Inflation through hidden Yukawa couplings in the extra dimension

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Based on work (in progress) with Y. Tatsuta (Waseda).

What we want to focus on

An inflation model $\leftrightarrow$ Symmetries

Planck unit in this talk

$$M_{\mathsf{Pl}} \simeq 2.4 \times 10^{18}\ \mathsf{GeV} \equiv 1.$$

Contents

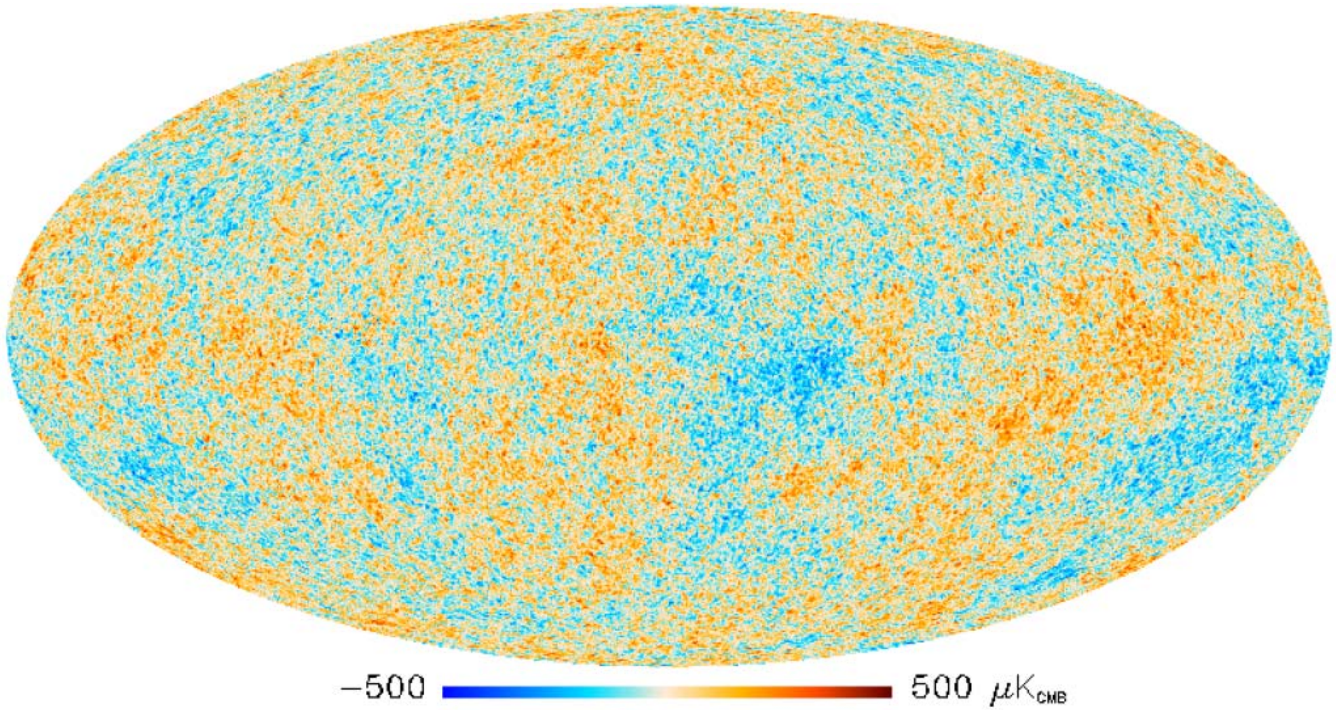
1. Introduction: Review of inflation

Cosmic Microwave Background (CMB)

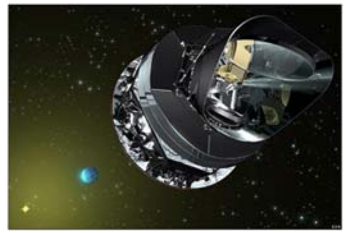
[Planck collaborations]

CMB fluctuation: $\Delta T/T \sim 10^{-5}$

where $T \sim 2.7$ K.

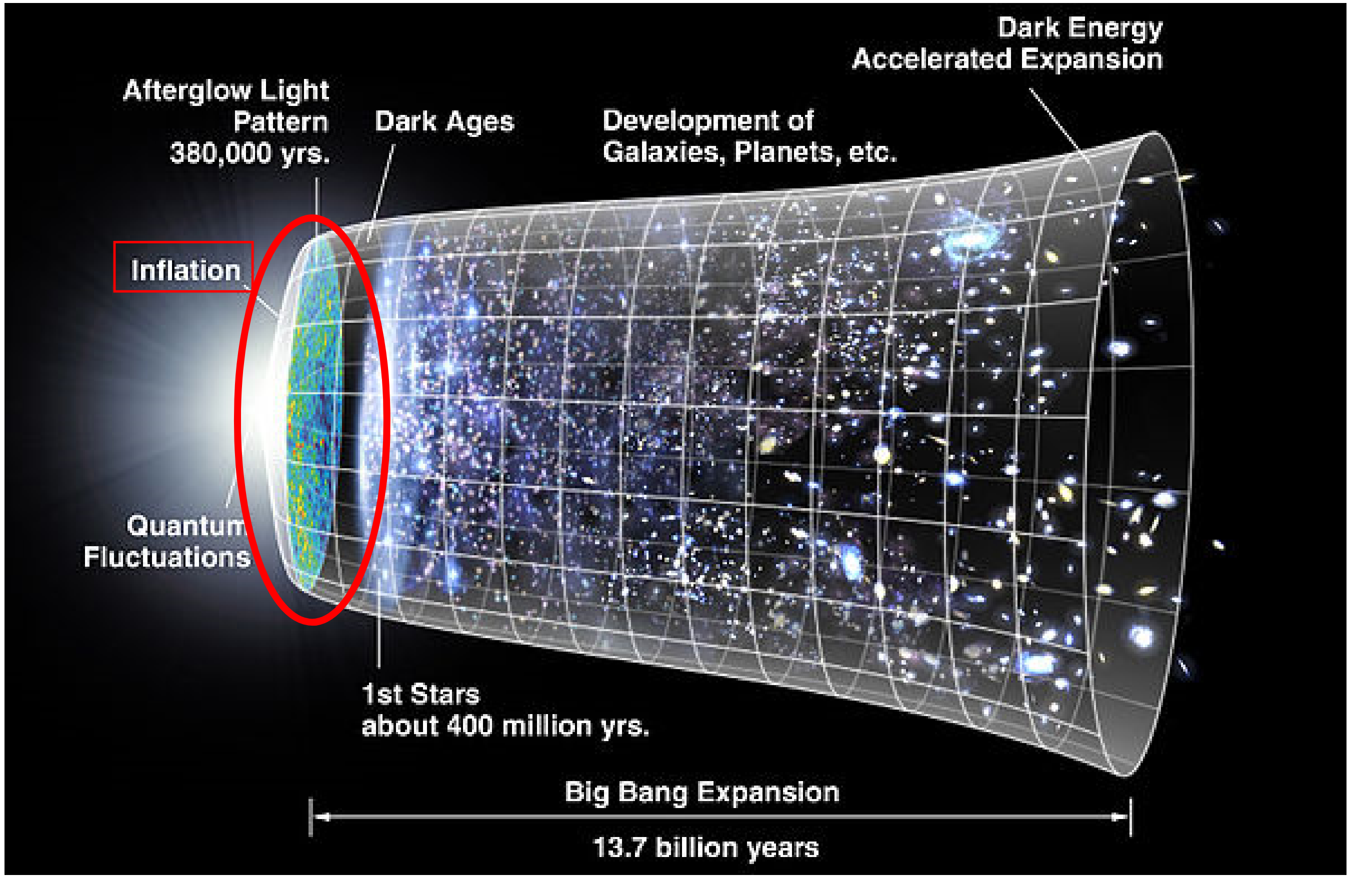


Planck satellite



Inflation: origin of CMB

Accelerating expansion of the universe



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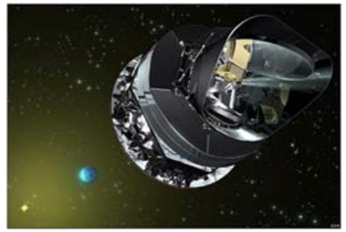
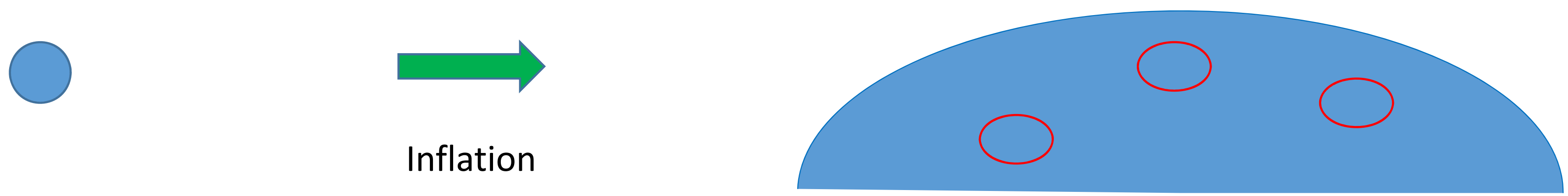


Why inflation?

- Generating <u>density fluctuations</u> : $\Delta T/T \sim 10^{-5}$

  = seeds of galaxies (= those of us)

- Solutions for fine-tuning problems by the expansion
  - Flatness problem: $\Omega_{curvature} << 1$
  - Horizon problem : $T \sim 2.7K$ in CMB all over the sky



(Flat) Freedman-Robertson-Walker metric

$$ds^2 = -dt^2 + a(t)^2 \delta_{ij} dx^i dx^j$$

a(t): Scale factor

$H = \frac{\dot{a}}{a}$: Hubble parameter

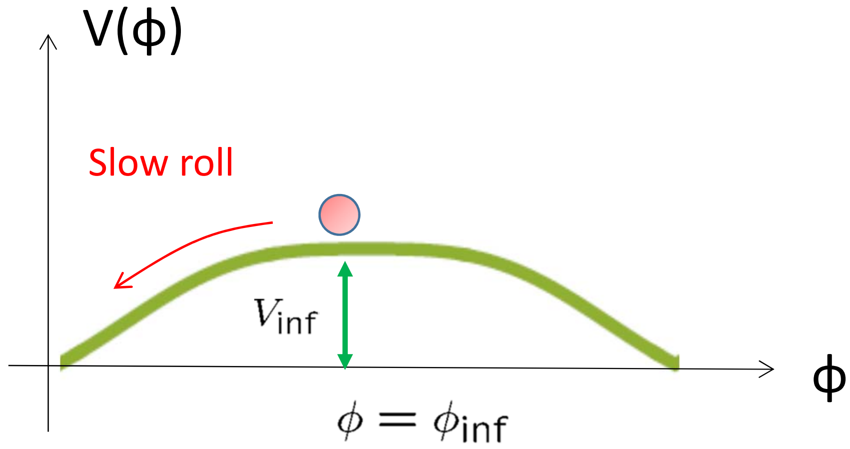
Inflation driven by an inflaton ϕ

- EOM

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

- Friedman Eq.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V\right)$$



- Slow-roll conditions

$$\frac{\dot{H}}{H^2} \ll 1, \quad \ddot{\phi} \ll H\dot{\phi} \quad \Longleftrightarrow \quad \epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \quad \eta = \frac{V''}{V} \ll 1$$

Inflation!!

$$a \propto e^{Ht}$$

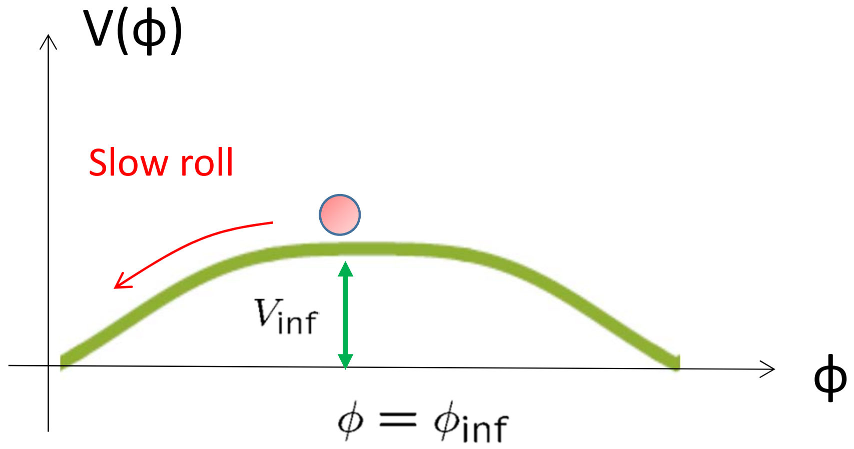
Inflation driven by an inflaton ϕ

- EOM

$$\dot{\phi} \simeq -\frac{V'}{3H}$$

- Friedman Eq.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \simeq \frac{1}{3}V$$



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Inflation!!

