기초과학연구원
Institute for Basic Science

Phenomenological implication of Continuum Clockwork

Chang Sub Shin (IBS-CTPU)

Based on works
1711.06228 with Kiwoon Choi, Sang Hui Im
1711.08270 with Jinn-Ouk Gong
1811.10655 with Kyu Jung Bae, Jeff Kost

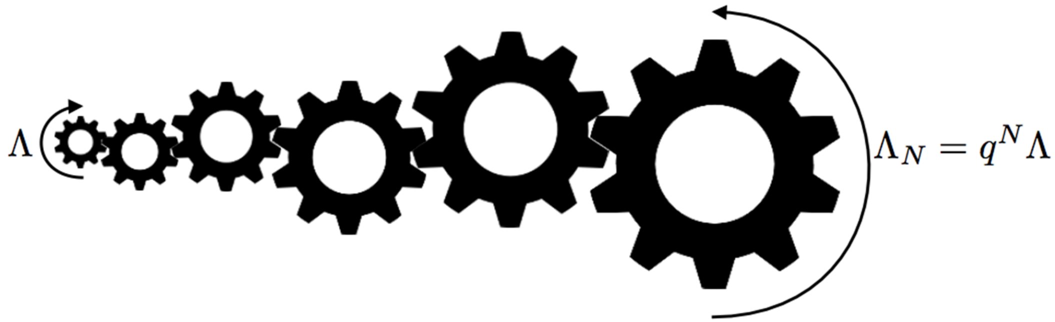
At IBS workshop
Dec. 4, 2018

Outline

Idea of discrete clockwork

- Clockwork axion

- Clockwork photon



Continuum limit of clockwork

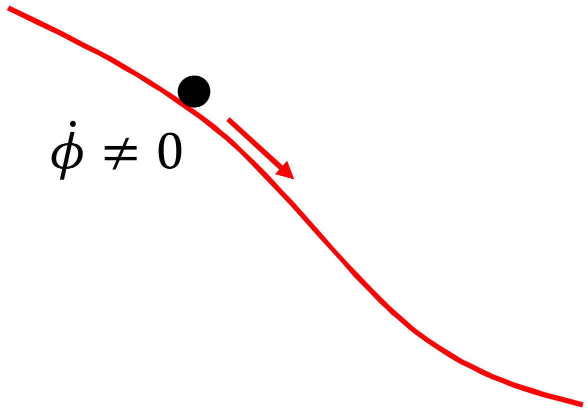
- Realization with 5d Geometry and Bulk/Boundary potentials

Phenomenological application

- Nontrivial wave-function renormalization

- Inflation, baryogenesis and dark matter via rolling Continuum CW ALPs

Conclusions



Idea of discrete clockwork mechanism

KNP mechanism

[Kim, Nilles, Peloso 04]

Proposal to obtain a trans-Planckian field excursion in the context of natural inflation

$$\frac{f^2}{2}(\partial_\mu \theta)^2 + \Lambda^4 \cos\theta \qquad : a = \theta f \in [0, 2\pi f]$$

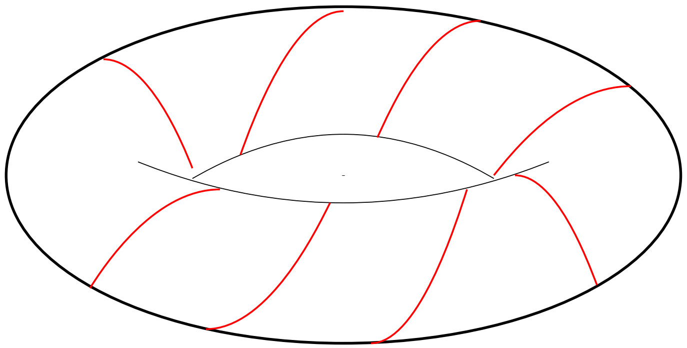
Introducing two axions with ($\Lambda_H \gg \Lambda$)

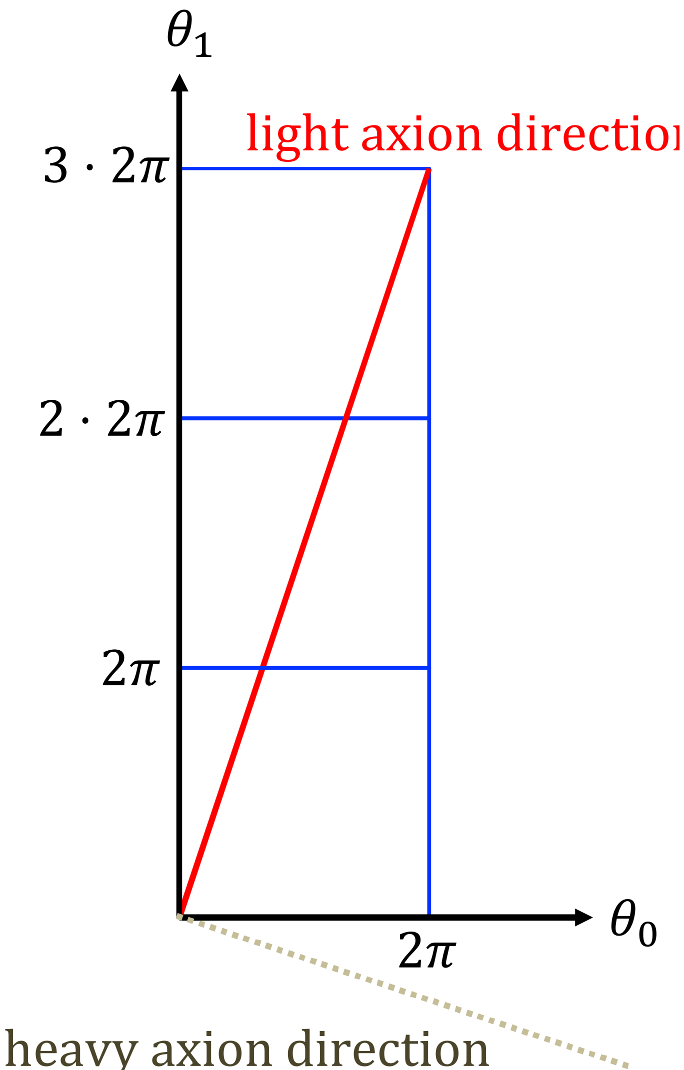
$$\frac{f^2}{2}\left((\partial_\mu \theta_0)^2 + (\partial_\mu \theta_1)^2\right) + \Lambda_H^4 \cos(3\theta_0 - \theta_1) + \Lambda^4 \cos\theta_0$$

Integrating out a heavy mode:

$$\frac{f^2(1+1/9)}{2}(\partial_\mu \theta_1)^2 + \Lambda^4 \cos\frac{\theta_1}{3}$$

$$: a = \sqrt{1+1/9}\,\theta_1 f \in [0, 3 \cdot 2\pi f\sqrt{1+1/9}]$$

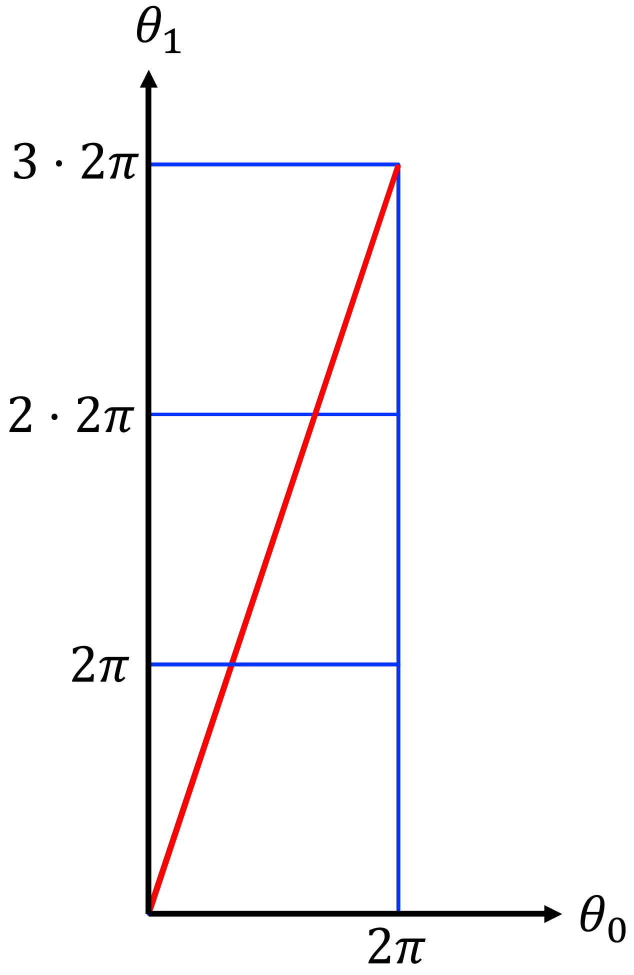




Extending KNP mechanism

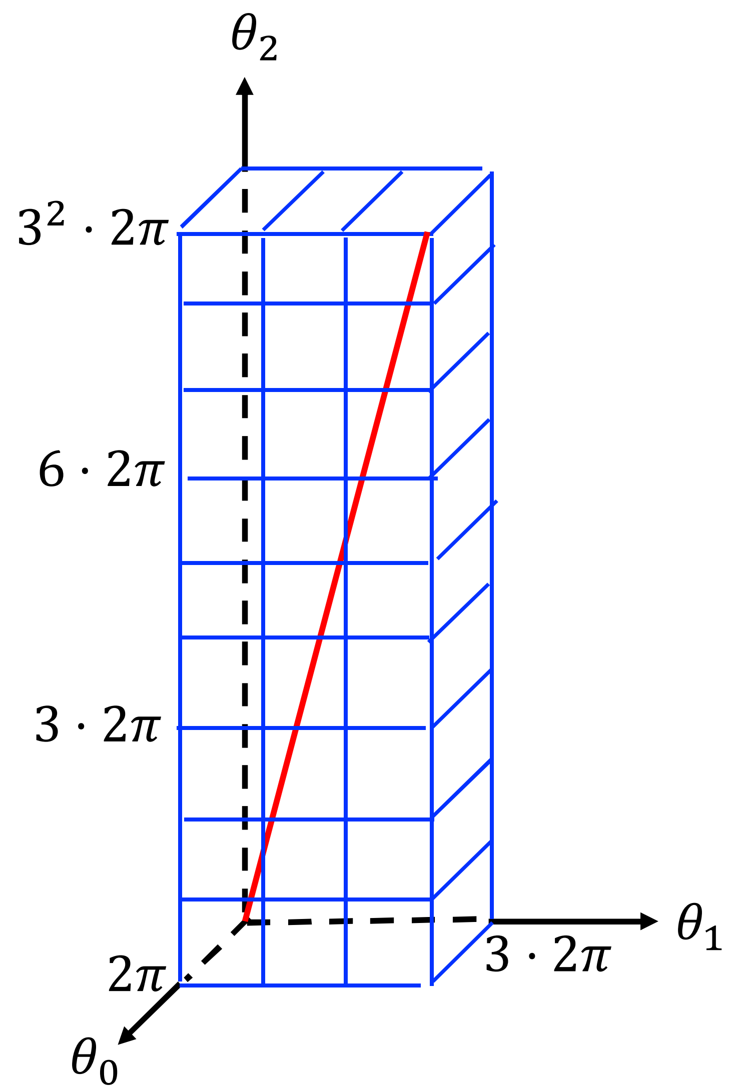
Adding one more axion : extending the axion period

$\Lambda_H^4 \cos(3\theta_0 - \theta_1)$



$$a = \sqrt{1 + 1/9}\,\theta_1 f \in [0, 3 \cdot 2\pi f\sqrt{1 + 1/9}]$$

$\Lambda_H^4 \cos(3\theta_0 - \theta_1) + \Lambda_H^4 \cos(3\theta_1 - \theta_2)$



$$a = \sqrt{1 + 1/9 + 1/81}\,\theta_2 f$$
$$\in [0, 3^2 \cdot 2\pi f\sqrt{1 + 1/9 + 1/81}]$$

Clockwork axion

[Choi, Kim, Yun 14]

