Large-Field inflation in String Theory and CMB Phenomenology

Many contributors; collaborators include

A. Westphal; L. McAllister; T. Wrase
R. Flauger; X. Dong, B. Horn; M. Dodelson, G. Torroba, L. Senatore, M. Zaldarriaga; M. Mirabayi

Related works by Kaloper, Sorbo, Lawrence, Pajer, Easther, Peiris, Xu, Meerburg, Spergel, Wandelt,Roberts, Dubovsky, D'Amico, Gobbetti, Kleban, Schillo, Gur-Ari; Marchesano, Shiu, Uranga, Palti, Weigand, Wenren, Schlaer, Lust, Hebecker, Kraus, Witowski, Ibanez, Valenzuela, Dine, Draper, Monteaux, Arends, Heimpel, Mayrhofer, Schick, Yonekura, Higaki, Kobayashi, Seto, Yamaguchi, Hassler, Massai, Grimm, Ibe, Harigaya, Amin, Hertzburg et al, Schmitz, Harigaya, Ibe, Yanagida...Kallosh-Linde (sugra)

cf the earlier N-flation scenario by Dimopoulos, Kachru, McGreevy, Wacker;...

and 2-axion alignment Kim/Nilles/Peloso...

+chromo-natural, (gauge) inflation Adshead/Martinec/Wyman, Ashoorioon,Sheikh-Jabbari et al

...

As they map the universe with extraordinary coverage and precision, CMB/LSS experiments are reaching unprecedented observational sensitivity to `fundamental' physics including quantum gravity.

--BICEP2(+ input from BICEP1, Keck Array, SPT/ACT, Planck,WMAP,...): Tour de Force B-mode detection, at a level consistent with inflationary quantum gravitational waves (uncertain model-dependent amplitude), but could be consistent with foregrounds (uncertain, complicated) [Flauger Hill Spergel '14]
--Planck +Joint analysis (+ B3, Spider, CLASS,...)

--Chance to develop systematic understanding in the next months, years as r/dust, NG etc play out.

Plan (Organizers: aim at grad students in any subfield of cosmology)

- Inflation and quantum gravity $r > .01 \leftrightarrow \Delta\Phi > M_p$
- Axion Monodromy
  - structure & recent examples
  - phenomenology (r, oscillations)

new/ongoing work on theoretical parameter ranges

*Inflation is (as of now) our only paradigm with theoretically controlled calculations of density perturbations,with the simplest scenarios fitting the data well. (independently of tensor modes)
*What is at stake is the observational lever to Quantum Gravity

*The model $V(\Phi)$ etc. is of interest insofar as it is connected to other physics.

** r> .01 strongly "UV" sensitive

Inflation + perturbations can be modeled in low energy quantum field theory and GR.

$$\dot{\phi}^2 \ll V = H^2 M_p^2 \ll M_p^4$$

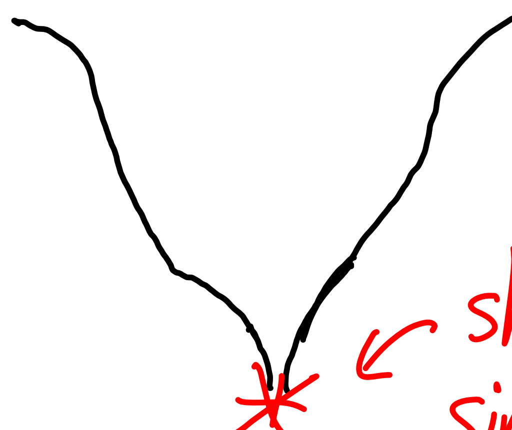
However, these do not provide a complete description. To see this, first note that the effective interaction strength of gravity <u>increases</u> with energy:

$$\lambda_G \sim G_N E^2 \sim \left(\frac{E}{M_p}\right)^2 \leftarrow 10^{19}\,\mathrm{GeV}$$

At short distances, quantum effects become important, along with any new degrees of freedom involved in a "UV completion" of the theory. This affects cosmology in several ways.

