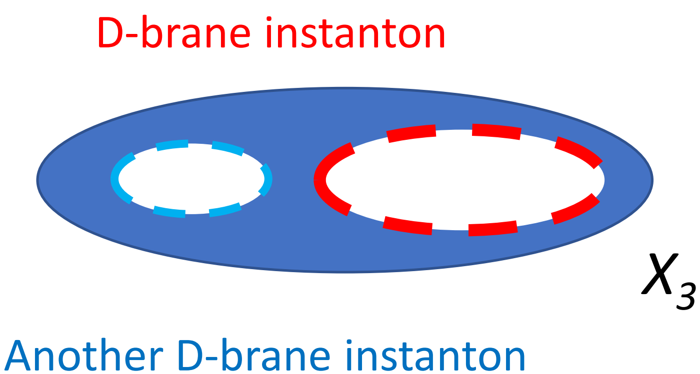

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Single instanton effect   another instanton effect

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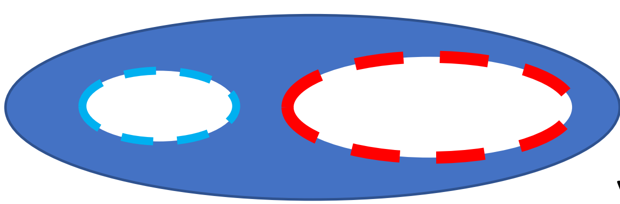
D-brane instanton



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Another D-brane instanton

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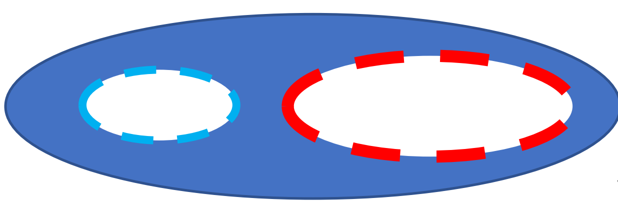

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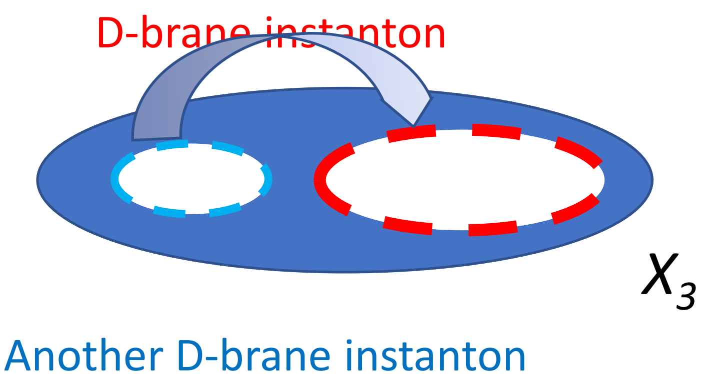

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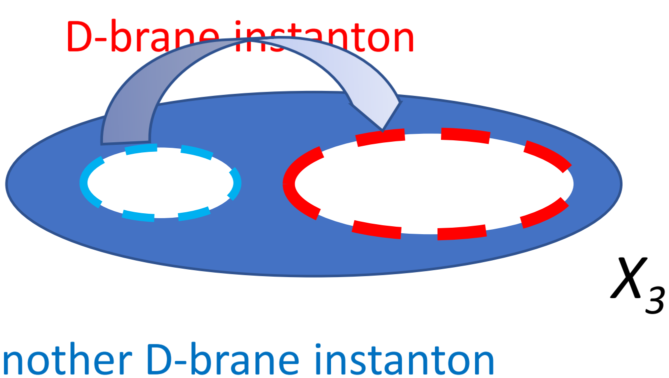
R.Blumenhagen and M.Schmidt-Sommerfeld, [2008]



This potential is highly suppressed...

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-> flat potential?

This potential is highly suppressed...

-> flat potential?

-> Inflation

Poly-instanton potential

- Divide superpotential to two parts,

$$W = W_{pert+single} + W_{poly}$$

- Suppose, there is a one moduli T^0, which appears only in poly-instanton superpotential, i.e.

$$W = W(T_i)|_{i\neq 0} + A_0 \exp[-a(T_i + Ce^{-a_0 T_0})]|_{i\neq 0}$$

- $A_0 = 0$, ⇨ $\mathrm{Im}\, T_0$ is massless, although $\mathrm{Re}\, T_0$ can be massive.

$$\because \mathrm{Re}\, T_0 \in K = -2\log V = K(T+\bar{T})$$

- When $A_0 \ll W(\langle T_i \rangle)|_{i\neq 0}$, mass of $\mathrm{Im}\, T_0$ can be the lightest scalar.