Considering N+1 axions with $\sum_{i=0}^{N-1} \Lambda_H^4 \cos(3\theta_i - \theta_{i+1})$

$$f_{eff} = q^N\, 2\pi f \sqrt{1 + q^{-2} + \cdots}$$

$$a = \sqrt{1 + 1/9 \cdots + 1/9^N}\, \theta_N f$$

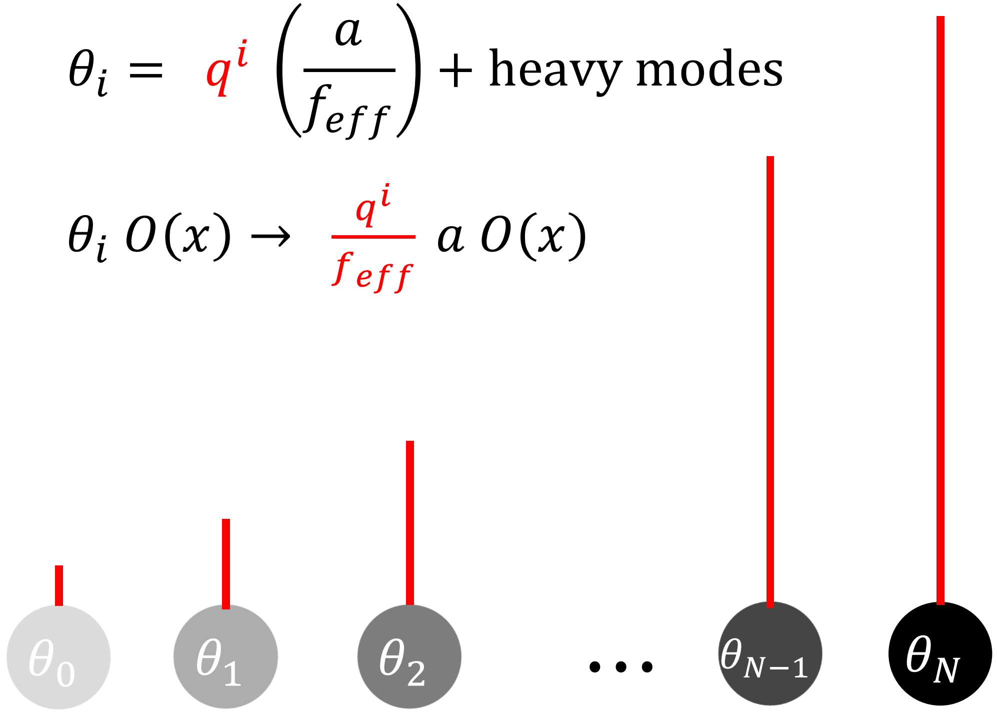
$$\in \left[0, 3^N \cdot 2\pi f \sqrt{1 + 1/9 \cdots + 1/9^N}\right]$$

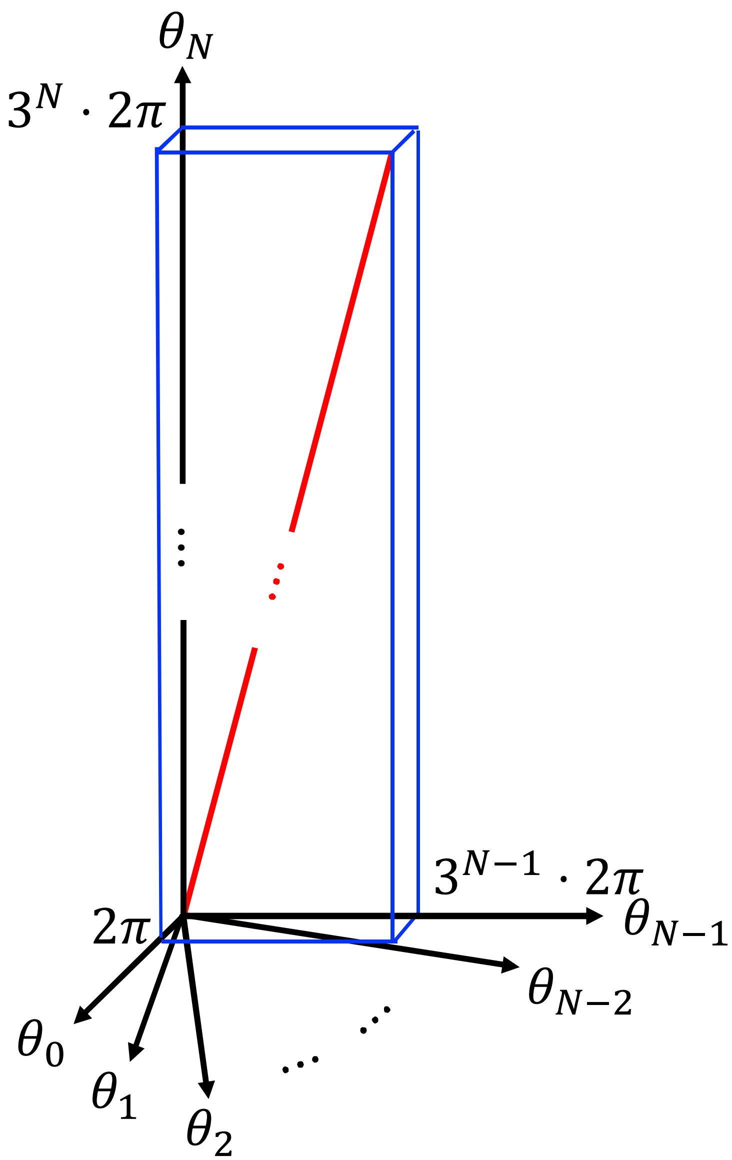
Exponential extending of the field excursion

Exponential localization of the lightest mode at the last site

$$\theta_i = q^i \left(\frac{a}{f_{eff}}\right) + \text{heavy modes}$$

$$\theta_i\, O(x) \to \frac{q^i}{f_{eff}}\, a\, O(x)$$



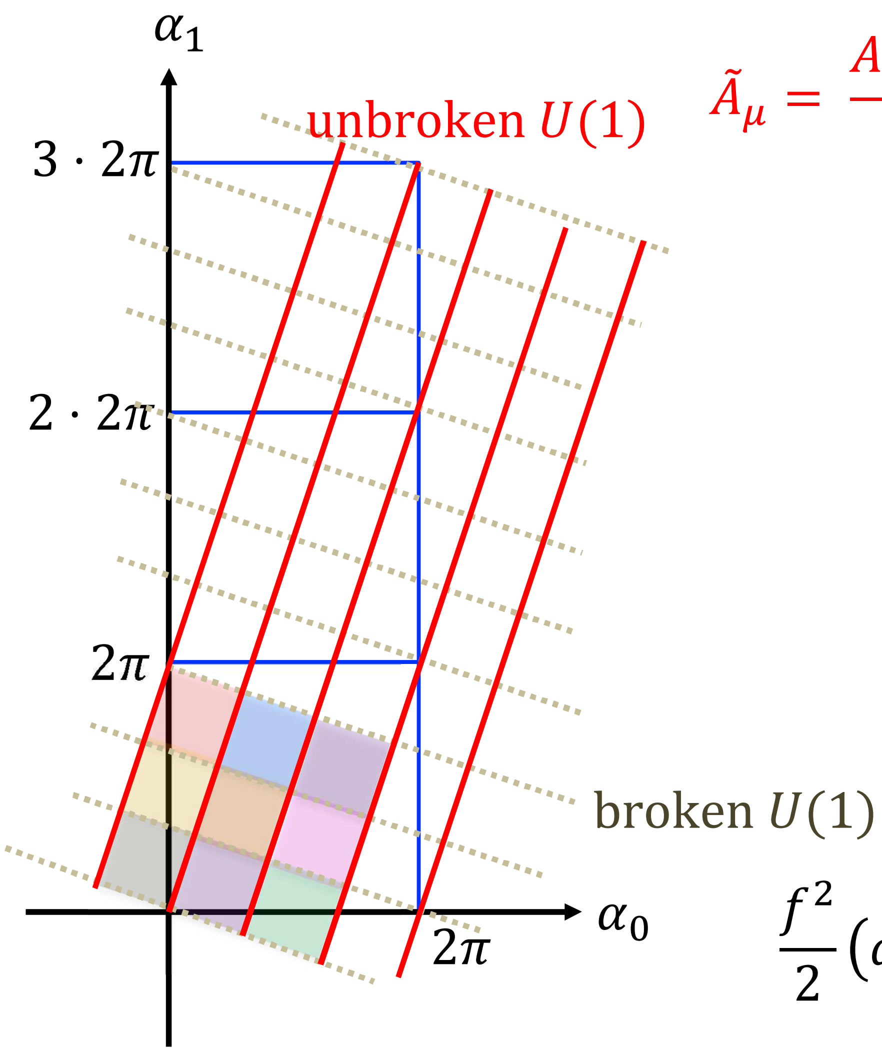


Clockwork photon

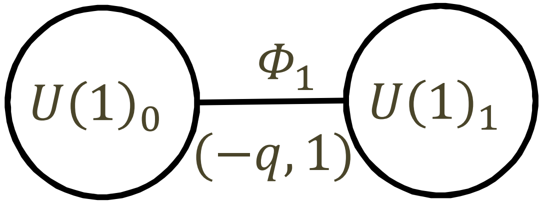
[Saraswat 16]

Staring from gauged $U(1)_0 \times U(1)_1$ $\quad (A_{0\mu} \to A_{0\mu} + g^{-1}\partial_\mu \alpha_0\,, A_{1\mu} \to A_{1\mu} + g^{-1}\partial_\mu \alpha_1)$

with a bilinear Higgs field: $\Phi_1 \to \exp[i(q\,\alpha_0 - \alpha_1\,)]\Phi_1$ $\;(\langle \Phi_1 \rangle = f \neq 0)$



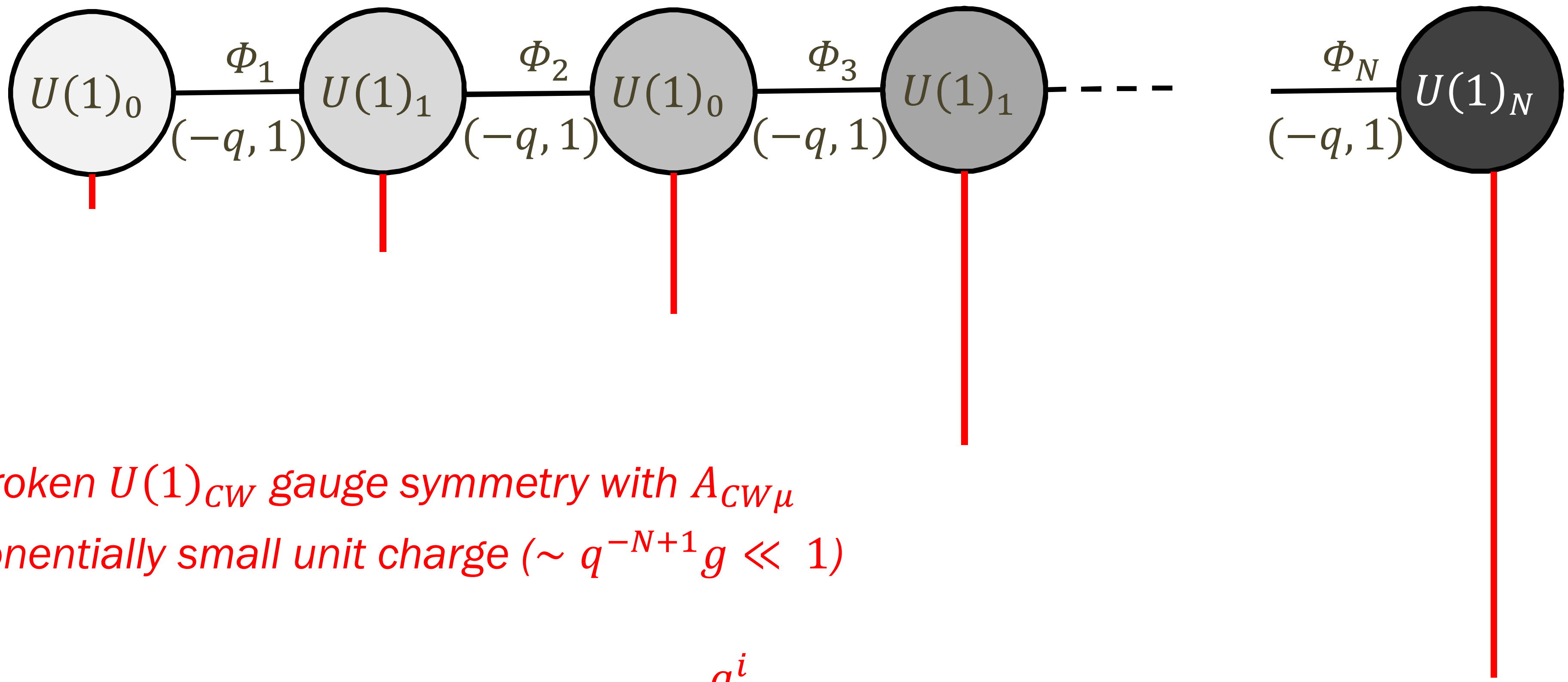
$$\tilde{A}_\mu = \frac{A_{0\mu} + q A_{1\mu}}{\sqrt{1+q^2}}$$



$$\frac{f^2}{2}\left(q\,A_{0\mu} - A_{1\mu}\right)^2$$

Clockwork photon [Giudice, McCullough 16]