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Metric perturbation

- Perturbations to FRW metric:

$$ds^2 = -dt^2 + a(t)^2 e^{2\zeta(t,\vec{x})}[\delta_{ij} + h_{ij}(t,\vec{x})]dx^i dx^j$$

ζ: Scalar perturbation from inflaton

h: Tensor perturbation

(gravitational wave itself from inflation energy V_{inf})

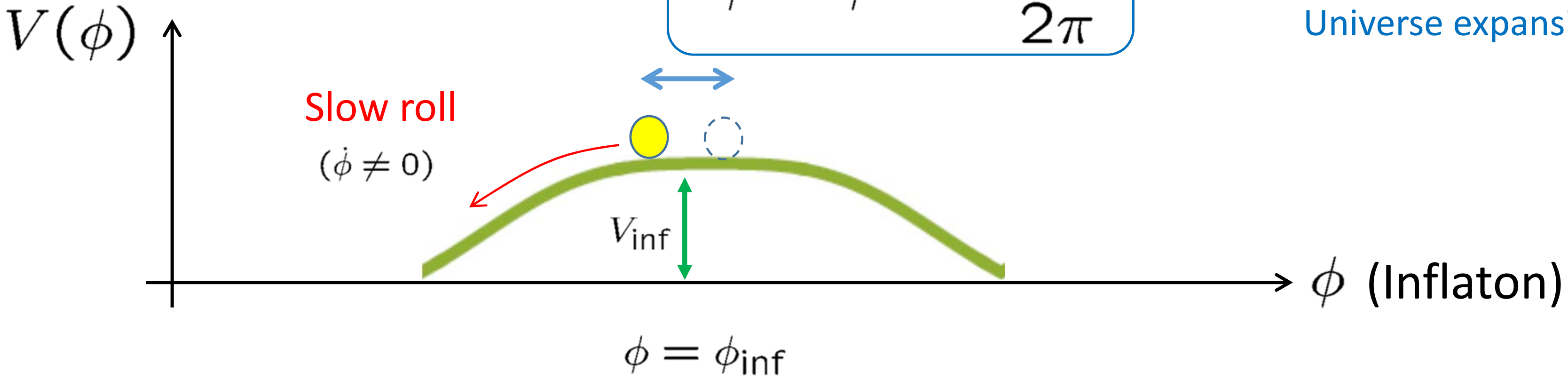
→ B-mode polarization in CMB photon

ζ = Inflaton's quantum fluctuation δϕ

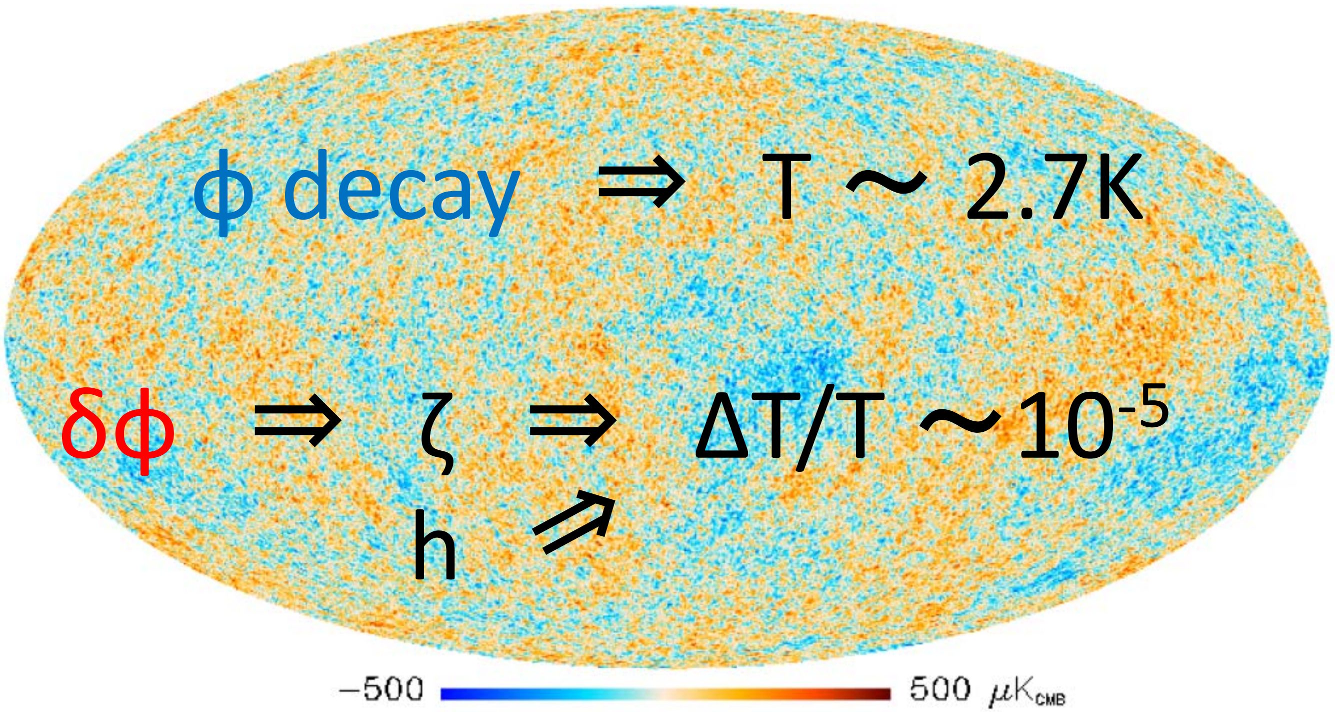
$$\zeta \sim \frac{\delta\rho_\phi}{\rho_\phi} \sim H\delta t \sim \frac{H}{\dot\phi}\delta\phi \sim \frac{V^{3/2}}{V'}$$

$$\delta\phi \sim \dot\phi\delta t \sim \frac{H}{2\pi}$$

Amplitude expanded by
Universe expansion



CMB fluctuation generated by inflaton



ϕ decay $\Rightarrow$ $T \sim 2.7\mathrm{K}$

$\delta\phi \Rightarrow \zeta \Rightarrow \Delta T/T \sim 10^{-5}$

$h \nearrow$ (⇗ toward $\Delta T/T$)

Theory and observations

[Planck collaboration]

$$P_\zeta \simeq \frac{2V}{3\pi^2 r}\left(\frac{k}{k_0}\right)^{n_s-1}$$

$$n_s \simeq 1 - 3\left(\frac{V'}{V}\right)^2 + 2\left(\frac{V''}{V}\right)$$

$$r \simeq 8\left(\frac{V'}{V}\right)^2$$

$$P_\zeta^{\text{obs}}(k = k_0) \simeq 2.5 \times 10^{-9}$$

$$k_0 = 0.002\text{Mpc}^{-1}$$

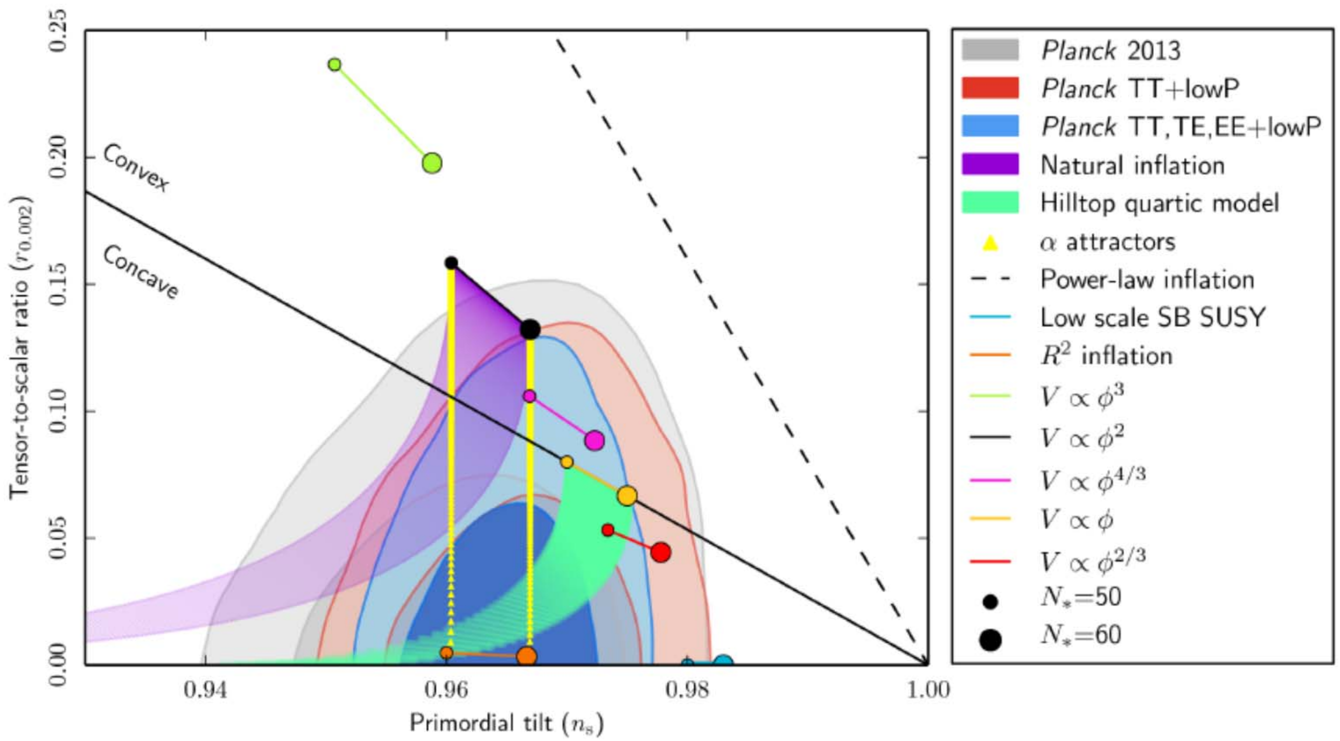
P_ζ : Power spectrum = $(\Delta T/T)^2$ from scalar, $P_\zeta \simeq (\Delta T/T)^2_{\text{scalar}}$

n_s: Spectral index = scale dependence of P_ζ

r: Tensor to scalar ratio = $(\Delta T/T)^2$ ratio of gravitational wave to scalar, $r \simeq \frac{(\Delta T/T)^2_{\text{tensor}}}{(\Delta T/T)^2_{\text{scalar}}}$