1)

Far past:

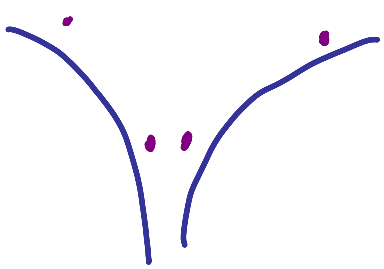


short-distance singularity

and/or "eternal inflation"

- No known controlled example of a singularity (bounce or otherwise) that gives viable phenomenology.

There is much more to do to understand initial conditions for cosmology. This is conceptually interesting, and may ultimately provide some sort of probability distribution for late time physics.

However, if it occurred, inflation diluted most relics of this early time , so let us move on to inflation in string theory + data

General Relativity describes gravity accurately at long distances

$$S = \int d^4x \sqrt{g}\, \frac{R}{G_N} + S_{\text{matter}} \rightarrow R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

GR breaks down for $\lambda_G \rightarrow 1$ (or before)

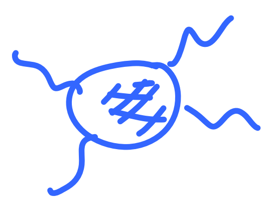
Quantum fluctuations $\rightarrow$

$$S = \int \left(\frac{R}{G_N} - V(\phi)\right)\left(1 + R\left(\frac{c_1}{M_*^2} + \tilde{c}_1 G_N\right) + \cdots\right)$$

$$+ \int (\partial\phi)^2 + k_1 \frac{(\partial\phi)^4}{M_*^2} + \cdots$$

$\leftarrow$ scale of "new physics"

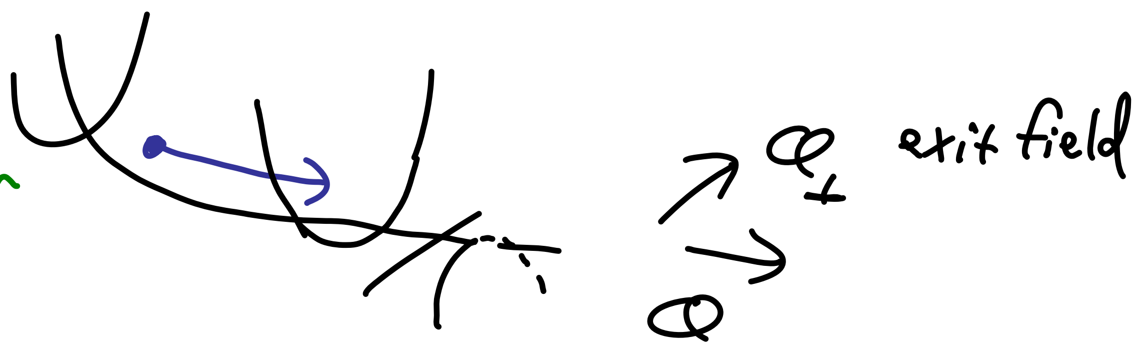
with corrections sensitive to short-distance physics



2) These corrections <u>matter</u> for inflation

e.g. A seemingly simple way to obtain inflation is to postulate a very flat potential for the inflaton $\varphi(x)$.

e.g. Linde '93 hybrid inflation

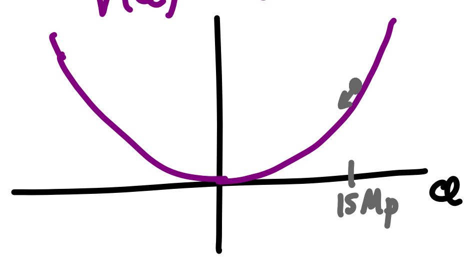


$$\varepsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 << 1 \qquad \eta \equiv M_p^2\left|\frac{V''}{V}\right| << 1$$