Clockwork U(1) can be constructed by introducing N+1 U(1) with N Higgs fields



Unbroken $U(1)_{CW}$ gauge symmetry with $A_{CW\mu}$

Exponentially small unit charge ($\sim q^{-N+1} g \ll 1$)

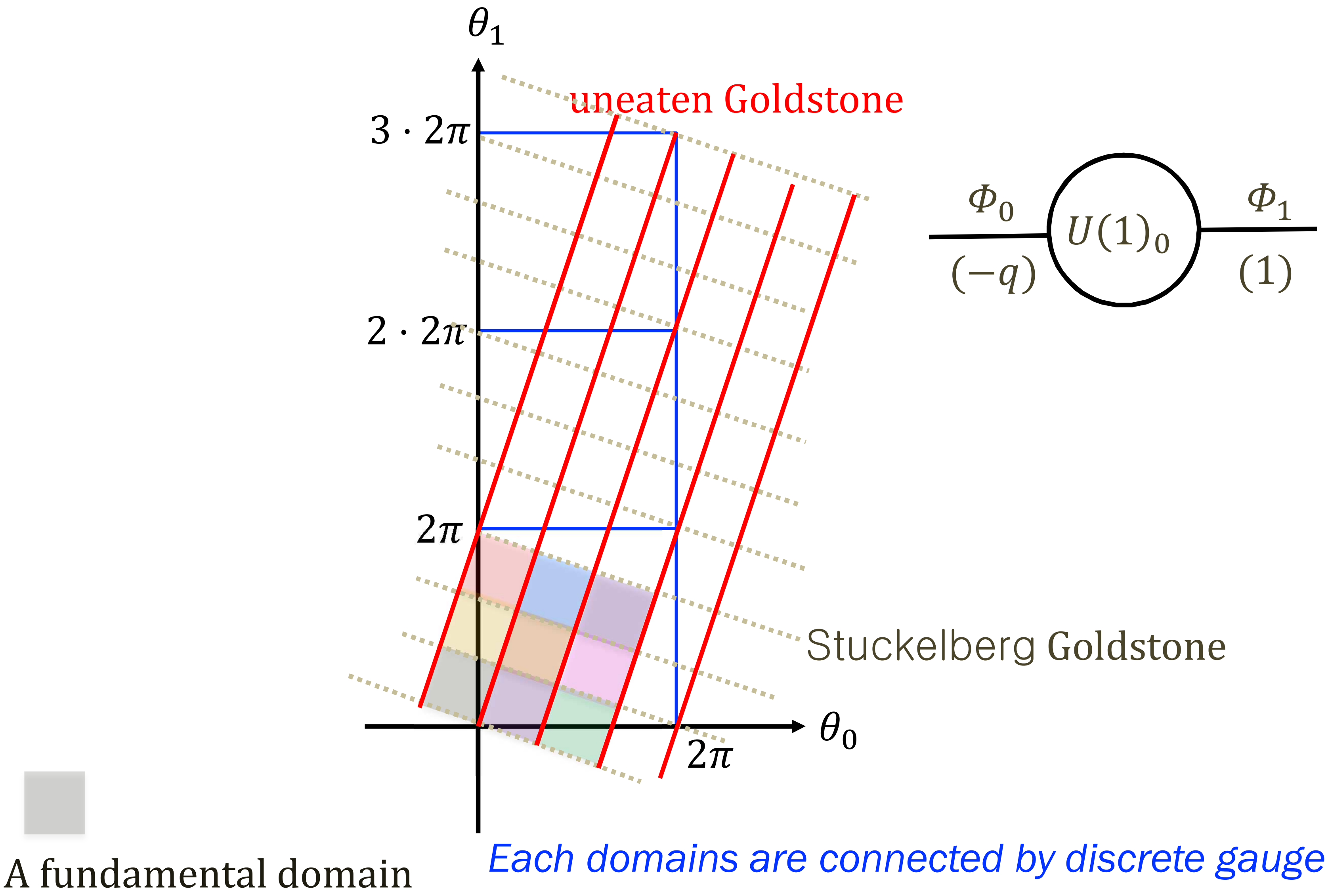
$$A_{i\mu} = \frac{q^i}{\sqrt{1+q^2+\cdots q^{2N}}} A_{CW\mu} + \text{heavy modes}$$

$$g\, Q_i\, A_i^{\mu}\, J_{i\mu}(x) \to \frac{q^i g Q_i}{\sqrt{1+q^2+\cdots q^{2N}}} A_{CW}^{\mu}\, J_{i\mu}(x)$$

Clockwork Goldstone

[Feng, Shiu, Soler, Ye 14]

Two Goldstone boson (θ_0, θ_1), one combination absorbed by the broken U(1) vector field

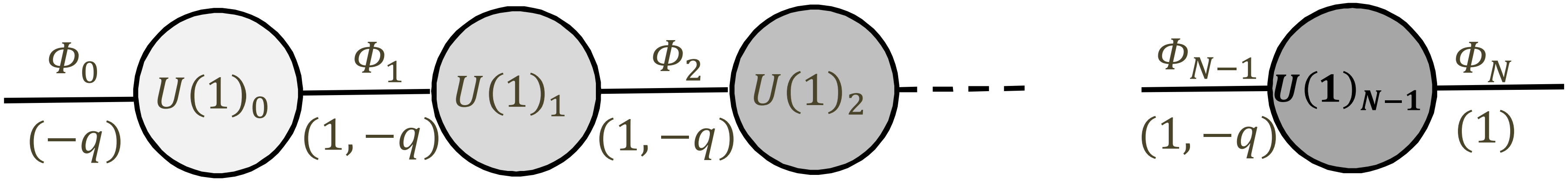


Each domains are connected by discrete gauge transformation

Clockwork Goldstone

[Bonnefoy, Dudas, Pokorski 1804.01112]

Among N+1 Goldstones, N combinations are eaten by vector bosons for the broken U(1)s.



Uneaten Goldstone mode:

$$a = f\,\frac{\theta_0 + q\,\theta_1 \cdots + q^N\theta_N}{\sqrt{1+q^2+\cdots+q^{2N}}}$$

The Goldstone boson field period from

$$\theta_0 + q\,\theta_1 \cdots + q^N\theta_N \in [0, 2\pi] \text{ in a fundamental domain}$$

is exponentially reduced as

$$a \in \left[0, 2\pi f/\sqrt{1+q^2+\cdots+q^{2N}} \sim 2\pi f\, q^{-(N+1)}\right]$$

Applications

For the CW zero mode

** Exponentially large (small) axion field period*

** Exponentially small U(1) unit charge*

** Couplings of the lightest mode to operators at two different sites are hierarchically different*

Inflation, relaxion, QCD axion

[Choi, Kim, Yun 14]
[Choi, Im 15]
[Kaplan, Rattazzi 15]
[Kehagias, Riotto 17]
[Park, CSS 18]

[Higaki, Jeong, Kitajima, Takahashi 14,15,16]
[Farina, Pappadopulo, Rompineve, Tesi 16]

Gravity *[Giudice, McCullough 16]*

Neutrino mass *[Giudice, McCullough 16]*
[Hambye, Teresi, Tytgat 16]
[Park, CSS 17]

Flavors, etc.

Continuum limit of CW

Up to quadratic order

CW mechanism up to quadratic order:

$$-\frac{1}{2}\sum_{i=0}^{N}(\partial_\mu \phi_i)^2 - \frac{1}{2}\sum_{i=0}^{N-1} M^2(\phi_{i+1} - q\phi_i)^2$$

Extension to a continuum limit: $\phi_i(x) \Rightarrow \Phi(x,y)$ $(m\pi R \gg 1)$

$$-\frac{1}{2}\int_0^{\pi R} dy\, \left[(\partial_\mu \Phi)^2 + (\partial_y \Phi - m\,\Phi)^2\right]$$

$$m = \frac{q-1}{\epsilon}\Big|_{q\to 1, \epsilon\to 0}$$

Physical interpretation:

- *Nontrivial 5D background geometry*

$$-\frac{1}{2}\int_0^{\pi R} dy \sqrt{-G}\, G^{MN}\partial_M\Phi\partial_N\Phi$$

$$ds^2 = e^{\frac{4}{3}my}(dx_\mu dx^\mu + dy^2)$$

$$\Phi \to e^{my}\Phi$$

- *Bulk and boundary mass terms in a flat 5D*

[Giudice, McCullough 16]

$$-\frac{1}{2}\int_0^{\pi R} dy\, \left[(\partial_M \Phi)^2 + m^2\Phi^2 + 2m\Phi^2(\delta(y) - \delta(y-\pi R))\right]$$

[Craig, Garcia, Sutherland 17]

Continuum clockwork axion (1)

[Choi, Im, CSS 17]

$$ds^2 = e^{\frac{4}{3}my}(dx_\mu dx^\mu + dy^2)$$

Defining frame in 5D is important :

Nontrivial 5D background geometry $\Theta \in [0, 2\pi]$

$$\int_0^{\pi R} dy\sqrt{-G}\left(-\frac{f^3}{2}G^{MN}\partial_M\Theta\partial_N\Theta\right) + \delta(y-y_*)\left(\frac{\Theta}{8\pi^2}\,G\tilde{G} + e^{i\Theta}\sqrt{-G_4}O(x)\right)$$

Flat zero mode profile along the 5th dim in the 5D field basis

$$\Theta(x,y) = \theta_{CW}(x) + e^{-my}\sum_{n=1}\text{KK modes}$$

Integrating out KK modes ($\theta_{CW}(x) \equiv \Theta(x, y_*)$)

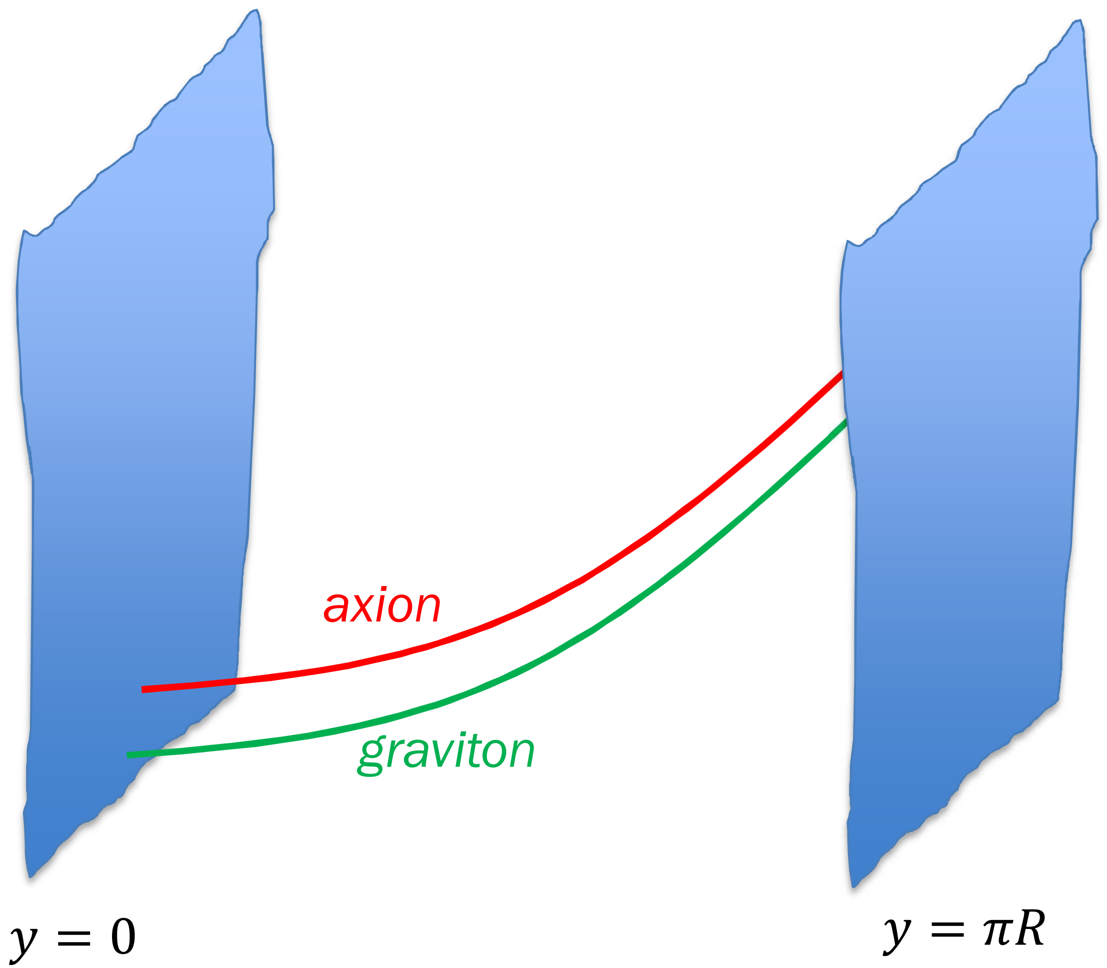
$$\frac{f^3}{4m}(e^{2m\pi R}-1)\left(\partial_\mu\theta_{CW}\right)^2 + \frac{\theta_{CW}}{8\pi^2}\,G\tilde{G} + e^{i\theta_{CW}}\,\tilde{O}(x)$$