(n_s, r)-contour: focus on small r

[Planck 2015 collaborations]



$$n_s = 0.968 \pm 0.006$$

$$r < 0.11 \ (95\% \ \text{CL})$$

(n_s, r)-contour: focus on small r

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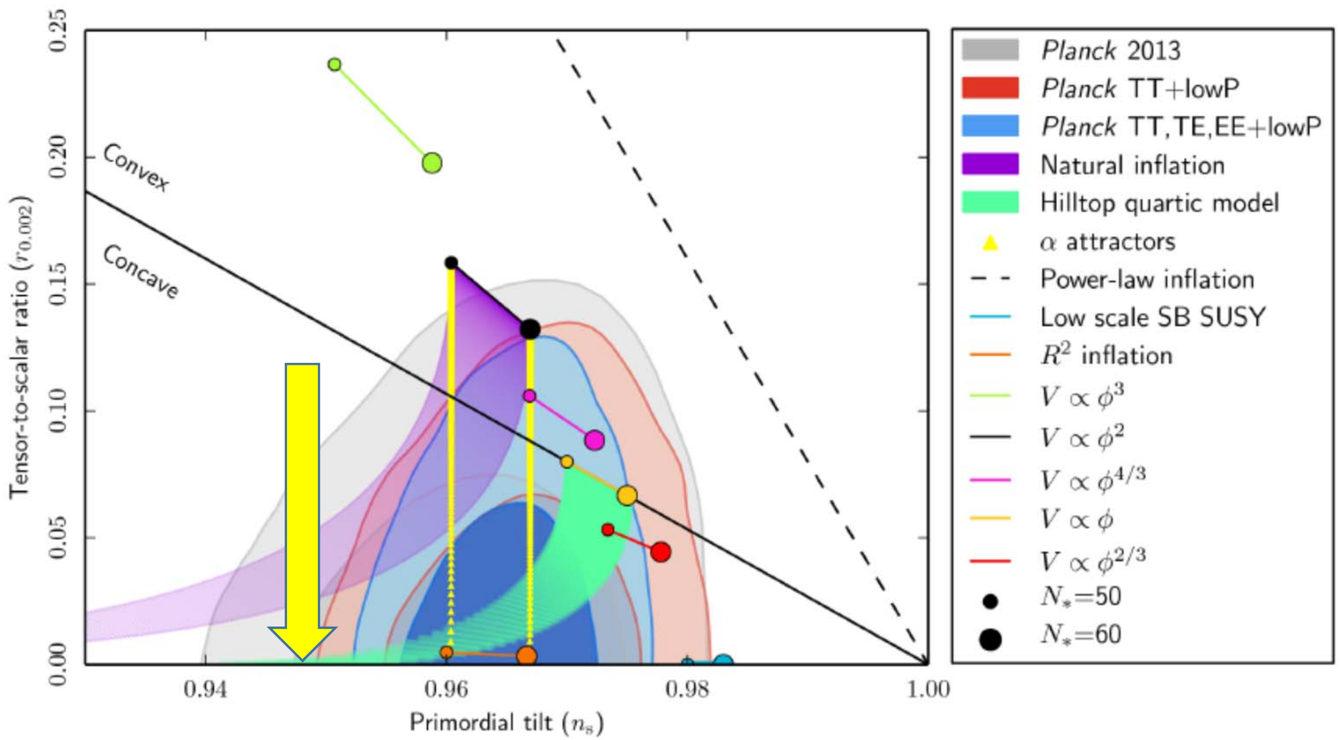


$$n_s = 0.968 \pm 0.006$$

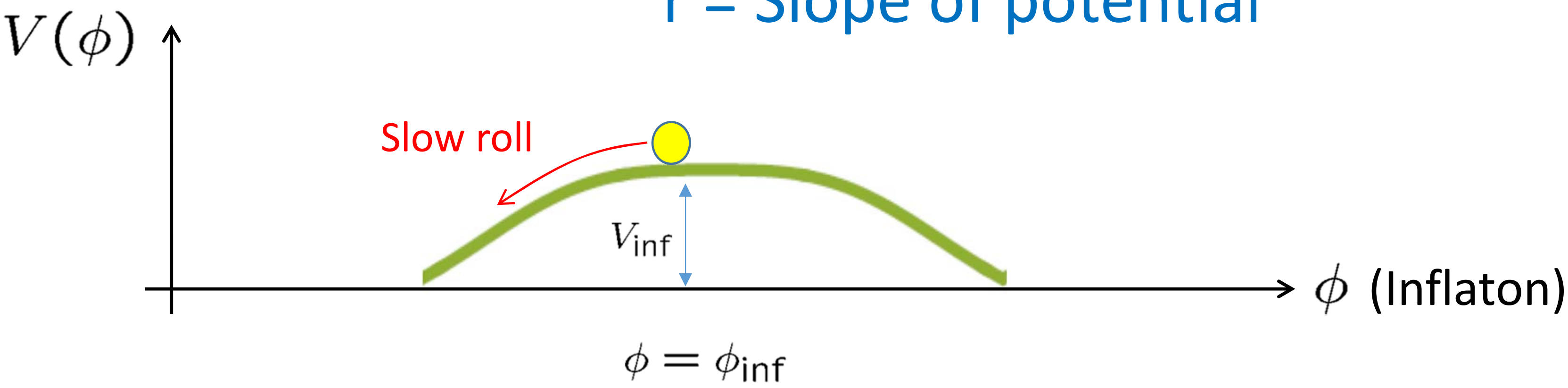
$$r < 0.11 \text{ (95\% CL)}$$

Small r can be favored.

2. Flat inflaton potential & symmetry

Inflaton potential: very small slope and curvature

r = Slope of potential



$$n_s = 1 - 3\left(\frac{V'}{V}\right)^2\Bigg|_{\phi=\phi_{\text{inf}}} + 2\left(\frac{V''}{V}\right)\Bigg|_{\phi=\phi_{\text{inf}}}, \qquad r = 8\left(\frac{V'}{V}\right)^2\Bigg|_{\phi=\phi_{\text{inf}}}.$$

Observations: ∧∧ 1 ∧∧ 1 ∧∧ 1

Control of potential flatness by shift symmetry

- Shift symmetry $\phi \to \phi + \text{const.}$ for a flat inflaton potential:

$$\boxed{V(\phi) = 0} \quad \text{if the symmetry is exact.}$$

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  - Chaotic (monodromy) inflation: softly-broken only by a single scale μ

[Linde]; [Silverstein, Westphal]; [McAllister, Silverstein, Westphal]

$$V(\phi) = \mu^{4-n}\phi^n.$$

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$$V(\phi) = \mu^{4-n}\phi^n.$$

  - Natural inflation: broken but a discrete shift symmetry below Λ [Freese, Frieman, Olinto]

$$\phi \to \phi + 2\pi f; \quad V(\phi) = \Lambda^4 \cos\left(\frac{\phi}{f}\right).$$

Natural inflation & discrete shift symmetry

Natural inflation: well-controlled by a discrete shift symmetry

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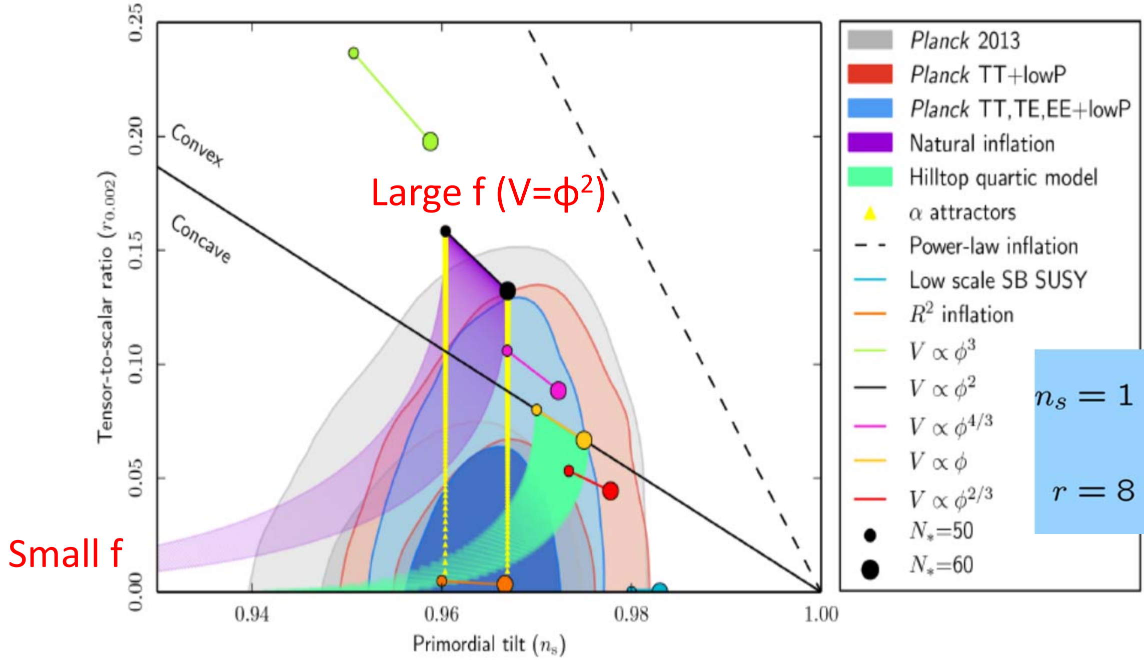
$$\phi \to \phi + 2\pi f; \quad V = \Lambda^4 \cos\left(\frac{\phi}{f}\right).$$

$$\left(\frac{V'}{V}\right)^2 \sim \frac{V''}{V} \sim \frac{1}{f^2} \ll 1.$$

Remark: $\dfrac{V^3}{V'^2} = \text{fixed}$

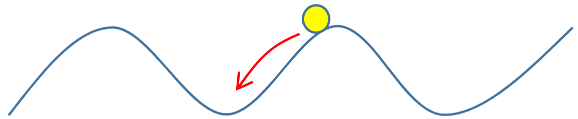


$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2;$$

$$r = 8\left(\frac{V'}{V}\right)^2.$$

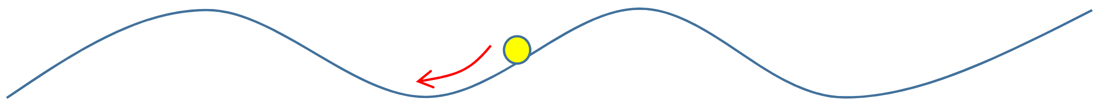
Natural inflation and f-dependence

- f→small: ϕ_{inf} is near hilltop for a long slow-roll:



$$\phi_{\text{inf}} \sim \pi f \to \epsilon \sim 0 \ll |\eta|.$$

- f → large: Chaotic inflation



$$V = \frac{m^2}{2}\phi^2, \quad r = 0.16\left(\frac{50}{N}\right), \quad \epsilon = \eta = \frac{1}{2N}$$

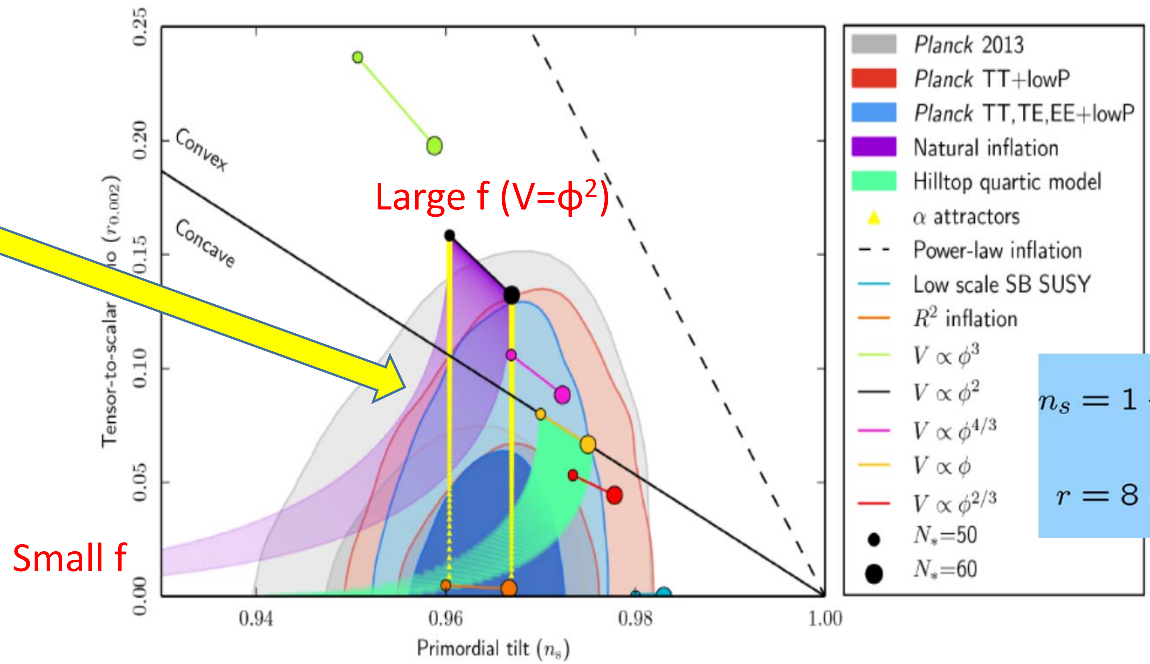
$$N = \log(a_f/a_{\text{inf}}) = \int_{t_{\text{inf}}}^{t_f} H dt \simeq \int_{\phi_f}^{\phi_{\text{inf}}} \frac{V}{V'} d\phi$$: e-folding

Natural inflation & discrete shift symmetry

Natural inflation: well-controlled by a discrete shift symmetry

$$\phi \to \phi + 2\pi f; \quad V = \Lambda^4 \cos\left(\frac{\phi}{f}\right).$$

- But, want a smaller r.
- f > 5 M_{Pl} :
  Weak gravity conjecture?