Q *Is the axion potential flat enough to satisfy the slow roll conditions?*

Poly-instanton axion potential

- All heavier modes are integrated out, we obtain the superpotential

$$W = W_0' + A_0' \exp[-aCe^{-a_0 T_0}]$$

$$V_F = e^K \left(\Sigma_{i,j=\mathrm{moduli}} K^{i\bar{j}} D_i W \, D_{\bar{j}} \overline{W} - 3|W|^2 \right)$$

- Assuming $A_0' \ll 1$,

$$-3e^K |W|^2 = -3e^K \left(|W_0'|^2 + \overline{W_0'} A_0' \exp[-a\, Ce^{-a_0 T_0}] + h.c. \right) + \mathcal{O}({A_0'}^2)$$

$$e^K K^{T_0 \overline{T_0}} |D_{T_0} W|^2 = e^K K^{T_0 \overline{T_0}} \{ |K_{T_0}|^2 \left(|W_0'|^2 + \overline{W_0'} A_0' \exp[-a\, Ce^{-a_0 T_0}] + h.c. \right)$$
$$+ K_{T_0} \overline{W_0'} A_0' a_0 a C e^{-a_0 T_0} \exp[-aCe^{-a_0 T_0}] + h.c. \} + \mathcal{O}({A_0'}^2)$$

$$\Downarrow$$

$$V_F = 2e^K \left| \overline{W_0'} A_0' \right|^2 \exp[-\delta \cos(a_0 \phi_0)] \{ (K^{T_0 \overline{T_0}} K_{T_0}|^2 - 3) \cos[\delta \sin(a_0 \phi_0) + \theta]$$
$$+ K^{T_0 \overline{T_0}} K_{T_0} \, a_0 \delta \cos[-a_0 \phi_0 + \delta \sin(a_0 \phi_0) + \theta] \} + (const)$$

$\delta = aC \exp[-a_0 \langle \tau_0 \rangle]$: magnitude of a Poly instanton effect

Poly-instanton axion potential

$$V_F = 2e^K \left|\overline{W_0'} A_0'\right|^2 \exp[-\delta\cos(a_0\phi_0)]\,\{(|K^{T_0\overline{T_0}}K_{T_0}|^2 - 3)\cos[\delta\sin(a_0\phi_0) + \theta]$$
$$+K^{T_0\overline{T_0}}K_{T_0}\, a_0\delta\cos[-a_0\phi_0 + \delta\sin(a_0\phi_0) + \theta]\} \ + (const)$$

- When $a_0\delta \gg 1$,

Poly-instanton axion potential

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- When $a_0\delta \gg 1$,

$$\boldsymbol{V = A(e^{-\delta\cos(a\phi)}\cos[\delta\sin(a\phi) - a\phi + \theta] + V_0)}$$

ϕ : canonically normalized field

- Sinusoidal function of a sinusoidal function

Poly-instanton axion potential

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- Sinusoidal function of a sinusoidal function

- When $a_0\delta \ll 1$,

$$V = A_1 \cos\theta + V_0 - \delta(A_1 - A_2)\cos[a\phi - \theta] + \frac{1}{2}\delta^2(A_1 - 2A_2)\cos(2a\phi - \theta) + \cdots$$

Natural inflation + modulation terms

Poly-instanton axion potential

$$V_F = 2e^K\left|\overline{W_0'}A_0'\right|^2 \exp[-\delta\cos(a_0\phi_0)]\,\{(|K^{T_0\overline{T_0}}K_{T_0}|^2-3)\cos[\delta\sin(a_0\phi_0)+\theta]$$
$$+K^{T_0\overline{T_0}}K_{T_0}\;a_0\delta\cos[-a_0\phi_0+\delta\sin(a_0\phi_0)+\theta]\}\;+(const)$$

- When $a_0\delta \gg 1$,

$$\boxed{\boldsymbol{V = A(e^{-\delta\cos(a\phi)}\cos[\delta\sin(a\phi)-a\phi+\theta]+V_0)}}$$

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ϕ : canonically normalized field

- Sinusoidal function of a sinusoidal function ⇨ Flat potential!

- When $a_0\delta \ll 1$,

$$V = A_1\cos\theta + V_0 - \delta(A_1 - A_2)\cos[a\phi - \theta] + \frac{1}{2}\delta^2(A_1 - 2A_2)\cos(2a\phi - \theta) + \cdots$$

⇨ Natural inflation + modulation terms

Numerical analysis

- Slow roll parameters,

$$\varepsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2, \eta = \frac{V_{\phi\phi}}{V}, \xi = \frac{V_\phi V_{\phi\phi}}{V^2} \ll 1 \text{ during inflation.}$$