- *Axion decay constant :* $f_{eff} \simeq \frac{e^{m\pi R}}{\sqrt{2m\pi R}}\sqrt{f^3\pi R} \gg \sqrt{f^3\pi R}$

  However, $M_{Pl} \simeq \frac{e^{m\pi R}}{\sqrt{2m\pi R}}\sqrt{M_5^3\pi R} \gg \sqrt{M_5^3\pi R}$
- *No hierarchically different couplings between different branes*

$$\left(\frac{f_{eff}}{M_{Pl}}\right)^2 = \left(\frac{f}{M_5}\right)^3$$

Continuum clockwork axion (1)



$$L_5 = \int_0^{\pi R} dy \sqrt{G_5} \simeq \frac{1}{m} e^{2m\pi R/3} \gg \pi R$$ *Warped large volume*

Continuum clockwork axion (2)

[Choi, Im, CSS 17]

Defining frame in 5D is important :

Bulk and boundary mass terms $\Theta \in [0, 2\pi]$ *with a* *periodic* $V(x) = V(x + 2\pi)$

$$\int_0^{\pi R} dy \; -\frac{f^3}{2}\left(\left(\partial_\mu \Theta\right)^2 + \left(\partial_y \Theta - m\, V(\Theta)\right)^2 \right) + \delta(y - y_*)\left(\frac{\Theta}{8\pi^2}\, G\tilde{G} + e^{i\Theta} O(x) \right)$$

Ex) $V(x) = \sin x = x + O\left(x^3\right)$

Localized zero in the 5D field basis at different positions for different $\langle \Theta \rangle$

e.g. at $\langle \Theta \rangle = 0$, $\partial_y \delta\Theta - m\delta\Theta$ *(localized at* $y = \pi R$*)*

at $\langle \Theta \rangle = \pi$, $\partial_y \delta\Theta + m\delta\Theta$ *(localized at* $y = 0$*)*

Integrating out KK modes ($\theta_{CW}(x) \equiv \theta(x, y_*)$*)*

$$\frac{f^2}{2} Z(\theta_{CW}, y_*) \left(\partial_\mu \theta_{CW}\right)^2 + \frac{\theta_{CW}}{8\pi^2}\, G\tilde{G} + e^{i\theta_{CW}}\, \tilde{O}(x)$$

- *Axion decay constant :* $f_{eff} \simeq (\sqrt{mR})\sqrt{f^3 \pi R}$ *. No exponentially large*
- *Hierarchically different couplings depending on the axion expectation value*

Continuum clockwork axion (2)

$$Z(\theta_{CW}, y_*) =$$

$$\frac{2(f/m)\tanh m\pi R}{\left(1+\frac{\cosh(m\pi R-2my_*)}{\cosh m\pi R}\right)-2\left(\sinh\frac{(m\pi R-2my_*)}{\cosh m\pi R}\right)\cos\theta_{CW}-\left(1-\frac{\cosh(m\pi R-2my_*)}{\cosh m\pi R}\right)\cos^2\theta_{CW}}$$

Nontrivial wave-function renormalization

For $m \to 0$ $\qquad Z(\theta_{CW}, y_*) \to f\pi R$

For $m\pi R \gg 1$ (at $y_* = 0$) $\qquad Z(\theta_{CW}, y_*) \to \frac{f}{m(1+2\,e^{-2m\pi R}-\cos\theta_{CW})}$

$$\sim \frac{f^3}{2m}\exp(2m\pi R)\ at\ \theta_{CW}=0$$

For $m\pi R \gg 1$ (at $y_* = \pi R$) $\qquad Z(\theta_{CW}, y_*) \to \frac{f}{m(1+2\,e^{-2m\pi R}+\cos\theta_{CW})}$

$$\sim \frac{f}{2m}\exp(2m\pi R)\ at\ \theta_{CW}=\pi R$$

Continuum clockwork photon (1)

[Choi, Im, CSS 17]

In nontrivial 5D background $U(1): A_M \to A_M + \partial_M \alpha \quad \alpha(x,y) \in [0, 2\pi]$

$$\int_0^{\pi R} dy \sqrt{-G} \left(-\frac{1}{4g_5^2} G^{MN} G^{PQ} F_{MP} F_{NQ} \right) + \delta(y - y_*) \left(\sqrt{-G_4}\, i\bar{\psi}\, e_a^{\mu} \gamma^a (\partial_\mu - iA_\mu)\psi \right)$$

Flat zero mode in the 5D field basis $A_\mu(x,y) = A_{CW\mu}(x) + e^{-my} \sum_{n=1} \text{KK modes}$

Integrating out KK modes $(A_{CW}(x) \equiv A(x, y_*))$

$$-\frac{3}{8g_5^2 m}(e^{2m\pi R/3} - 1)\, (F_{CW})_{\mu\nu} (F_{CW})^{\mu\nu} + \bar{\tilde{\psi}}\, i\gamma^\mu \left(\partial_\mu - i\, A_{CW\mu}\right) \tilde{\psi}$$

- *Gauge coupling :* $g_{eff} \simeq e^{-m\pi R/3} g_5 \sqrt{m} \ll g_5/\sqrt{\pi R}$

  <u>However,</u> for charged fields at a boundary $\frac{m_\psi}{M_5} < \frac{g_5}{\sqrt{R}}, \ \frac{m_\psi}{M_{Pl}} \leq \frac{M_5}{M_{Pl}} \sim e^{-m\pi R} \ll g_{eff}$

- *No hierarchically different couplings for different branes*

Continuum clockwork photon (2)

[Choi, Im, CSS 17]

For 5D gauge symmetry,

bulk and boundary mass terms from the Stuckelberg kinetic term ($\theta(x,y) \to \theta + \alpha$)

$$\int_0^{\pi R} dy \left\{ -\frac{1}{4g^2} F_{MN}^2 - \frac{M^2}{2g^2} (\partial_M \theta - A_M)^2 \left(1 + \frac{2c_1}{M} \left(\delta(y) - \delta(y - \pi R)\right)\right)\right\}$$

Integrating out KK modes,

$$-\frac{1}{4}(F_{CW})^2_{\mu\nu} - \frac{M^2}{2}(1 - c_1^2)\left(\partial_\mu \theta - A_{CW\mu}\right)^2 + \bar{\psi} i \gamma^\mu \left(\partial_\mu - i\, e^{-c_1 M (\pi R - y_*)} A_{CW\mu}\right)\psi$$

For $c_1^2 = 1$: CW gauge symmetry realizes not as $U(1)_{CW}$ but as $\mathbb{R}_{CW}$ from 5D $U(1)$!

Massless $\phi \equiv M\sqrt{1 - c_1^2}\,\theta$ decoupled

- *Is it really OK? Well.. if starting from the 5D Higgs $H(x,y) = f^3\left(1 + \frac{\rho(x,y)}{f}\right) e^{i\theta(x,y)}$,*

$$\frac{M^2}{2}\left((1 - c_1^2) + c_2 \frac{h(x)}{f}\right)\left(\partial_\mu \theta - A_{CW\mu}\right)^2$$

$c_1^2 \to 1$: *strong coupling regime (breakdown of perturbative theory) strongly disfavor*

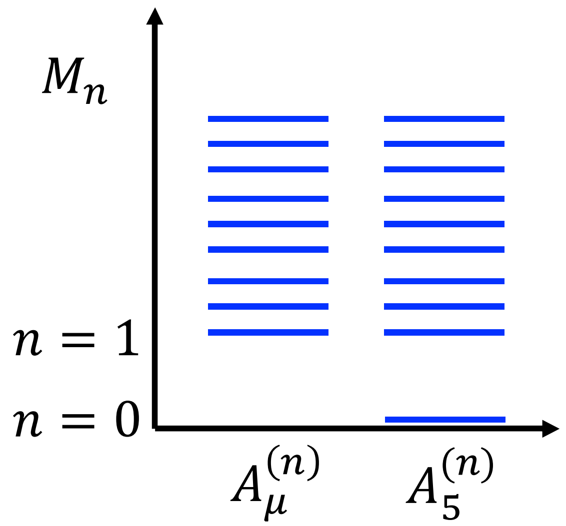
Continuum clockwork Goldstone

[Choi 03] [Choi, Im, CSS 17]

[Flacke, Gripaios, March-Russell, Maybury 06]

In nontrivial 5D background

$$\int_0^{\pi R} dy\sqrt{-G}\left(-\frac{1}{4g_5^2}G^{MN}G^{PQ}\,F_{MP}F_{NQ}\right)$$



Opposite boundary condition $A_\mu(y=0) = A_\mu(\pi R) = 0$:

$$F_{\mu 5}^2 = \left(\partial_\mu A_5 - \partial_y A_\mu\right)^2$$

Except zero-mode, all modes becomes massive vector bosons

Integrating out KK modes, $\left(\theta_{CW}(x) = \int_0^{\pi R} dy\, A_5\,(x,y)\right)$

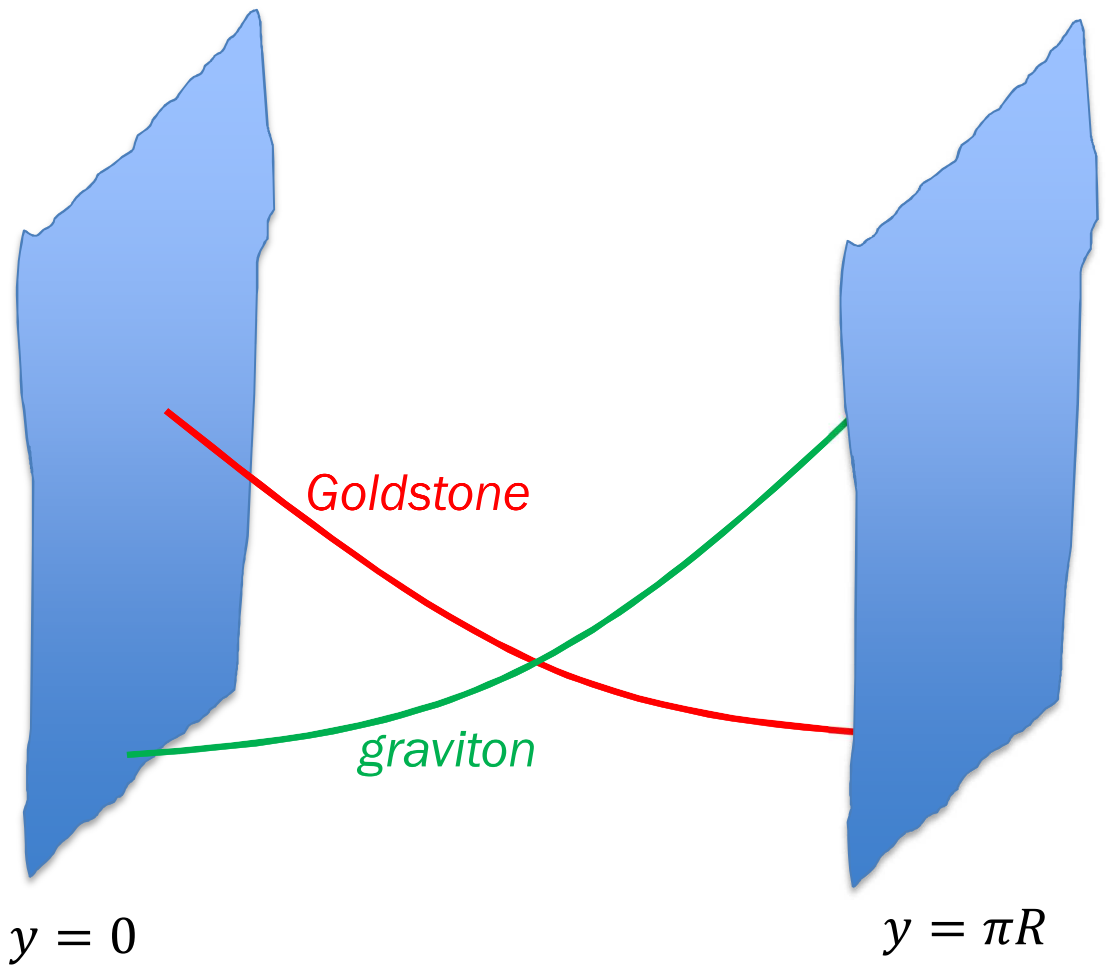
The zero mode kinetic term becomes

$$\mathcal{L}_{eff} = -\frac{m}{3g_5^2}\frac{\left(\partial_\mu \theta_{CW}\right)^2}{(1-e^{-2m\pi R/3})}$$