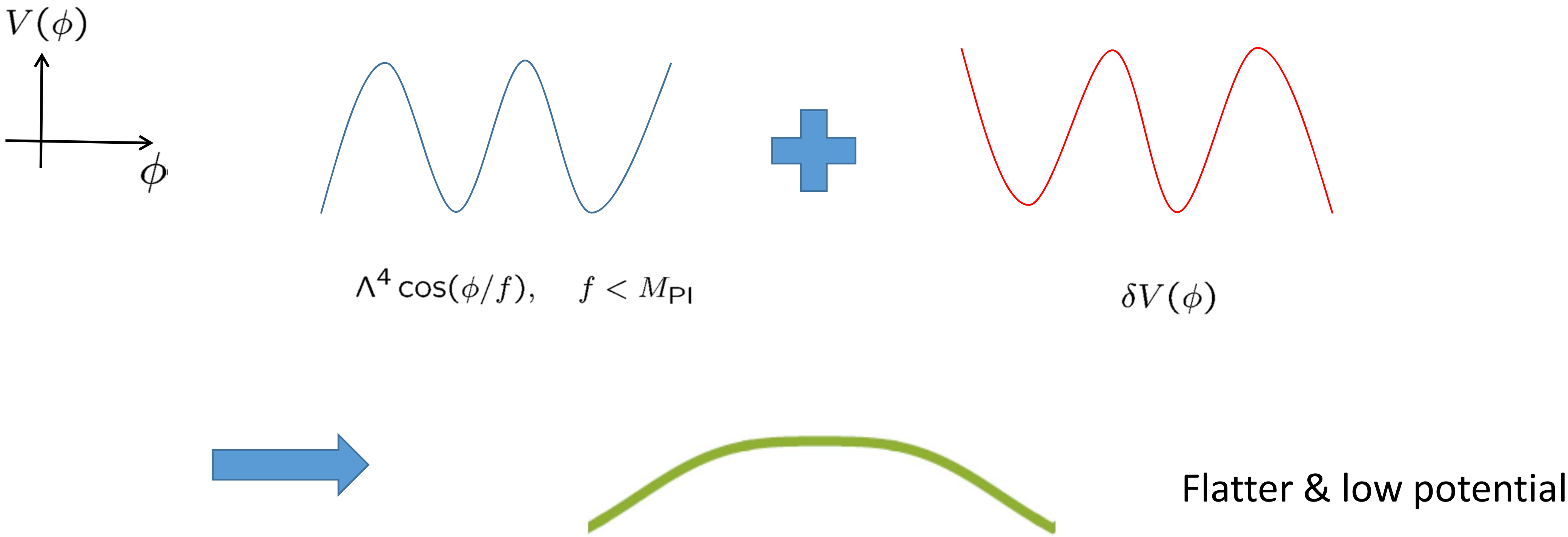


$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2;$$

$$r = 8\left(\frac{V'}{V}\right)^2.$$

Natural inflation for a small r?

- An idea: a cancellation against a big cosine function in potential



Multi-natural inflation: a bottom-up approach

[Czerny, Takahashi]; [Czerny, TH, Takahashi]; [TH, Takahashi]; [Kobayashi, Takahashi];[Czerny, Kobayashi, Takahashi]

- Modification for it: Adding cosine function(s) to natural inflation

$$V(\phi) = V_0 - \Lambda^4 \left[\cos\left(\frac{\phi}{f_1}\right) + B \cos\left(\frac{\phi}{f_2} + \theta\right) \right].$$

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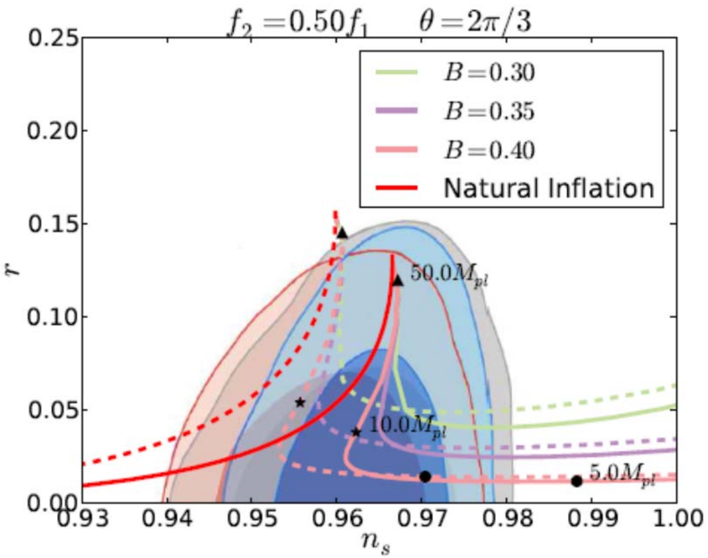


- r < 0.11
- f_1, $f_2 < M_{Pl}$ via a tuning: $B \sim \left(f_2/f_1\right)^2, \ \theta \sim -\pi(f_1/f_2)$

  → Good against weak gravity conjecture.

Cf. Possible to have a modulation for $f_1 >> f_2$ & $B << 1$ (Running n_s).

A UV completion and compactification

- Q. How is this model controlled? :
    - What are discrete symmetries for control?
    - What are their origins?

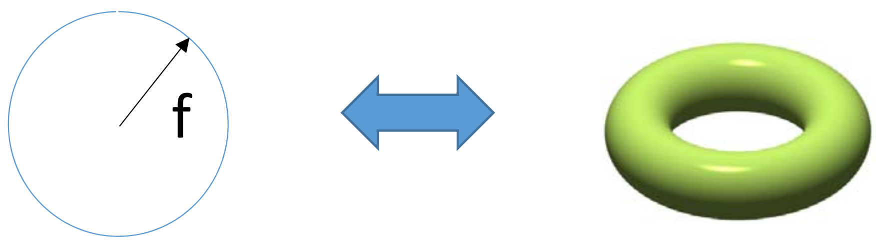
- A. Discrete symmetry from compactification of extra dimension

  ∵ Discreteness = Compactness

$$\phi \equiv \phi + 2\pi f$$

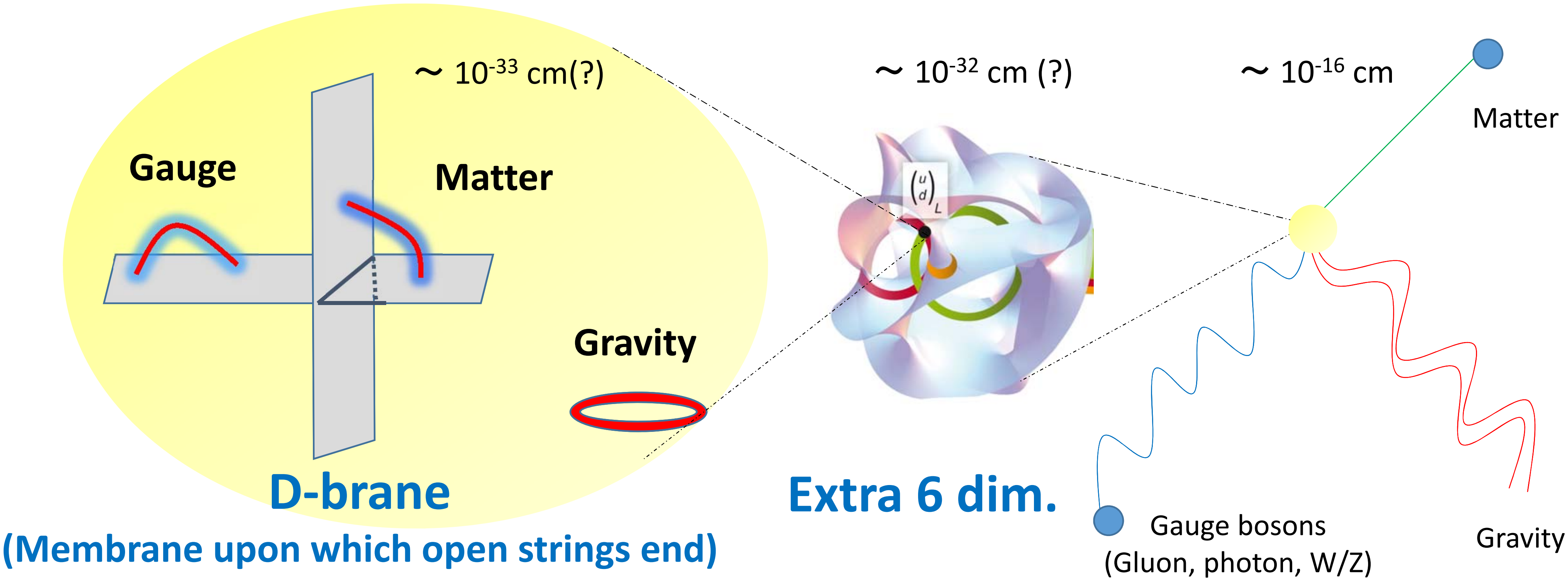
ϕ-space
on a circle

Compactification of extra dim.
relevant to ϕ-periodicity



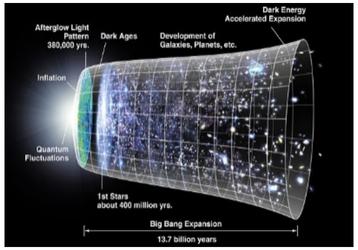
3. A UV completion in the string theory

String theory as the origin of forces & matter



String theory compactification on torus

- Let 10D = 4D spacetime + 2d torus (T^2) + X_4 (something)



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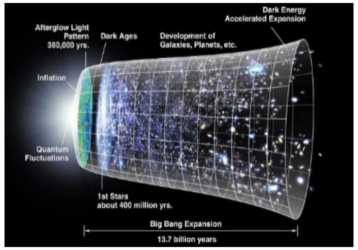

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- Consider intersecting D6-branes in IIA model; just one direction of D6 on T^2

  (Similarly, possible to consider magnetized D-branes in IIB model)

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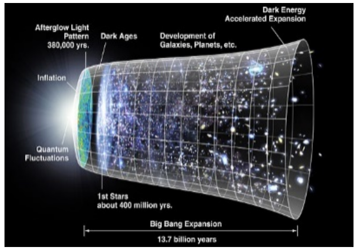

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- Consider intersecting D6-branes in IIA model; just one direction of D6 on T^2

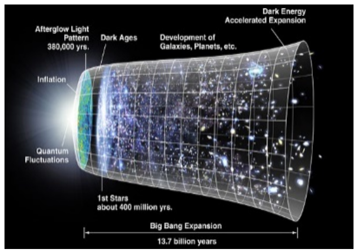
  (Similarly, possible to consider magnetized D-branes in IIB model)

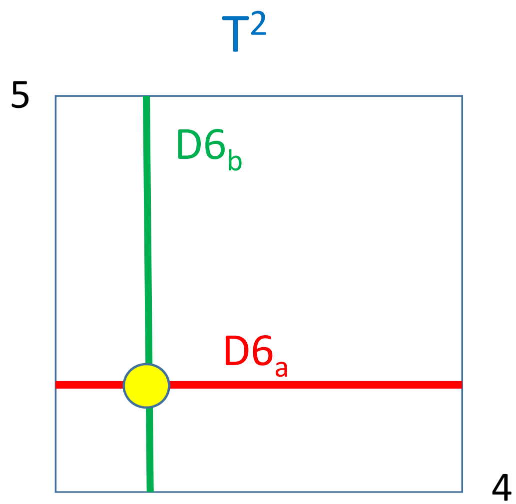
- Inflation energy: SUSY-breaking by Izawa-Yanagida-Intriligator-Thomas (IYIT)

$$W = y_{ijk} X^i Y^j \Phi^k \quad \rightarrow \quad y_{ijk} \mathcal{M}^{ij} \Phi^k + Z\left[\mathrm{Pf}(\mathcal{M}) - \Lambda^4_{SU(2)}\right]$$