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\varphi, \partial\varphi)$: $\dfrac{V(\varphi-\varphi_0)^2}{M_p^2} \to \Delta\eta \sim 1$

This UV Sensitivity is greatest in the case of **"Large-field Inflation"** where the inflaton ϕ ranges over more than a distance M_p

e.g. $V(\phi) = \frac{1}{2}m^2\phi^2$ A. Linde '83



$$\left\{ \begin{aligned} \varepsilon &= \tfrac{1}{2}\left(\frac{V'}{V}M_p\right)^2 \\ \eta &= M_p^2 \left|\frac{V''}{V}\right| \end{aligned} \right\} \sim \left(\frac{M_p}{\phi}\right)^2 \Rightarrow \phi \sim 15\, M_p$$

In General:

★ "Lyth Bound": $\dfrac{\Delta\phi}{M_p} \sim \left(\dfrac{r}{0.01}\right)^{\frac{1}{2}}$

cf Turner

UV sensitive if $\gtrsim 1$

observable

→ Control with approximate shift symmetry (Wilsonian 'natural')

Lyth "~~Bound~~"

$$N_e = \int \frac{da}{a} = \int \frac{da}{dt}\frac{dt}{a} = \int H\,dt$$

$$= \int \frac{H M_p}{\dot\phi}\frac{d\phi}{M_p} = \sqrt{8}\, r^{-\frac{1}{2}} \frac{\Delta\phi}{M_p}$$

using

$$r = \frac{\gamma\gamma}{\zeta\zeta} = \frac{\text{tensor}}{\text{Scalar}} \sim \frac{\frac{H^2}{M_p^2}}{\frac{H^4}{\dot\phi^2}}$$

and assuming no strong variation of $HM_p/\dot\phi$, and no exotic sources

$r = \dfrac{\text{Tensor}}{\text{Scalar}}$ is related to field range in simple inflation

$$\boxed{\frac{\Delta\phi}{M_p} \sim \frac{r^{\frac{1}{2}}}{\sqrt{8}} N_e >> 1}$$

highly UV sensitive if $\gtrsim 1$

BICEP2

if contains primordial component

• An ∞ sequence of possible terms

$$V \to V\left(1 + \sum_n c_n \frac{(\phi-\phi_0)^n}{M_p^n}\right)$$

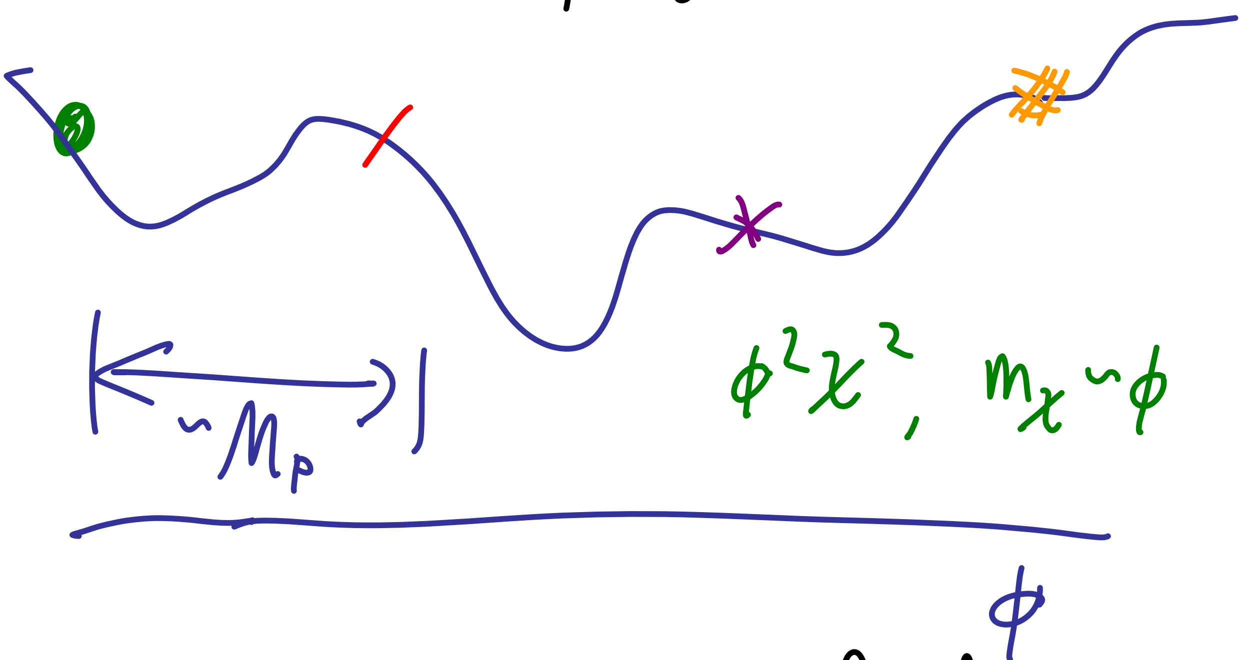
infinitely "UV-sensitive"