- *Axion decay constant :* $f_{eff} \simeq \sqrt{\frac{m}{g_5^2}} \leq M_5$ $\quad\left(\frac{f_{eff}}{M_{Pl}}\right) \sim e^{-m\pi R}$

  Similar to the masses of low KK modes $(f_{eff}/M_{KK}(n=1,2,) \sim 1/\sqrt{m\pi R})$

Continuum clockwork Goldstone



(Generalized) Linear Dilaton

The nontrivial 5D background *[Antoniadis, Arvanitaki, Dimopoulos, Giveon 11]*

$$ds^2 = e^{\frac{4}{3}my}(dx_\mu dx^\mu + dy^2)$$

can be obtained from Linear Dilaton Model ($\xi = 1, \Lambda_5, \Lambda_4 < 0$)

$$\int_0^{\pi R} dy\sqrt{-G}\, e^{\xi S}\left(\frac{M_5^3}{2} R + \frac{M_5^3}{2} G^{MN}\partial_M S \partial_N S - \Lambda_5 - \frac{\Lambda_4}{\sqrt{G_{55}}}\big(\delta(y) - \delta(y-\pi R)\big)\right)$$

In the Einstein frame, ($c = \xi/\sqrt{4\xi^2 - 3}$)

$$\int_0^{\pi R} dy\sqrt{-G}\left(\frac{M_5^3}{2} R - \frac{M_5^3}{2} G^{MN}\partial_M S \partial_N S - e^{-2cS/\sqrt{3}}\Lambda_5 - \frac{e^{-cS/\sqrt{3}}\Lambda_4}{\sqrt{G_{55}}}\big(\delta(y) - \delta(y-\pi R)\big)\right)$$

[Choi, Im, CSS 17]

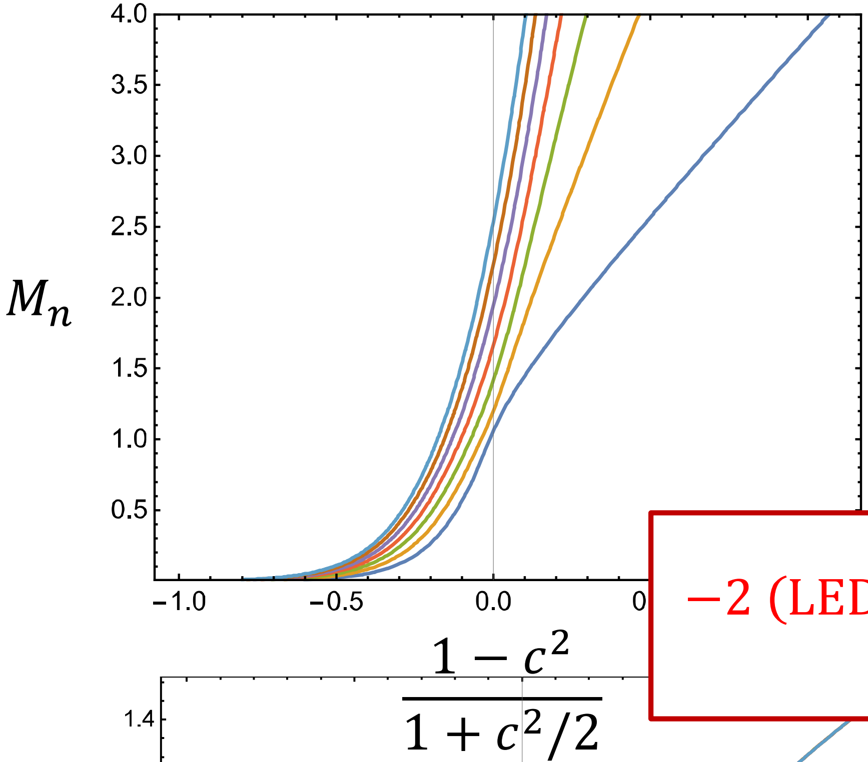
For $\xi \neq 1 (c \neq 1)$, *more general metric realized* $ds^2 = e^{2k_1 y}\, dx_\mu dx^\mu + e^{2c^2 k_1 y}\, dy^2$

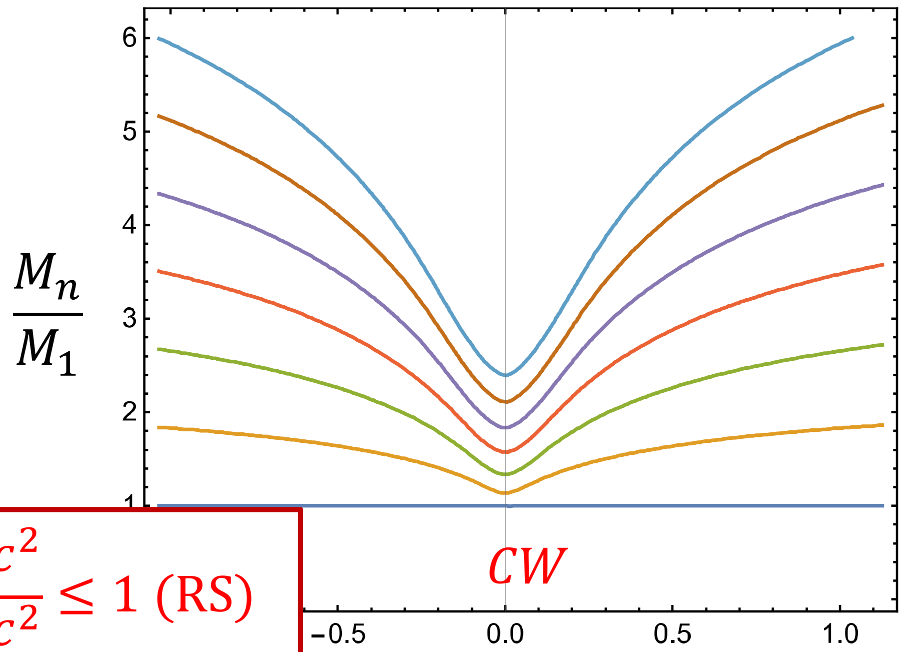
$$k_1 = \sqrt{\frac{2\Lambda_5}{3(c^2 - 4)}}$$

(Generalized) Linear Dilaton

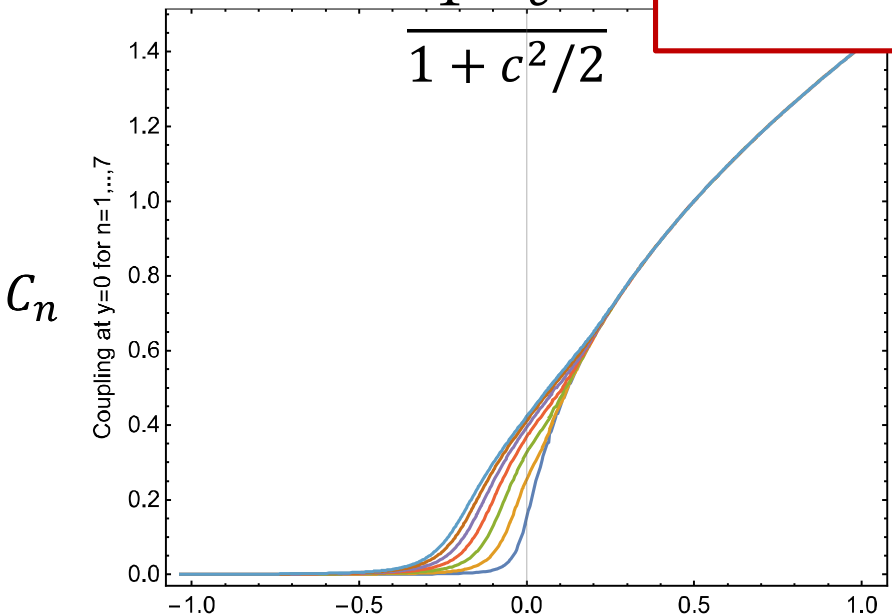
[Choi, Im, CSS 17]