- And the observed values are given by

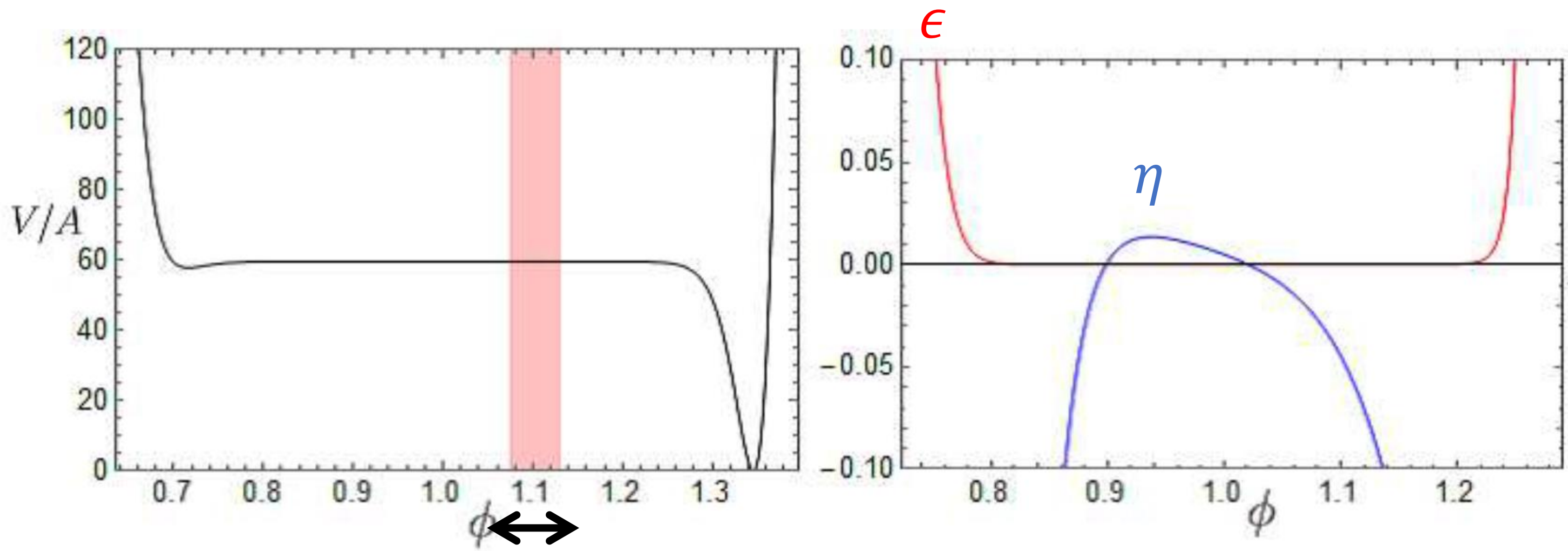
$$P_\xi = \frac{V}{24\pi^2\epsilon} = 2.20 \pm 0.10 \times 10^{-9}, n_s = 1 + 2\eta - 6\epsilon = 0.9655 \pm 0.0062,$$

$$r = 16\epsilon < 0.12,$$

$$\boldsymbol{V = A(e^{-\delta \cos(a\phi)} \cos[\delta \sin(a\phi) - a\phi + \theta] + V_0)}$$

δ	θ	A	n_s	r	N_e	α_s	m_ϕ^2
8.0	4.13	3.29×10^{-16}	0.953	6.02×10^{-7}	61.9	-3.66×10^{-4}	6.70×10^{-11}
9.0	3.16	3.46×10^{-16}	0.959	9.30×10^{-7}	58.6	-4.66×10^{-4}	1.27×10^{-10}
10.0	2.11	2.18×10^{-16}	0.963	7.65×10^{-7}	56.8	-4.70×10^{-4}	1.26×10^{-10}
11.0	7.25	1.08×10^{-16}	0.966	4.24×10^{-7}	61.7	-3.98×10^{-4}	8.31×10^{-11}
12.0	6.28	8.89×10^{-17}	0.966	4.89×10^{-7}	55.7	-4.61×10^{-4}	1.12×10^{-10}

Table 1: Examples of parameters and observables.



$\Delta\phi \ll 1$ small field inflation

Figure 1: The inflation potential with $\delta = 8.0$. The red and blue curves correspond to ε and η, respectively.

δ	θ	A	n_s	r	N_e	α_s	m_ϕ^2
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Table 1: Examples of parameters and observables.