An example of D6-brane configuration

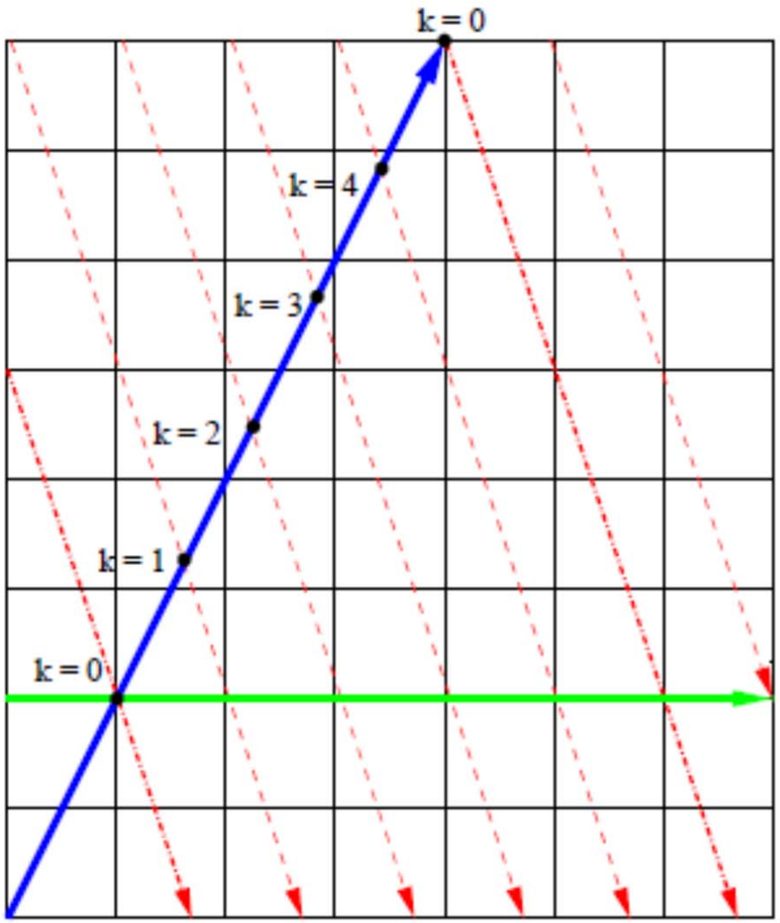
Spacetime	0	1	2	3	4	5	6	7	8	9
$D6_a$	○	○	○	○	○	×	○	×	○	×
$D6_b$	○	○	○	○	×	○	×	○	○	×

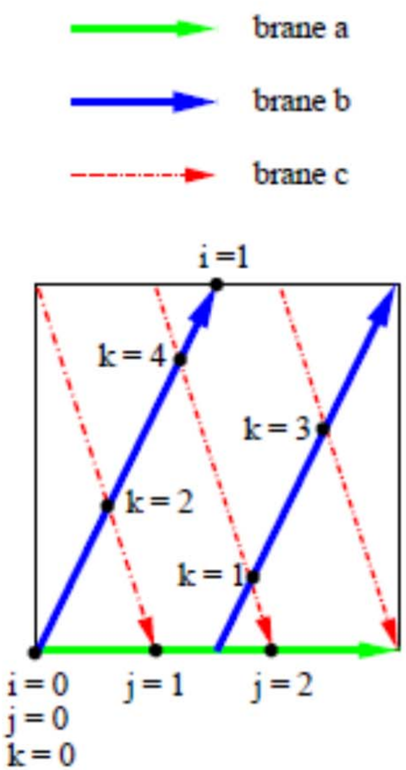




An example of D6-branes on T^2

[Cremades-Ibanez-Marhesano]





- Branes (gauge theories) = lines
- Matter = Intersection points
- Yukawa coupling = Sum of triangles (Winding modes)

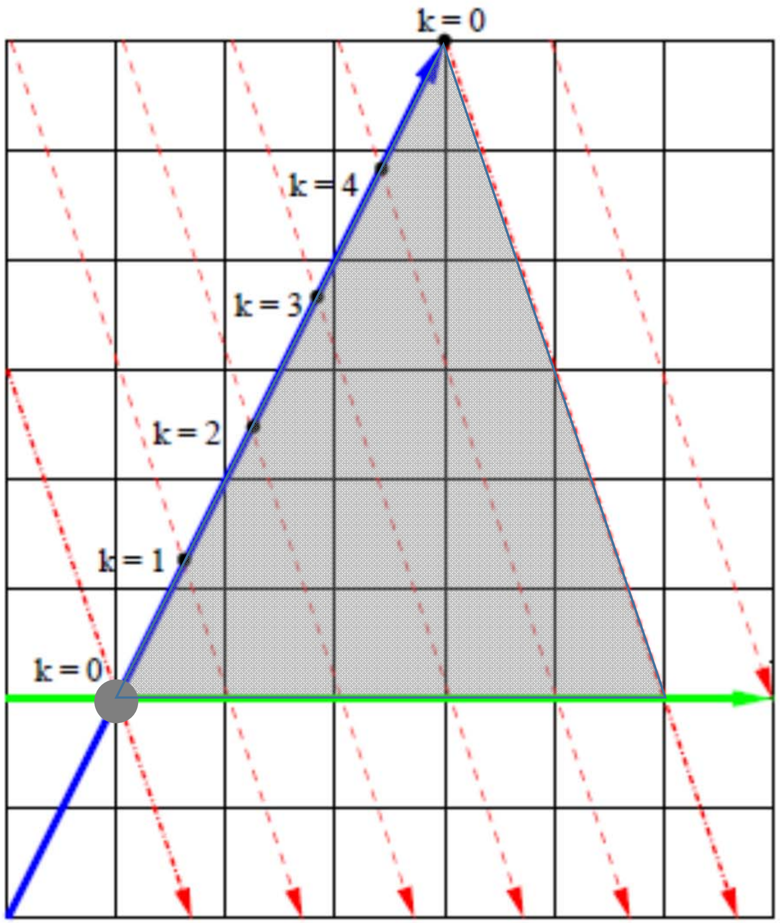
#(a▪b) = 2 (i = 0,1)

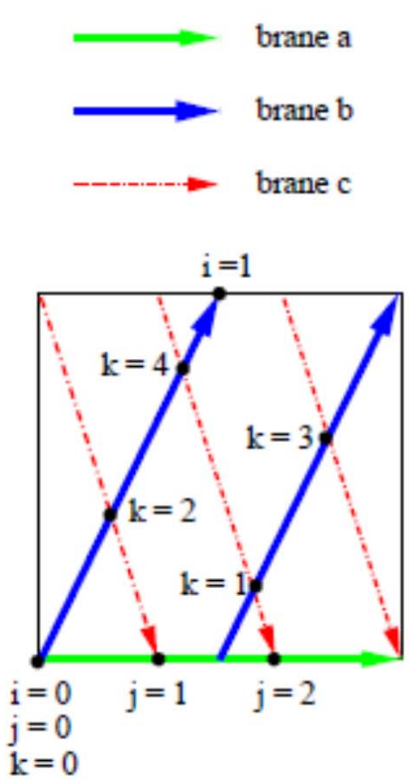
#(c▪a) = 3 (j= 0,1,2)

#(b▪c) = 5 (k =0,1,2,3,4)

Example: Parts of D6-branes on T^2

[Cremades-Ibanez-Marhesano]





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(Winding modes)

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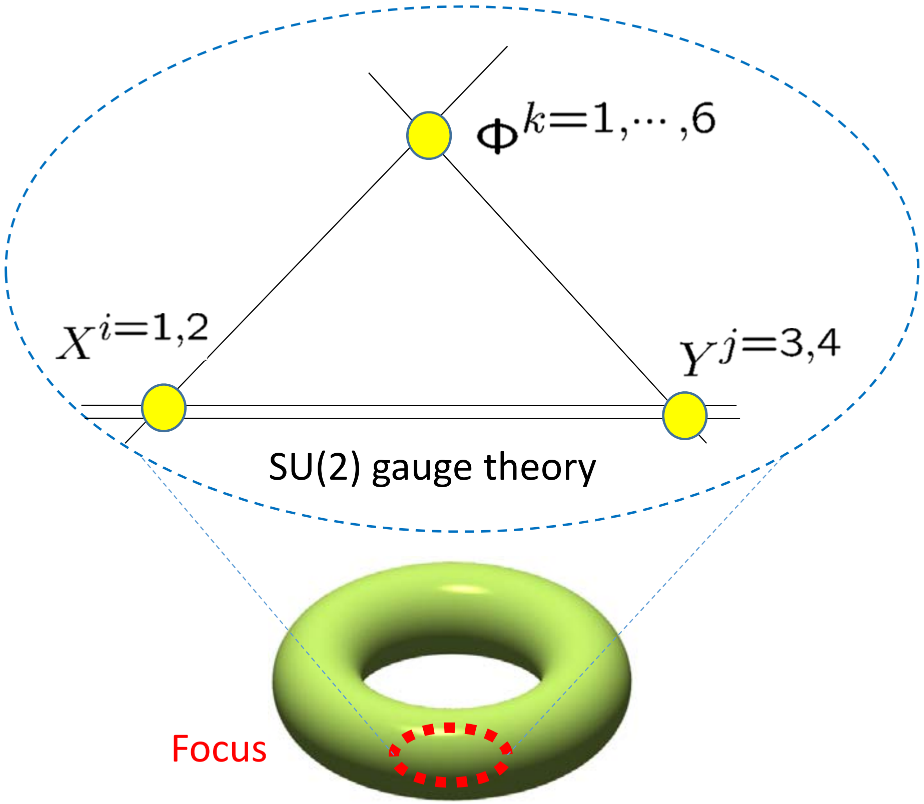
Intersecting D-branes on 2D torus

- Discrete symmetries from “Torus property × D-brane configuration”:



$$W = y_{ijk} X^i Y^j \Phi^k$$

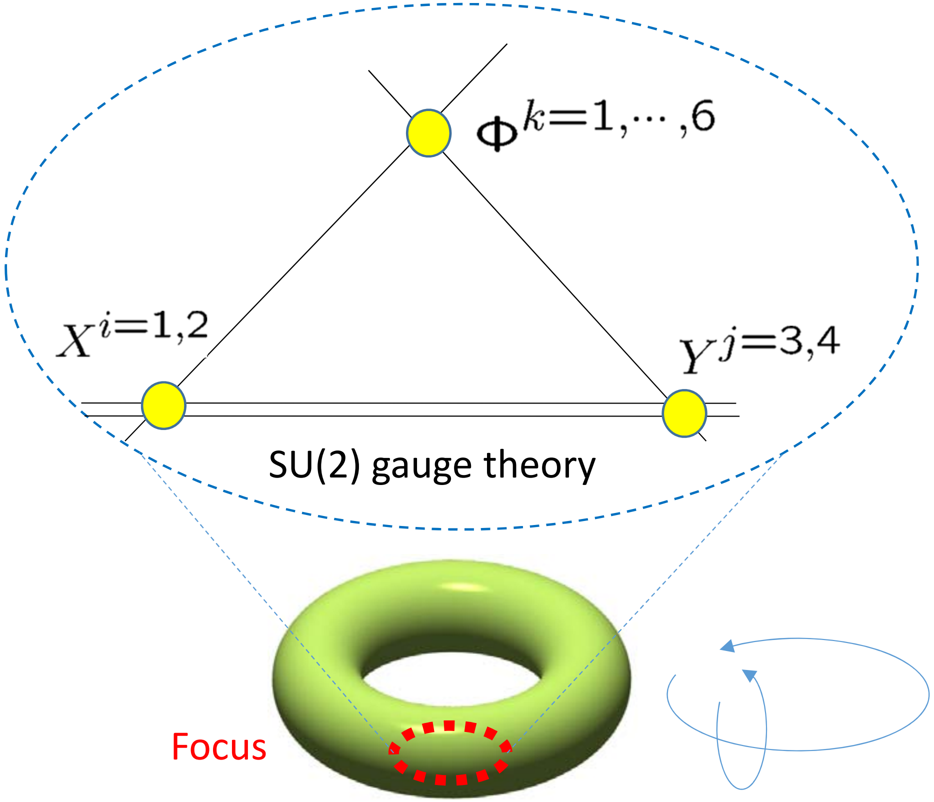
$SL(2,\mathbb{Z}) \times$ (periodicity) $\times (\mathbb{Z}_2)^2$

relevant to control y_{ijk} .