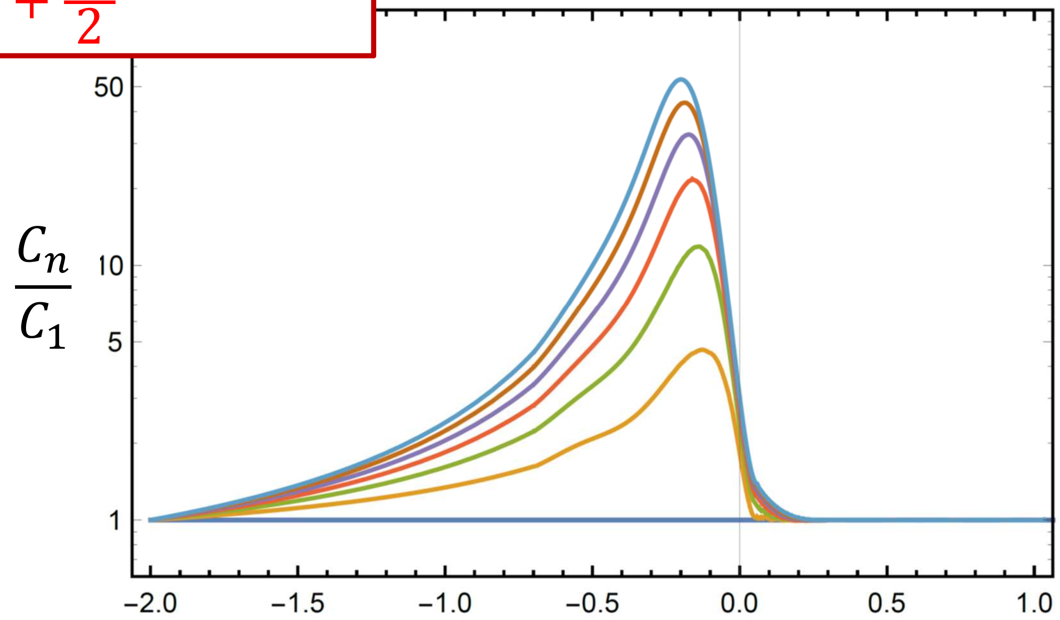
KK spectrum and couplings





$$-2\ (\text{LED}) \le \frac{1-c^2}{1+\frac{c^2}{2}} \le 1\ (\text{RS})$$

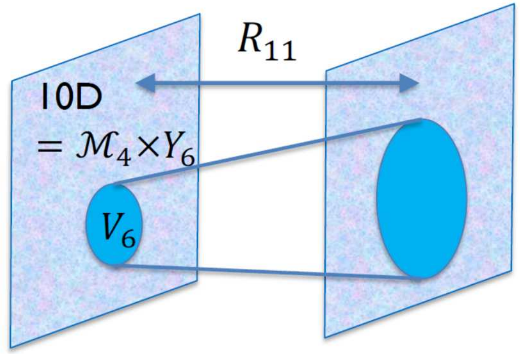




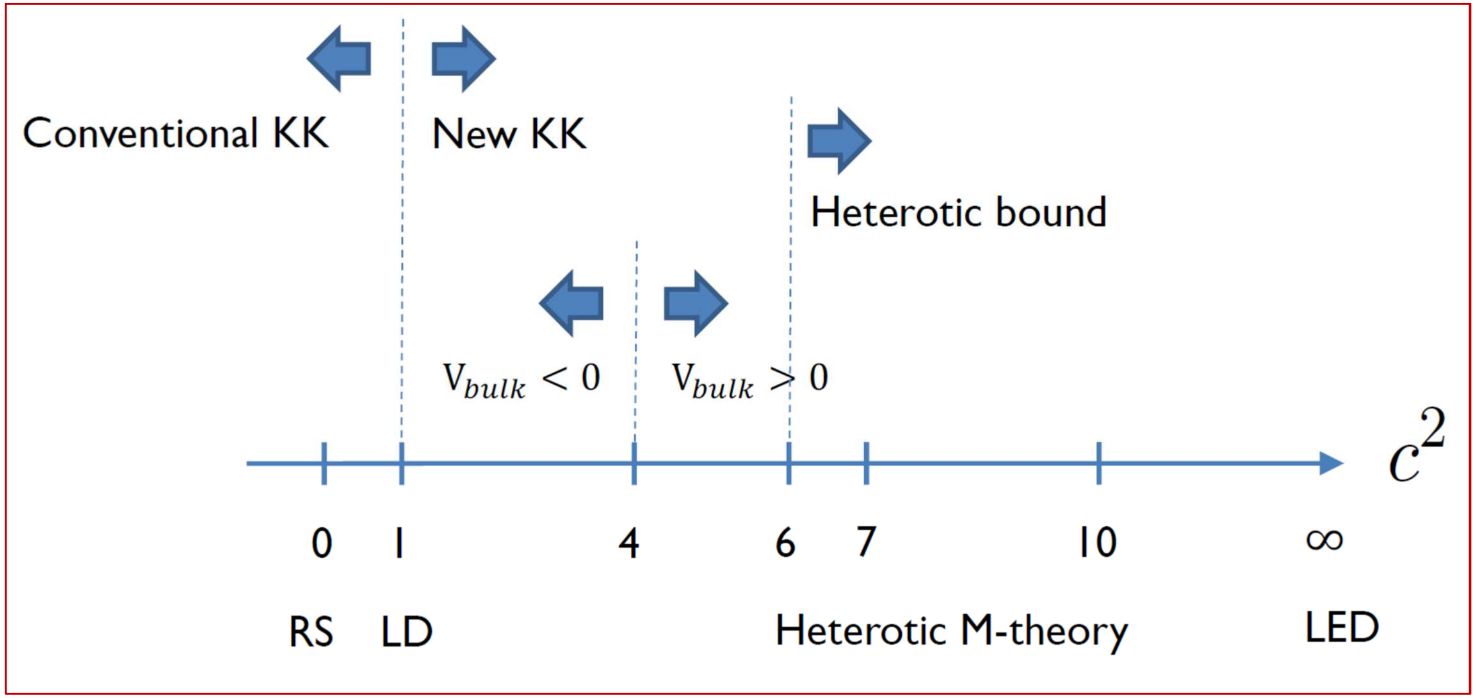
(Generalized) Linear Dilaton

Can we realize $c^2 > 1$? In heterotic M-theory $c^2 \geq 6$ is obtained

[Im, Nilles, Olechowski 1811.11838]



$$R_{11} \gg V_6^{1/6} \sim \frac{1}{M_{11}}$$



From Sang Hui's talk slides

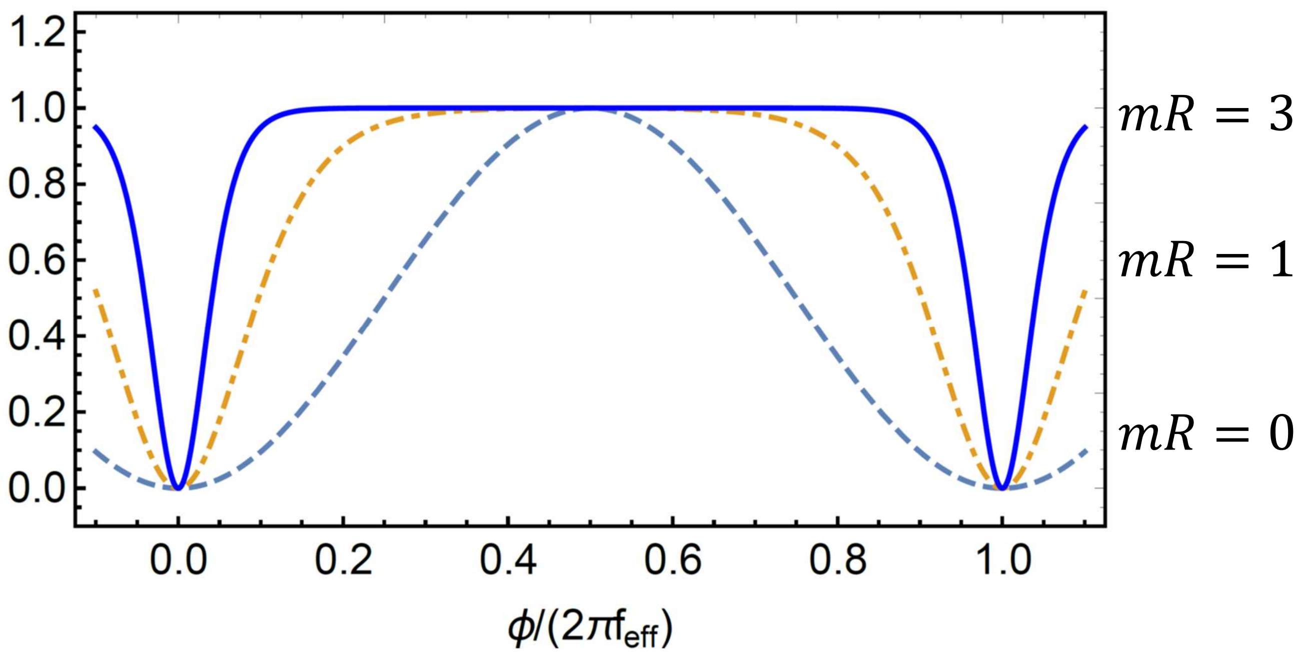
Phenomenological application of CCW axions

Deform the axion potential

Nontrivial wave-function renormalization

$$-\frac{f^2}{2}Z(\theta_{CW},y_*)\left(\partial_\mu\theta_{CW}\right)^2+\Lambda^4\cos\theta_{CW}=\frac{1}{2}\left(\partial_\mu\phi\right)^2+\Lambda^4\cos\theta_{CW}[\phi]$$

E.g. for $y_*=\pi R$, $Z(\theta_{CW}=0,\pi R)\sim O(1)$, $Z(\theta_{CW}=\pi,\pi R)\sim e^{2m\pi R}\gg 1$

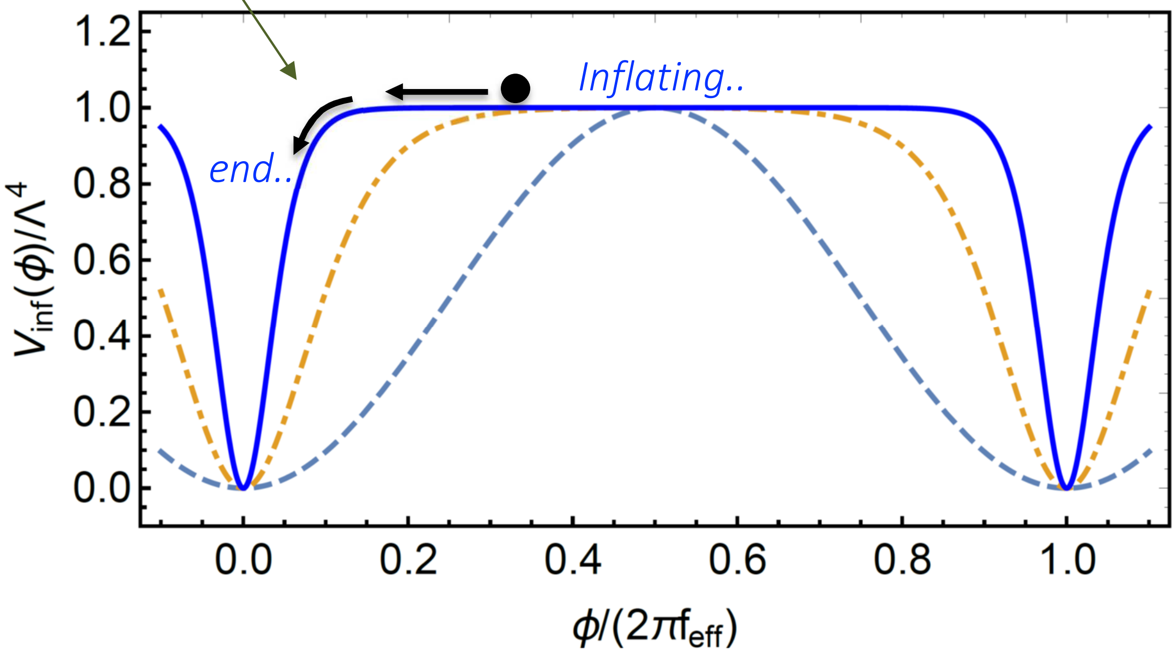


Natural Cliff Inflation *[Gong, CSS 17]*

The slope of the potential around the extremum is exponentially sensitive to $m\pi R$.

$$\tanh^2\left(\frac{\phi}{2f}\right)$$

Approximately, for $e^{m\pi R} >> 1$
: same type of Higgs (R^2) inflation with a much smaller f (<< M_{Pl})



(m=0 : vanilla natural inflation)

Slow role parameters: $\epsilon = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2, \ \eta = M_{Pl}^2 \frac{V''}{V}$

Observables

Amplitude of the curvature perturbation: $A_{\mathcal{R}} = \frac{V}{24\pi^2 M_{Pl}^4 \epsilon}$, *spectral tilt:* $n_{\mathcal{R}} = 1 - 6\epsilon + 2\eta$

tensor to scalar ratio: $r = 16\epsilon$

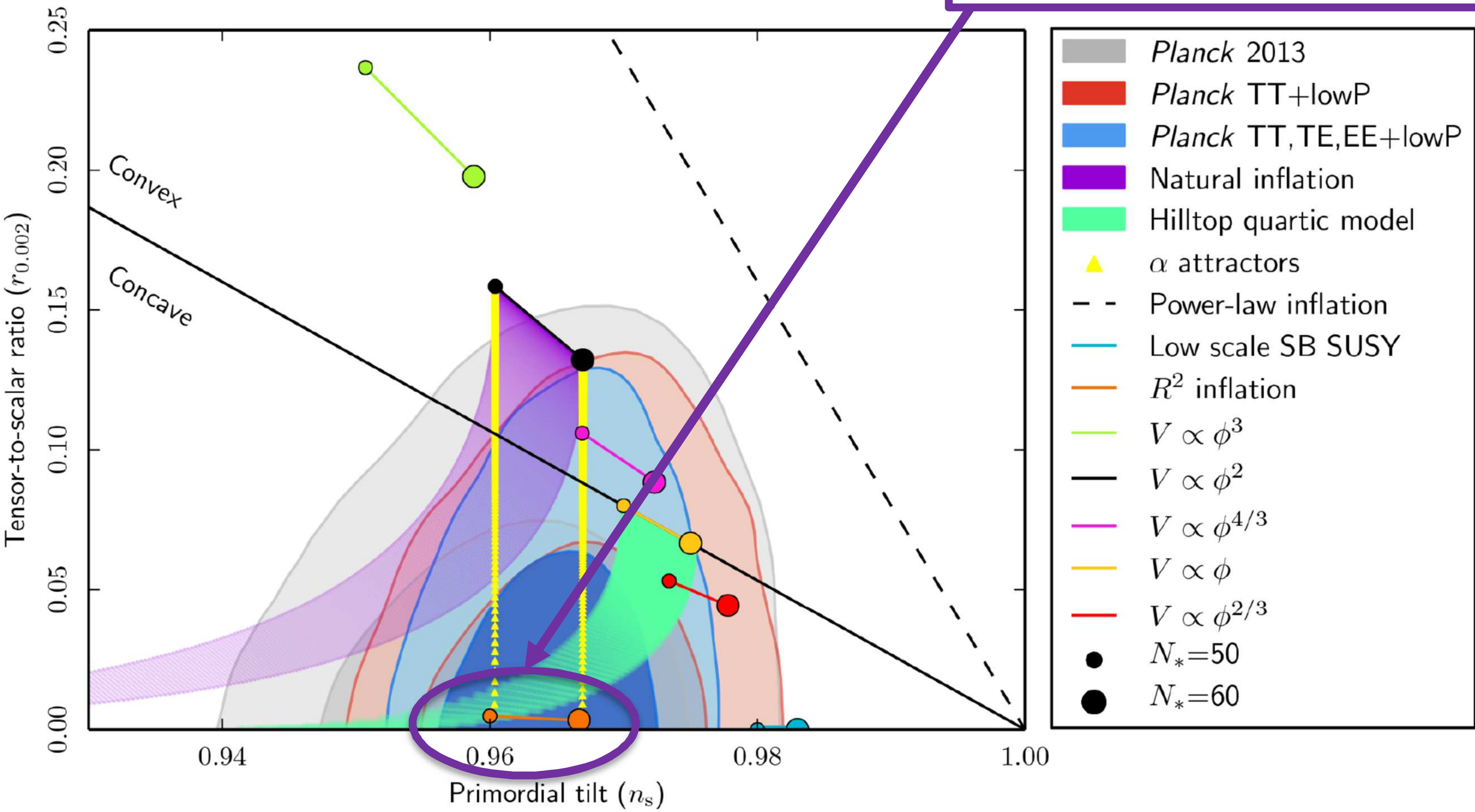
Natural Cliff Inflation [Gong, CSS 17]