Analytical analysis

- Derivations of the potential

$$V_\phi = A\delta a e^{-\delta\cos a\phi}\left[-\sin(\delta\sin a\phi - 2a\phi + \theta) + \frac{1}{\delta}\sin(\delta\sin a\phi - a\phi + \theta)\right]$$

$$\sim A\delta a e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 2a\phi + \theta)]$$

$$V_{\phi\phi} \sim A\delta^2 a^2 e^{-\delta\cos a\phi}[-\cos(\delta\sin a\phi - 3a\phi + \theta)]$$

$$V_{\phi\phi\phi} \sim A\delta^3 a^3 e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 4a\phi + \theta)]$$

$$\Rightarrow \quad \frac{\epsilon}{\eta} \sim e^{-\delta\cos a\phi}$$

$$|\eta| \sim \frac{|V_{\phi\phi\phi}|\Delta\phi}{V} \sim \frac{A\delta^3 a^3 e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 4a\phi + \theta)]}{A\,V_0} \sim \delta^2 a^2 \sqrt{\epsilon}\,\Delta\phi$$

+ Lyth relation : $r \sim 10^{-2}(\Delta\phi)^2$

$\Rightarrow$ $r \sim \dfrac{10^{-2}\eta^2}{\delta^4 a^4 \epsilon}$ To realize $\eta \sim -0.1$, $\boxed{\epsilon^2 \sim \dfrac{10^{-7}}{\delta^4 a^4}}$ e.g. $\delta = 10, a = 2\pi$ -> $\epsilon = 10^{-7}$, $r \sim 10^{-6}$

Without fine tunings, large δa realize the inflation!

Analytical analysis

- Derivations of the potential

$$V_\phi = A\delta a e^{-\delta\cos a\phi}\left[-\sin(\delta\sin a\phi - 2a\phi + \theta) + \frac{1}{\delta}\sin(\delta\sin a\phi - a\phi + \theta)\right]$$

$$\sim A\delta a e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 2a\phi + \theta)]$$

$$V_{\phi\phi}\sim A\delta^2 a^2 e^{-\delta\cos a\phi}[-\cos(\delta\sin a\phi - 3a\phi + \theta)]$$

$$V_{\phi\phi\phi}\sim A\delta^3 a^3 e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 4a\ldots$$

$$m_\phi^2\sim V_{\phi\phi}\sim AV_0\delta^2 a^2\sim 10^{-10}$$

$$\alpha_s = \frac{\mathrm{dlog}\ n_s}{\mathrm{dlog}\ k}\sim -2\xi\sim -10^{-3}$$

$$\frac{\epsilon}{\eta}\sim e^{-\delta\cos a\phi}$$

$$|\eta|\sim\frac{|V_{\phi\phi\phi}|\Delta\phi}{V}\sim\frac{A\delta^3 a^3 e^{-\delta\cos a\phi}[-\sin(\delta\sin a\phi - 4a\phi + \theta)]}{A\,V_0}\sim\delta^2 a^2\sqrt{\epsilon}\,\Delta\phi$$

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$$r\sim\frac{10^{-2}\eta^2}{\delta^4 a^4\epsilon}$$

To realize $\eta\sim -0.1$,

$$\epsilon^2\sim\frac{10^{-7}}{\delta^4 a^4}$$

e.g. $\delta = 10, a = 2\pi$
-> $\epsilon = 10^{-7},\ r\sim 10^{-6}$

Without fine tunings, large δa realize the inflation!

Summery of my talk

- Here, we introduce new type of axion inflation model, poly-instanton axion inflation.
- Poly-instanton is a non-perturbative effect in string theory, which induce superpotential like,

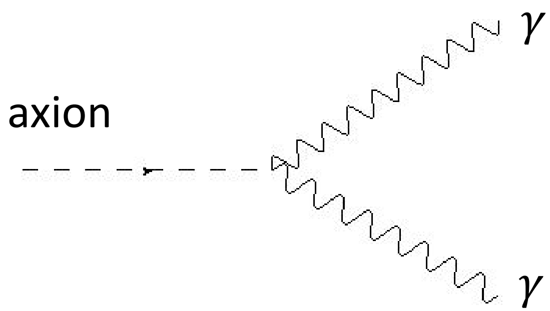
$$\delta W = Ae^{-a\left(T_i + Be^{-2\pi T_j}\right)}$$

- And it can realize a small field inflation.

Thank you!

Test : cosmological history

- Inflaton may decay to photon as,



$$f_{vis} = f_0 + B_{vis} e^{-b_{vis} T_0}.$$

$$\Gamma \sim \gamma^2 \left(\frac{m_\phi}{10^{13}\mathrm{GeV}} \right)^3 \ \mathrm{GeV},$$

where $\gamma = B_{vis} b_{vis} e^{-b_{vis} \tau_0}.$

when this is dominant decay mode,

$$T_r = \left(\frac{\pi^2 g_*}{90} \right)^{-1/4} \sqrt{\Gamma M_{Pl}} \sim 10^9 \gamma \left(\frac{m_\phi}{10^{13}\mathrm{GeV}} \right)^{3/2} \ \mathrm{GeV},$$

Reheating temperature is rather low.