(preliminary result)

Intersecting D-branes on 2D torus

- Torus property × D-brane configuration ∼ SL(2,Z) × periodicity × $(Z_2)^2$



$$W = y_{ijk} X^i Y^j \Phi^k$$

$$y_{ijk} \sim \quad \vartheta \begin{bmatrix} a \\ b \end{bmatrix} (\nu, \tau) = \sum_{l=-\infty}^{\infty} e^{\pi i (a+l)^2 \tau} e^{2\pi i (a+l)(\nu+b)}$$

$$\tau = (B + iA)/\alpha'$$

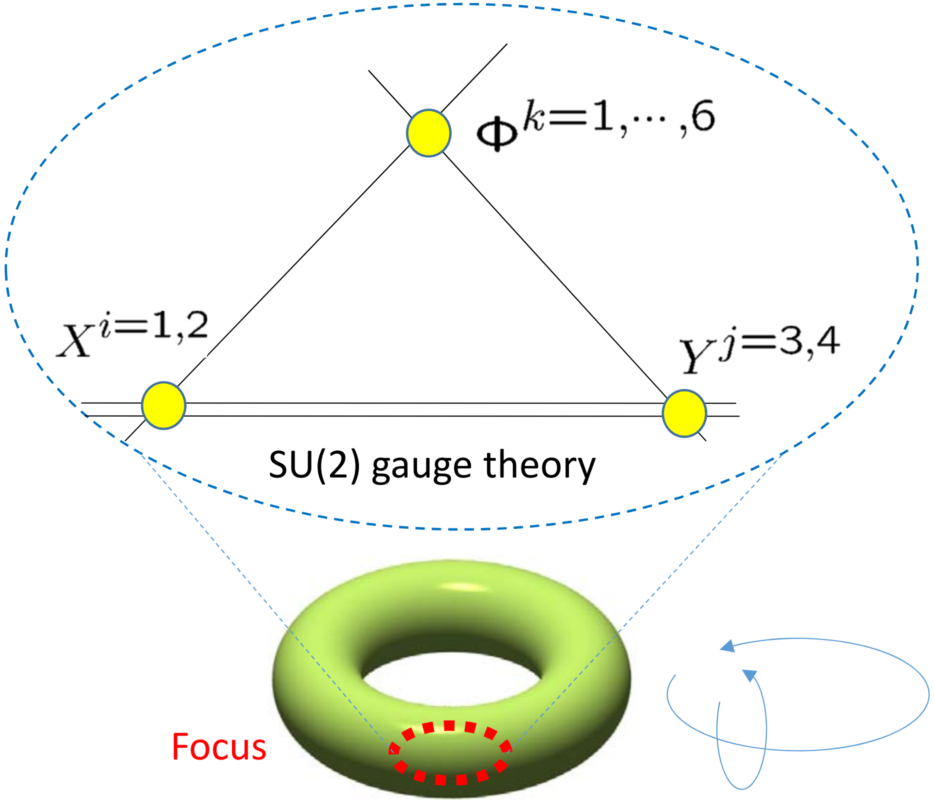
B: NS B-field axion, A: torus area

ν + b: brane position moduli

a: brane intersection #-dependent number

Intersecting D-branes on 2D torus

- Torus property × D-brane configuration ∼ SL(2,Z) × periodicity × $(Z_2)^2$



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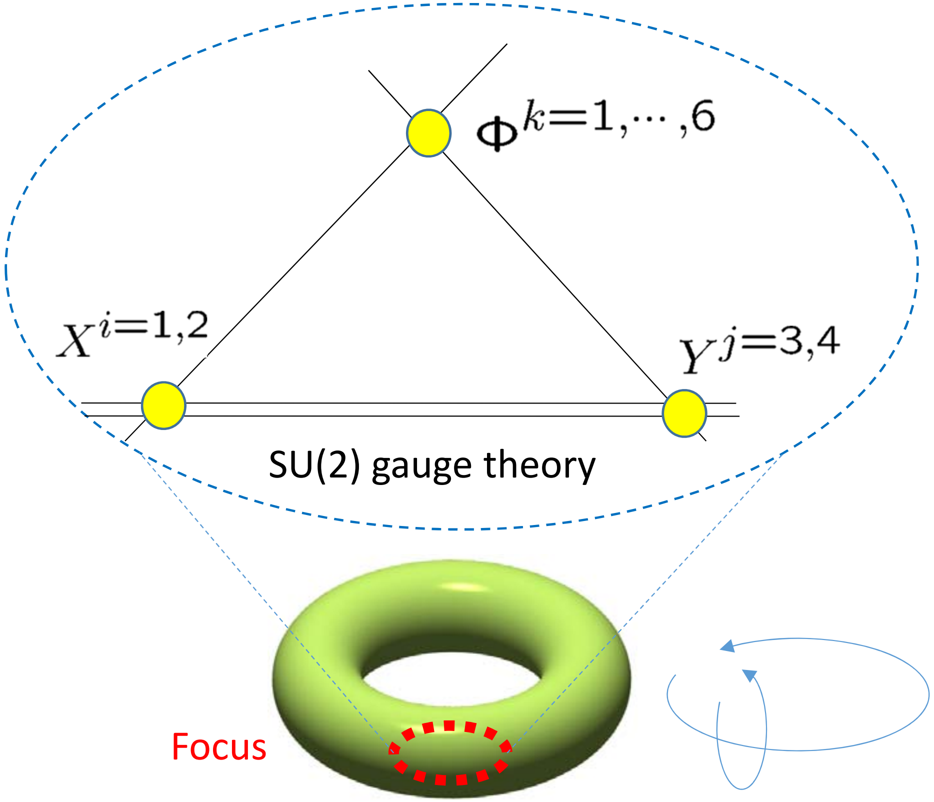
$$\tau = (B + iA)/\alpha'$$

- Periodicity : $\nu \to \nu + n + m\tau, \quad m, n \in \mathbb{Z}.$
- $SL(2,\mathbb{Z})$: $\tau \to \dfrac{a\tau + b}{c\tau + d}, \quad ad - bc = 1, \quad a, b, c, d \in \mathbb{Z}.$

(T-dual of complex structure on T^2)

Intersecting D-branes on 2D torus

- Torus property × D-brane configuration ∼ SL(2,Z) × periodicity × $(Z_2)^2$



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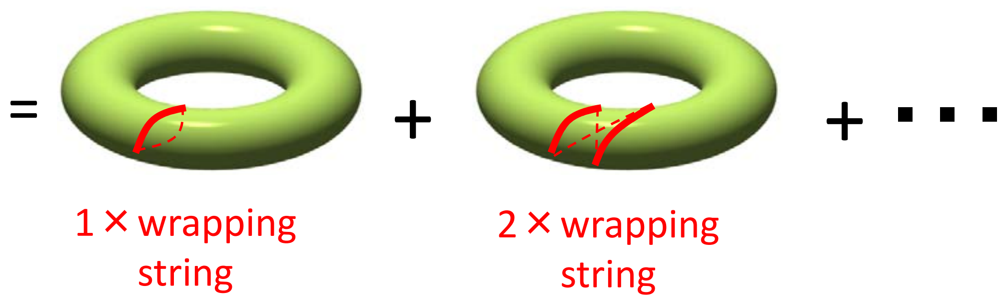
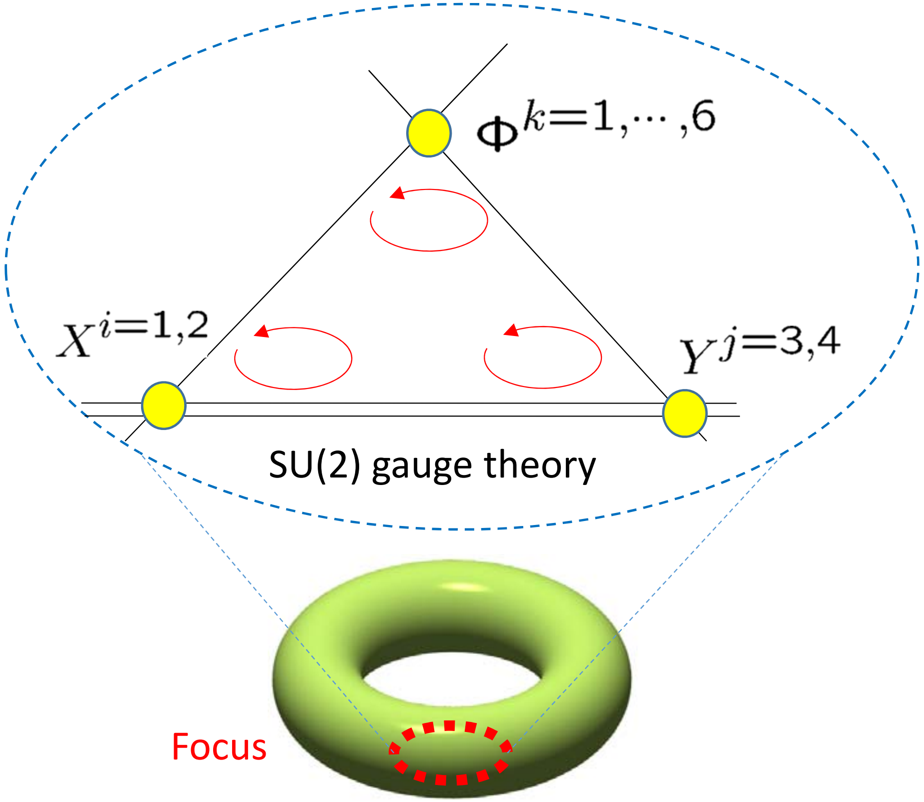


Intersecting D-branes on 2D torus

- Torus property × D-brane configuration ∼ SL(2,Z) × periodicity × $(Z_2)^2$



$$W = y_{ijk} X^i Y^j \Phi^k$$

$(\mathbb{Z}_2 \times \mathbb{Z}_2)$ invariant Yukawa coupling y_{ijk} :

1. $(X^i, Y^j, \Phi^k) \to (-X^i, -Y^j, \Phi^k)$
2. $\to (X^i, -Y^j, -\Phi^k)$

Low energy W & explicit form of Yukawas

- Low energy W in IYIT model:

$$W = y_{ijk}\mathcal{M}^{ij}\Phi^k$$

with taking $\mathrm{Pf}(\mathcal{M}) = -\mathcal{M}_{13}\mathcal{M}_{24} = \Lambda^4.$

$(|\mathcal{M}_{13}| = |\mathcal{M}_{24}|)$

$$y_{131} = y_{243} = \vartheta\begin{bmatrix}0\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{1}{2}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

$$y_{241} = y_{135} = \vartheta\begin{bmatrix}\frac{1}{3}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{5}{6}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

$$y_{142} = y_{236} = \vartheta\begin{bmatrix}\frac{5}{12}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{11}{12}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

$$y_{232} = y_{144} = \vartheta\begin{bmatrix}\frac{1}{12}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{7}{12}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

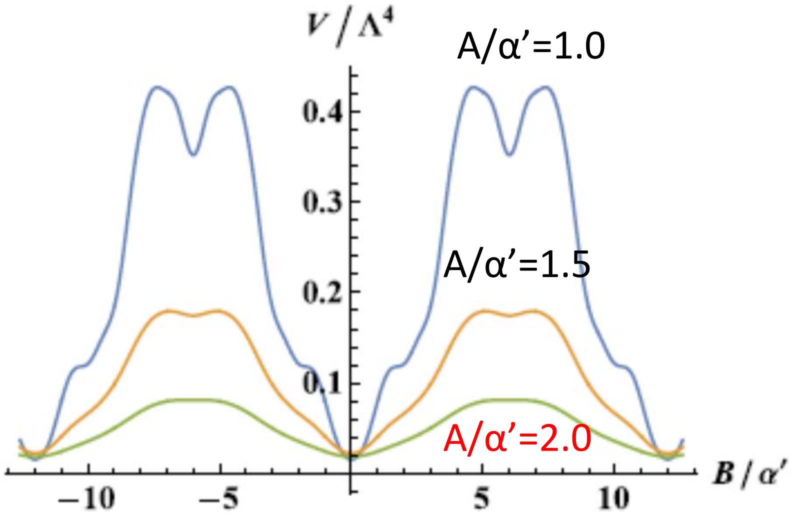
$$y_{133} = y_{245} = \vartheta\begin{bmatrix}\frac{1}{6}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{2}{3}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

$$y_{234} = y_{146} = \vartheta\begin{bmatrix}\frac{1}{4}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha') + \vartheta\begin{bmatrix}\frac{3}{4}\\0\end{bmatrix}(\varphi, 6(B+iA)/\alpha'),$$