The slope of the potential around the extremum is exponentially sensitive to $m\pi R$.

$$N_e = \frac{1}{M_{Pl}}\frac{1}{2\pi}\int_{\phi_f}^{\phi_i}\frac{d\phi}{\sqrt{\epsilon}} \approx \left(\frac{f}{2M_{Pl}}\right)^2 \exp\left(\frac{\phi_i}{f}\right)$$

$$n_R \approx 1 - \frac{2}{N_e}, \qquad r \approx \frac{8}{N_e^2}\left(\frac{f}{M_{Pl}}\right)^2$$

PLANCK 2013(2015)



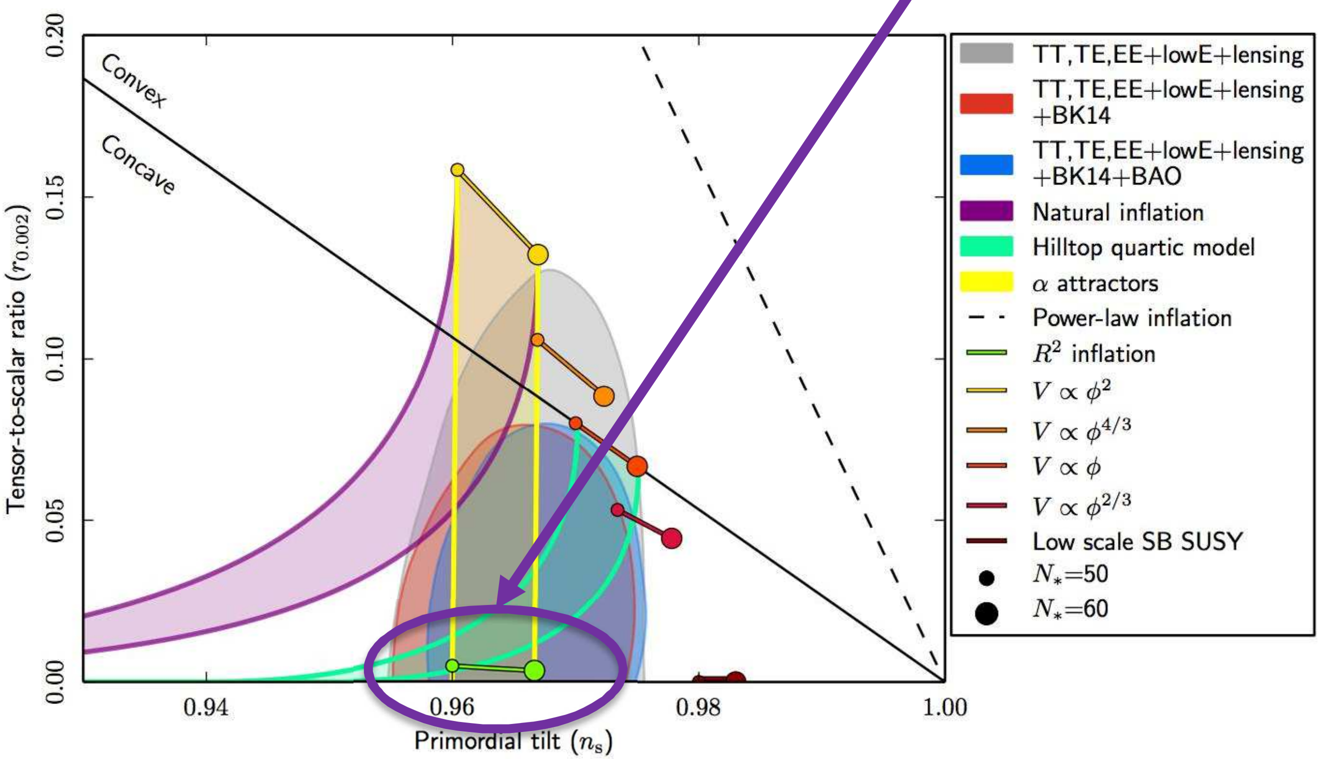
Natural Cliff Inflation *[Gong, CSS 17]*

The slope of the potential around the extremum is exponentially sensitive to $m\pi R$.

$$N_e = \frac{1}{M_{Pl}}\frac{1}{2\pi}\int_{\phi_f}^{\phi_i}\frac{d\phi}{\sqrt{\epsilon}} \approx \left(\frac{f}{2M_{Pl}}\right)^2 \exp\left(\frac{\phi_i}{f}\right)$$

$$n_R \approx 1 - \frac{2}{N_e}, \qquad r \approx \frac{8}{N_e^2}\left(\frac{f}{M_{Pl}}\right)^2$$

PLANCK 2018

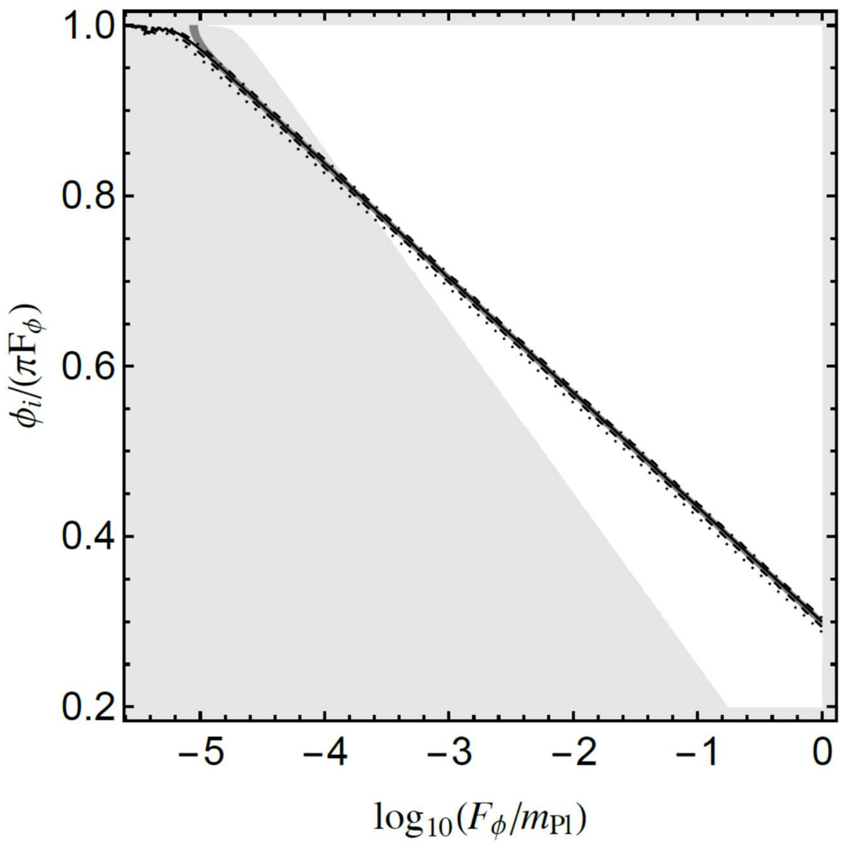


Natural Cliff Inflation *[Gong, CSS 17]*

Inflation with a sub-Planckian periodic potential can be achieved without tuning of initial position of ϕ_i.

$$N_e = \frac{1}{M_{Pl}}\frac{1}{2\pi}\int_{\phi_f}^{\phi_i}\frac{d\phi}{\sqrt{\epsilon}} \approx \left(\frac{f}{2M_{Pl}}\right)^2 \exp\left(\frac{\phi_i}{f}\right)$$

$$n_R \approx 1 - \frac{2}{N_e}, \qquad r \approx \frac{8}{N_e^2}\left(\frac{f}{M_{Pl}}\right)^2$$



$$F_\phi = f_{\rm eff} \simeq 10 f_*$$

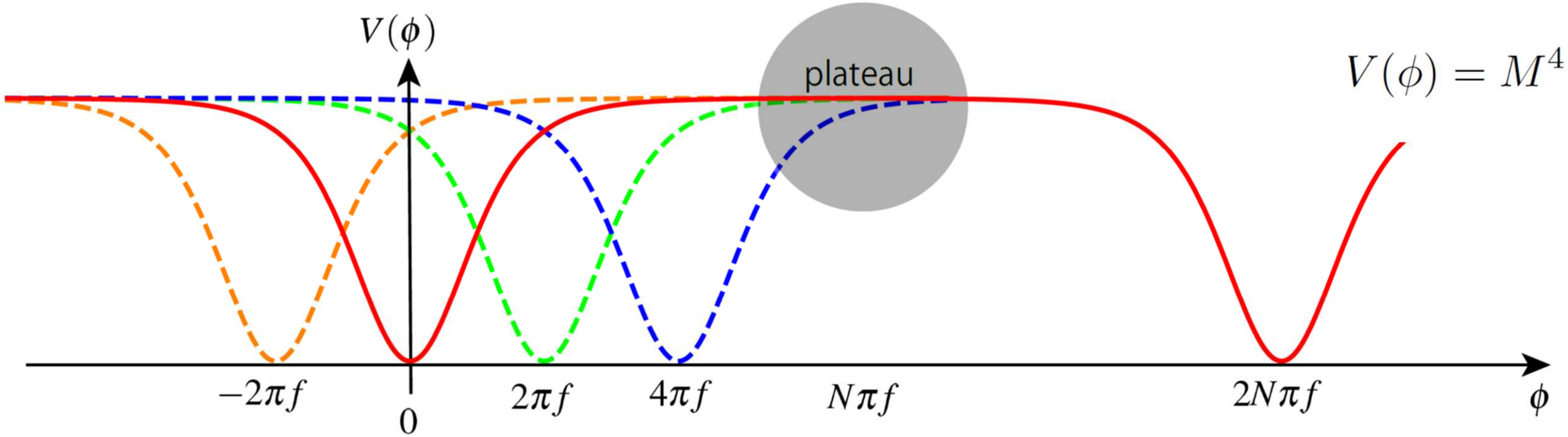
FIG. 2. The number of e-folds N and the specral index $n_{\mathcal{R}}$ in the $\log_{10}(F_\phi/m_{\rm Pl})$-$\phi_i/(\pi F_\phi)$ plane. We set $N = 40$ (dotted), 50 (dashed), 60 (solid) and 70 (dot-dashed), and $0.96 < n_{\mathcal{R}} < 0.97$ (dark shade). $r < 0.07$ is satisfied everywhere shown in this plot. The regime beyond the perturbative constraint $\Lambda^4/(2f_5^3 m) > 0.1$ (light shade) is also shown.

Reheating can be done by boundary interactions between the inflaton and the photons in the SM.

$$\int d^5x\sqrt{-g}\,\delta(y-y_b)c_\gamma\theta(x,y)F_{\mu\nu}(x)\tilde{F}_{\mu\nu}(x) \;\Rightarrow\; \delta\mathcal{L}_{\rm eff} = \frac{c_\gamma}{f}e^{-m(\pi R-y_b)}\delta\phi F\tilde{F}$$

Comparing with other deformed Natural Inf.

Scalar potentials induced by an anomalous coupling between the inflaton and a confining large N pure Yang-Mills gauge group [Nomura et.al. 1706.08522, 1711.10490]

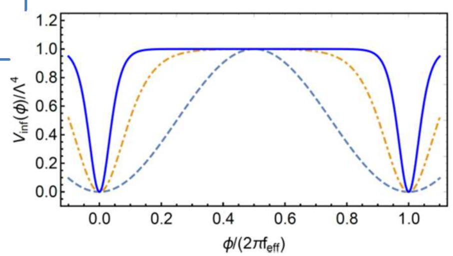


$$V(\phi) = M^4\left[1 - \frac{1}{(1+(\phi/F)^2)^p}\right]$$

$$-\frac{1}{2}(\partial_\mu\phi)^2 - V_{\rm pure}(\phi) + \frac{\phi}{8\pi^2 f}(F_{\mu\nu}\tilde{F}^{\mu\nu})_{SM}$$

N multi branches (tunneling is allowed), field independent coupling to the SM

$$-\frac{1}{2}(\partial_\mu\phi)^2 - \Lambda^4(1-\cos\theta_{CW}[\phi]) + \frac{\theta_{CW}[\phi]}{8\pi^2}(F_{\mu\nu}\tilde{F}^{\mu\nu})_{SM}$$



One branch, field dependent coupling to the SM

: different (p)reheating history

Spontaneous baryogenesis and dark matter

[Bae, Kost, CSS 1811.10655]

If the CCW axion couples to $SU(2)_L \times U(1)_Y$ gauge fields,

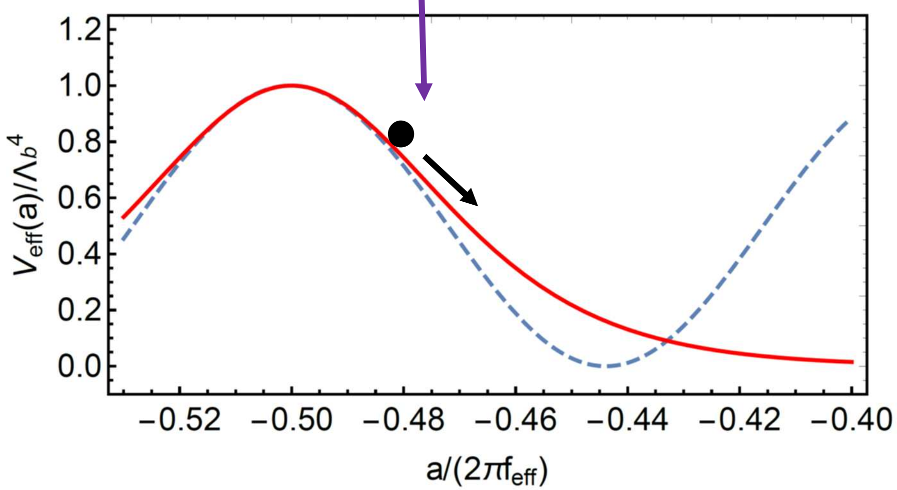
$$-\frac{1}{2}(\partial_\mu \phi)^2 - \Lambda^4(1-\cos\theta_{CW}[\phi]) + \frac{\theta_{CW}[\phi]}{8\pi^2}(c_1 W\widetilde{W} + c_2 B\tilde{B})$$

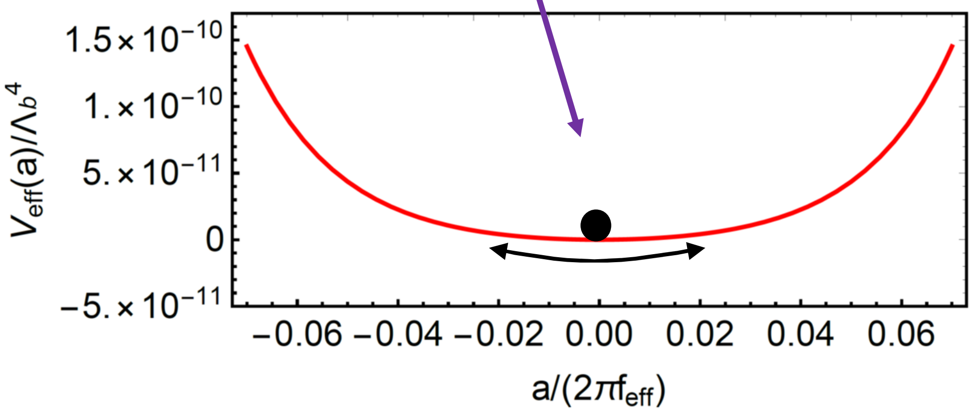
the rolling axion can generate a baryon asymmetry due to B+L anomaly

$$(\partial_\mu J_B^\mu) = \frac{N_f}{8\pi^2}(W_{\mu\nu}\widetilde{W}^{\mu\nu} - B_{\mu\nu}\tilde{B}^{\mu\nu})$$

Most of baryon asymmetry is generated during this period

Coherent oscillation gives the dark matter abundance ?

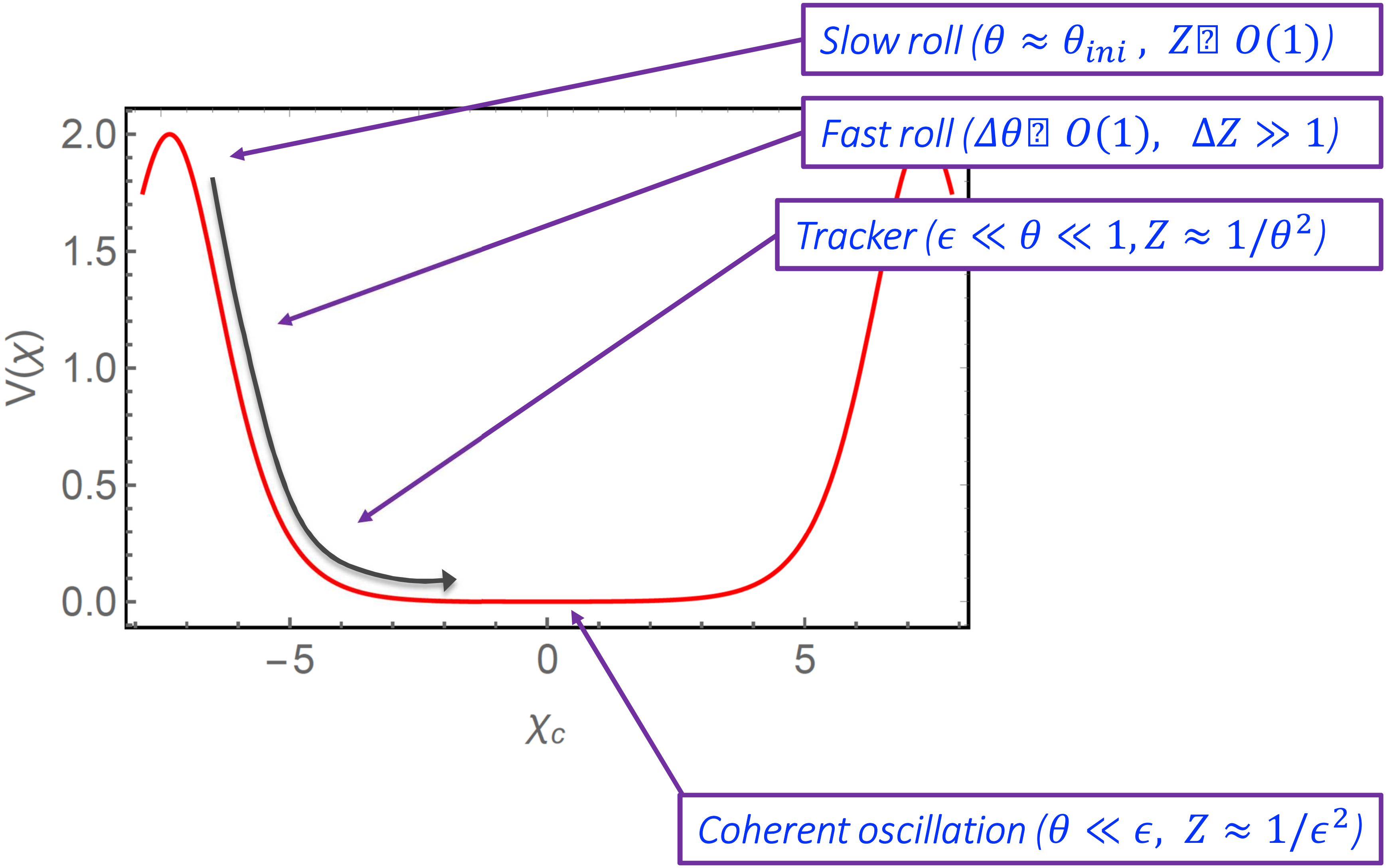




$$Z(\theta_{CW}) \sim 1/(1 + \epsilon^2 - \cos\theta_{CW})$$

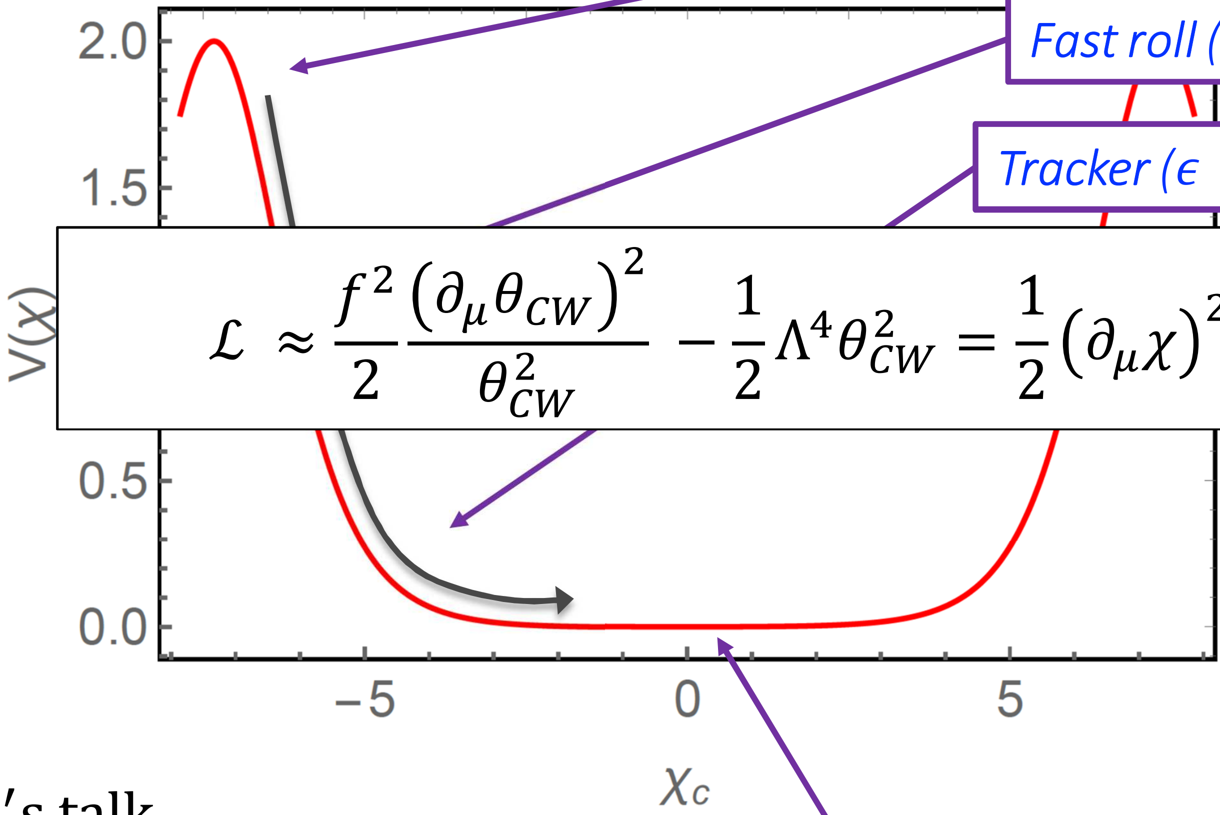
[Bae, Kost, CSS 1811.10655]

The Journey with the rolling axion (in the canonical field basis)



$$Z(\theta_{CW}) \sim 1/(1+\epsilon^2-\cos\theta_{CW})$$

The Journey with the rolling axion (in the canonical field basis) [Bae, Kost, CSS 1811.10655]



Slow roll $(\theta \approx \theta_{ini},\ Z? \ O(1))$

Fast roll $(\Delta\theta ?\ O(1),\ \ \Delta Z \gg 1)$

Tracker $(\epsilon \ll \theta \ll 1, Z \approx 1/\theta^2)$

$$\mathcal{L} \approx \frac{f^2}{2}\frac{(\partial_\mu\theta_{CW})^2}{\theta_{CW}^2} - \frac{1}{2}\Lambda^4\theta_{CW}^2 = \frac{1}{2}(\partial_\mu\chi)^2 - \frac{\epsilon^2\Lambda^4}{2}e^{2|\chi|/f}$$

See Jeff′s talk

Coherent oscillation $(\theta \ll \epsilon,\ Z \approx 1/\epsilon^2)$

$$\mathcal{L} \approx \frac{f^2}{2}\frac{(\partial_\mu\theta_{CW})^2}{\epsilon^2} - \frac{1}{2}\Lambda^4\theta_{CW}^2 = \frac{1}{2}(\partial_\mu\chi)^2 - \frac{\epsilon^2\Lambda^4}{2f^2}\chi^2$$

Conclusions

- *Discrete clockwork has very special features*

- *Natural extension to the continuum limit via 5D theory construction shows similar feature (spectrum and couplings relative to different KK modes). However the global structure is quite different*

- *Continuum clockwork axion is an example to provide a nontrivial wave-function*

- *Inflation, baryogenesis and dark matter could be related with rolling axion with deformed potential by CCW mechanism*