Scalar potential

$$\frac{V}{\Lambda^4} \simeq \left(|y_{131}|^2 + |y_{133}|^2 + |y_{135}|^2 - 2\mathrm{Re}\left(y_{131}^* y_{133} + y_{133}^* y_{135} + y_{135}^* y_{131}\right)\right)$$
$$= 4\left(-e^{-\frac{3}{2}\pi A/\alpha'}\cos\left(\frac{3}{2}\pi\phi/f\right) + e^{-\frac{1}{6}\pi A/\alpha'}\cos\left(\frac{1}{6}\pi\phi/f\right) - e^{-\frac{2}{3}\pi A/\alpha'}\cos\left(\frac{2}{3}\pi\phi/f\right)\right)$$

$$V(\phi) \sim C - \lambda\phi^4 \quad \text{for } A/\alpha' \simeq 2.$$



- Inflaton ϕ:

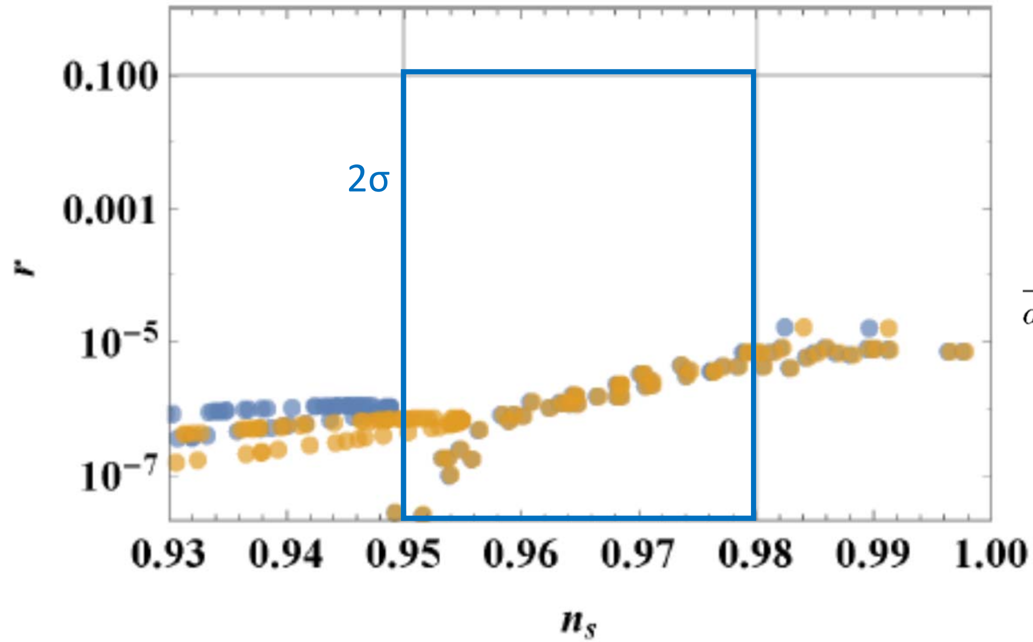
$$\frac{\phi}{f} \equiv 6 - \frac{B}{\alpha'}$$

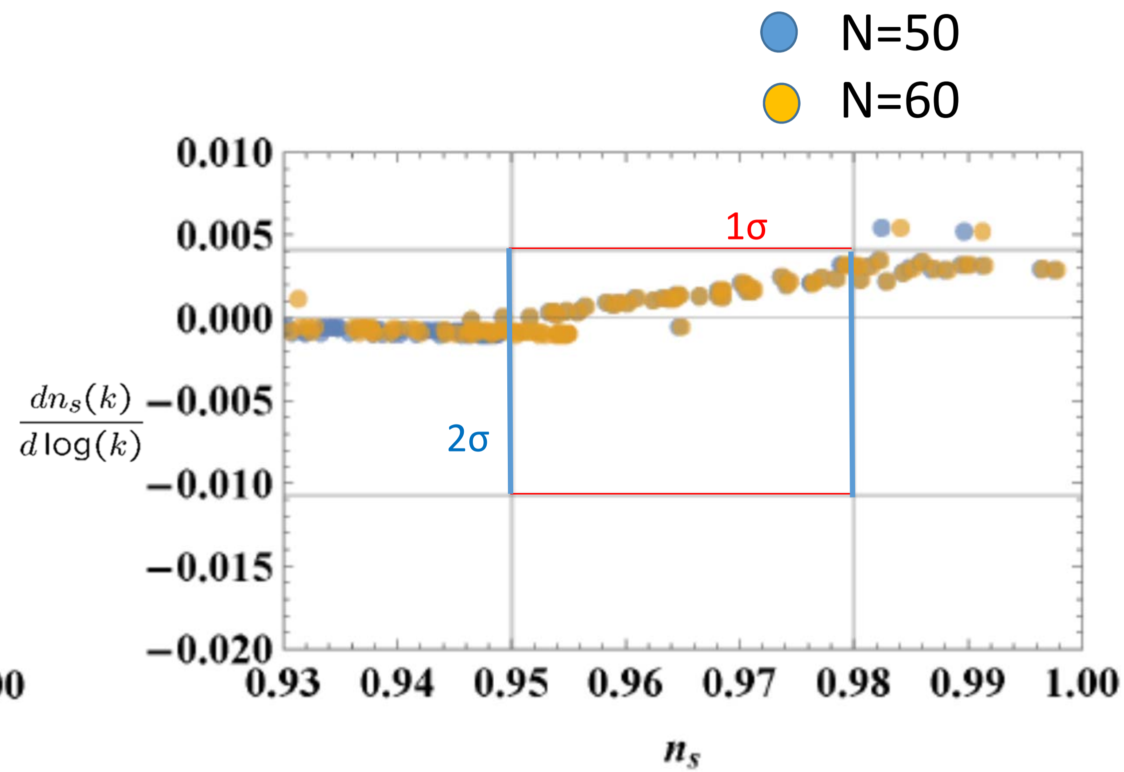
- Decay constant f:

$$\mathcal{L}_{\text{kin}} \equiv \frac{f^2}{2}[\partial(B/\alpha')]^2 \equiv \frac{1}{2}(\partial\phi)^2$$

Results for string inspired case of $f = \frac{\alpha'}{\sqrt{2}A} M_{\rm Pl}$

Plots for $1.65 \leq A/\alpha' \leq 1.95$.





$A/\alpha' \sim 1.81$; $f \sim 0.39 M_{\rm Pl}$ for Planck results

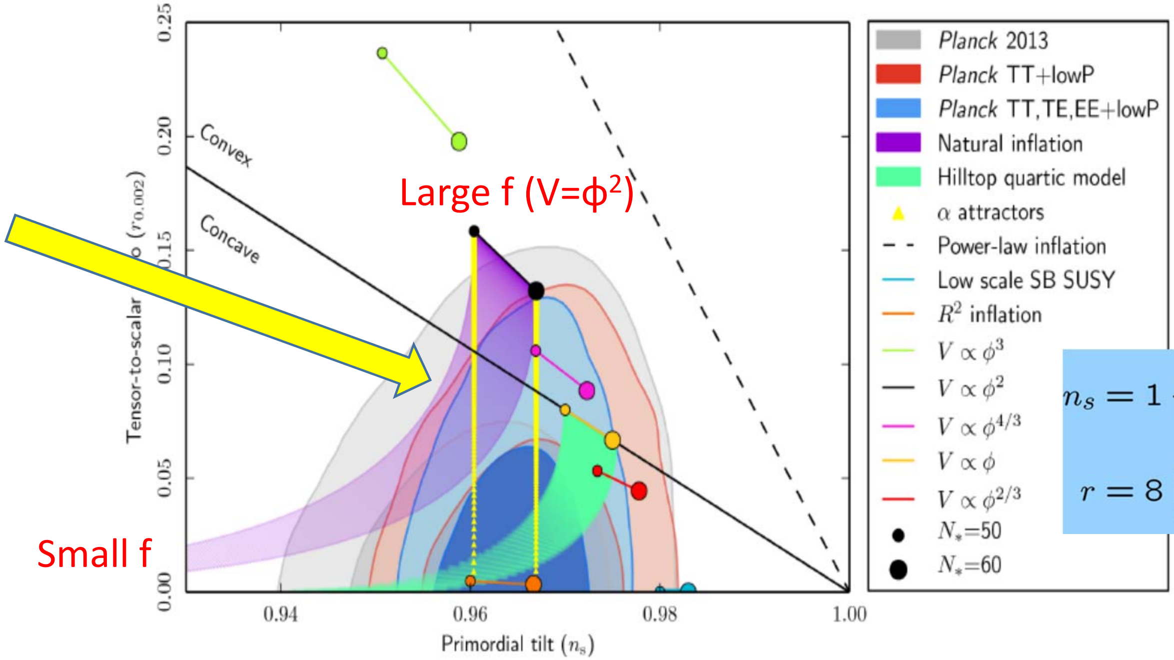
4. Review of other attempts for natural inflation

Natural inflation & discrete shift symmetry

Natural inflation: well-controlled by a discrete shift symmetry

$$\phi \to \phi + 2\pi f; \quad V = \Lambda^4 \cos\left(\frac{\phi}{f}\right).$$

- $f > 5\ M_{Pl}$:
  Weak gravity conjecture?



$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2;$$

$$r = 8\left(\frac{V'}{V}\right)^2.$$

Aligned natural inflation for $f > M_{Pl}$

- Two axions: $\phi_1 \to \phi_1 + 2\pi f_1$, $\phi_2 \to \phi_2 + 2\pi f_2$ [Kim, Nilles, Peloso]

$$V = \Lambda_1^4 \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right) + \Lambda_2^4 \cos\left(m_1 \frac{\phi_1}{f_1} + m_2 \frac{\phi_2}{f_2}\right) \qquad n_i, \ m_i \ \in \mathbb{Z}$$

For $\Lambda_1 >> \Lambda_2$, $\phi \equiv \frac{f_1 f_2}{\sqrt{(n_1 f_1)^2 + (n_2 f_2)^2}}\left(-n_2 \frac{\phi_1}{f_2} + n_1 \frac{\phi_2}{f_1}\right)$ becomes inflaton:

$$V_{\rm eff} = \Lambda_2^4 \cos\left(\frac{\phi}{f_{\rm eff}}\right)$$

$$f_{\rm eff} = \frac{\sqrt{(n_1 f_1)^2 + (n_2 f_2)^2}}{|n_1 m_2 - n_2 m_1|}$$

The weak gravity conjecture

[Arkani-hamed, Motl, Nicolis, Vafa]

The conjecture: “The gravity is the weakest force.”

$$q \gtrsim \frac{m}{M_{\mathrm{Pl}}}.$$

$$\left(F_{U(1)} = \frac{q^2}{r^2} \gtrsim F_g = G_N \frac{m^2}{r^2} \right)$$

- But, one might have an axion interaction of $M_{\mathrm{Pl}} < f$: $\mathcal{L} = \frac{\phi}{f}\mathcal{O} < \frac{\phi}{M_{\mathrm{Pl}}}\mathcal{O}.$

- What if we have a weaker force than gravity?

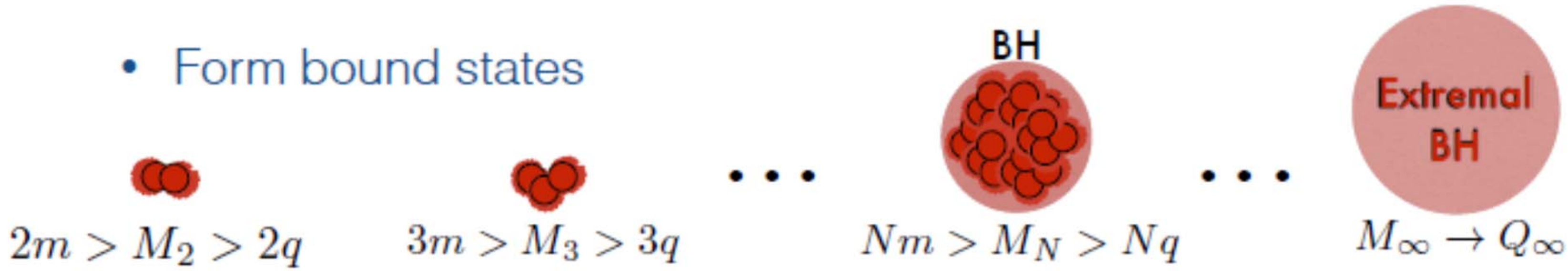
$M_P \equiv 1$

The Weak Gravity Conjecture

[Slide from G. Shiu]

- Take a U(1) and a single family with q < m (~~WGC~~)

- Form bound states



- All these (BH) states are stable. Trouble w/ remnants Susskind '95

($G_N \to 0$ via Bekenstein-Hawking formula)

- Need a light state into which they can decay

$$\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

The weak gravity conjecture for axion

[Arkani-hamed, Motl, Nicolis, Vafa]

The conjecture for axion potential via one instanton effect:

$$\frac{1}{f} \gtrsim \frac{S}{M_{\mathrm{Pl}}}.$$

$$V_{1-\mathrm{inst}} = e^{-S} M_{\mathrm{Pl}}^4 \cos\left(\frac{\phi}{f}\right)$$

- Axion interaction for $M_{Pl} < f$: $\mathcal{L} = \frac{\phi}{f}\mathcal{O} < \frac{\phi}{M_{\mathrm{Pl}}}\mathcal{O}.$

A possible loophole

[Slide from G. Shiu]

- The WGC requires f·m<1 for ONE instanton, but not ALL

$$V = e^{-m}\left[1 - \cos\left(\frac{\Phi}{F}\right)\right] + e^{-M}\left[1 - \cos\left(\frac{\Phi}{f}\right)\right]$$

With $1 < m \ll M,\qquad F \gg M_P > f,\qquad M \times f \ll 1$

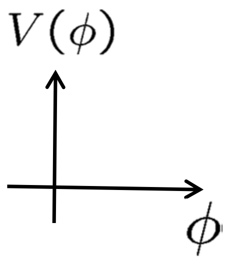
Multi-natural inflation!

- The second instanton fulfills the WGC, but is negligible, an "spectator". Inflation is governed by the first term.

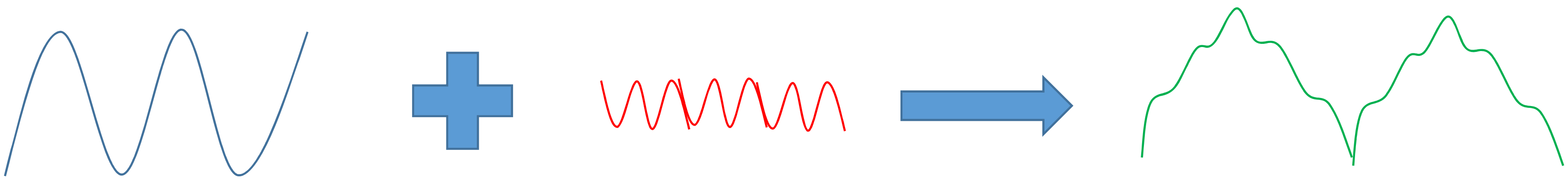
Potential with modulations

Again, [Czerny, Takahashi]; [Czerny, TH, Takahashi]; [TH, Takahashi]; [Kobayashi, Takahashi];[Czerny, Kobayashi, Takahashi]; [TH, Kobayashi, Seto, Yamaguchi]

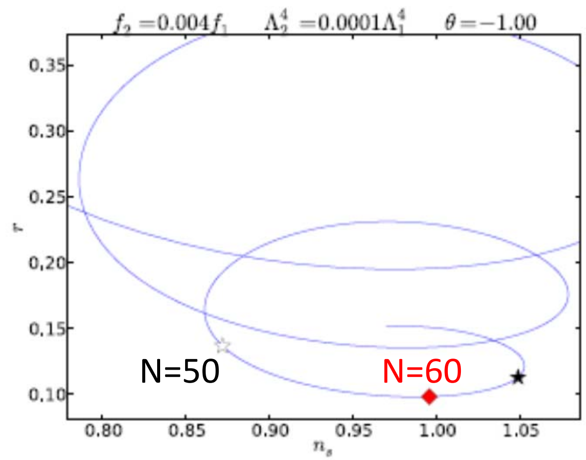
- Potential studied independently regardless of WGC:

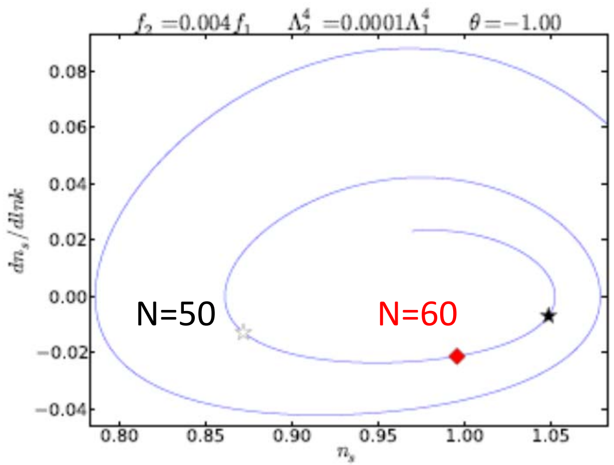


$\Lambda^4 \cos(\phi/F), \quad F \gtrsim M_{\rm Pl}$ $\quad\quad \delta V(\phi) = \epsilon \Lambda^4 \cos(\phi/f), \quad f < M_{\rm Pl}.$



[Czerny, Kobayashi, Takahashi]
1403.4589

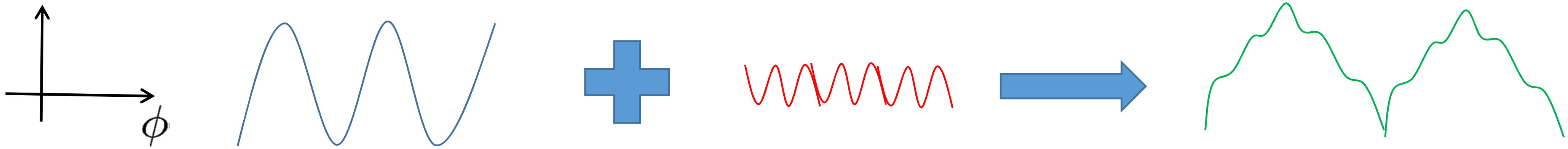




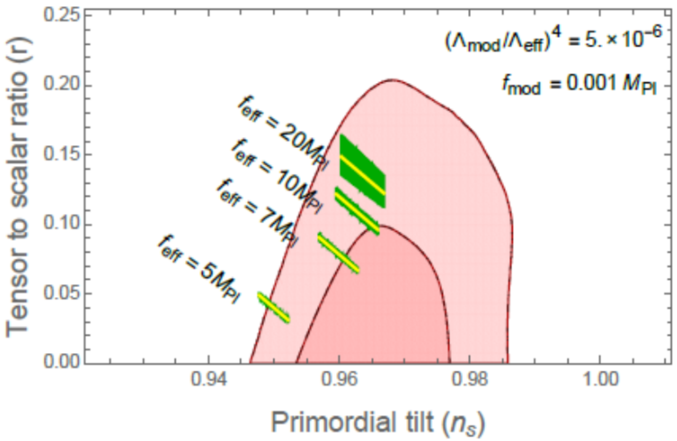
Recent studies of potentials with modulation

- Potential via WGC = Multi-natural inflation!:

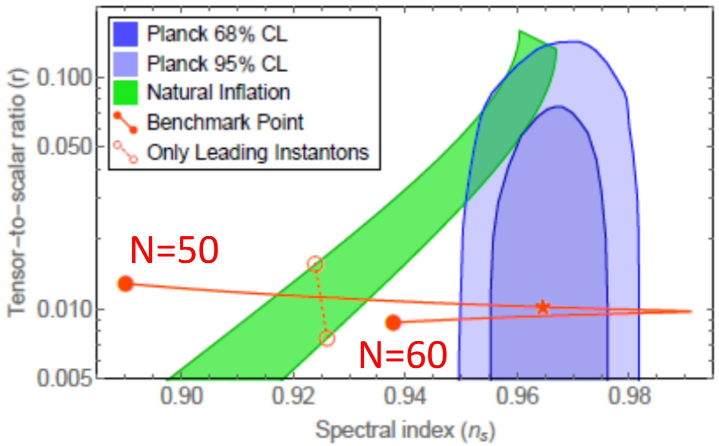
$V(\phi)$ $\qquad \Lambda^4 \cos(\phi/F), \quad F \gtrsim M_{\rm Pl}$ $\qquad \delta V(\phi) = \epsilon \Lambda^4 \cos(\phi/f), \quad f < M_{\rm Pl}.$



[Choi et al.]
1511.07201



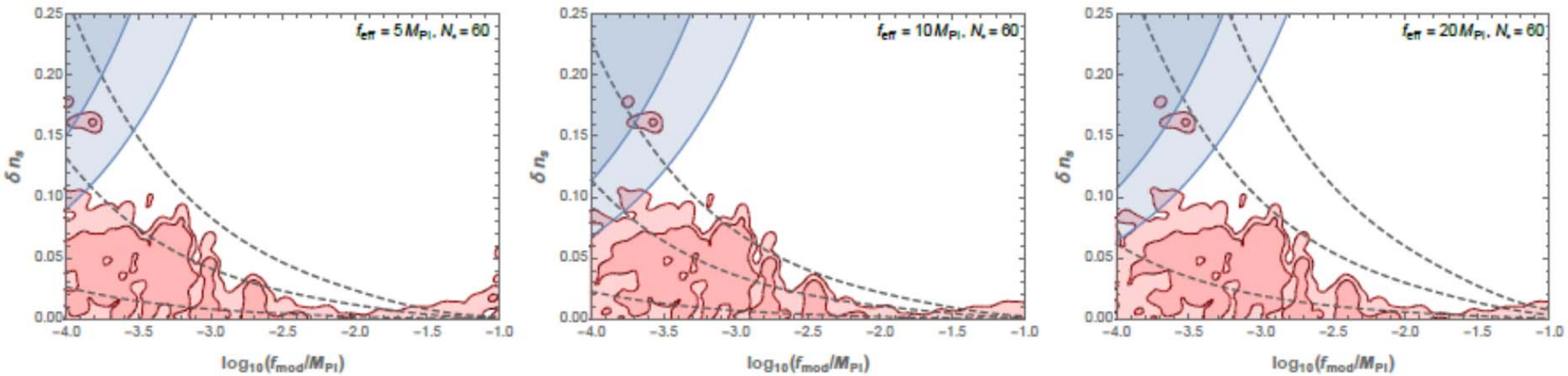
[Kappl et al.]
1511.05560



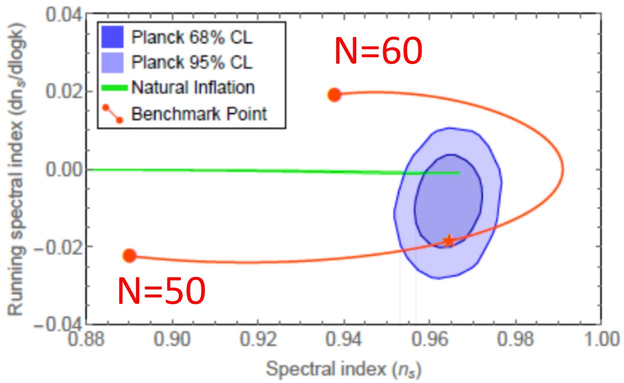
Potential with modulations: running n_s

$$= \frac{dn_s(k)}{d\log(k)}$$

[Choi et al.]
1511.07201



[Kappl et al.]
1511.05560



4. Conclusion & discussion

Conclusion

- Planck result can suggest a small r (< 0.11).

- Discrete symmetries control an inflation model; ∃ multi-instantons.

- UV completion: compactification periodicity and brane configuration:

$SL(2,\mathbb{Z}) \times \text{(periodicity)} \times (\mathbb{Z}_2)^2$ + constraint on torus area ($A/\alpha' \sim 2$).

(preliminary result)

- General message:

Compactification may help slow roll inflation due to discrete symmetries.

Discussion

- Moduli stabilization during inflation required:

$H_{inf} \sim$ gravitino mass < Heavy moduli.

Flux + racetrack (KL) model would help this issue.

Otherwise, slow roll inflation may be broken by a large inflaton mass via:

- Heavy moduli-inflaton mixing
- Quantum corrections from SUSY-breaking.

Appendix

The Weak Gravity Conjecture

[Slide from G. Shiu]

Arkani–Hamed et al. ‘06

- For bound states to decay, there must ∃ a particle w/

$$\frac{q}{m} \geq \text{“1”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

Strong-WGC: satisfied by *lightest* charged particle

Weak-WGC: satisfied by *any* charged particle