must be suppressed (e.g. symmetry)

→ Determined by Quantum Gravity theory

→ B-modes test string-theoretic large-field inflation in particular.

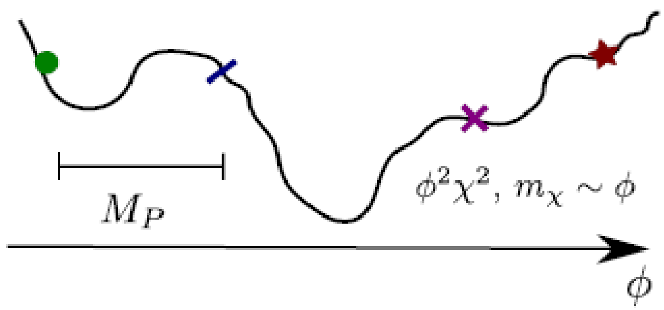
A common prejudice was:



Over a large distance in field space, $V(\phi)$ could be strongly corrected by ϕ's couplings to whatever degrees of freedom UV-complete gravity.

- Can postulate a symmetry, but one wonders if QG has it — this is a strong statement about the classical theory

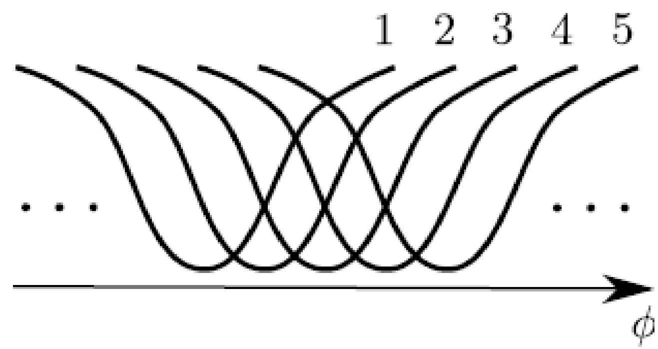
Parameterized ignorance of quantum grav.



New degrees of freedom each ΔΦ~M$_P$

No continuous global symm. in QG

String Theory axions (and duals)



From ubiquitous Axion-Flux couplings

Discrete shift symm., f<<M_p

[cf Chaotic Infl.(Linde), Natural Infl. (Freese et al)]

Experimental probes of QG are rare, so we do not know much about it empirically.

Thought-experimental and mathematical probes are quite powerful, e.g.

- Black hole thermodynamics

$$S = \frac{A}{4G_N}, \quad T_{\text{Hawking}} \sim \frac{1}{R_{\text{Schwarzchild}}}$$

- UV finiteness, spacetime singularities

String theory is a strong candidate for QG.

- Recover $S = \frac{A}{4G_N}$ (in special calculable examples)

↳ AdS/CFT duality, holography

- UV-finite amplitudes and spacetime singularity resolutions
- Intricate connections among different limits

↳ including landscape of vacua, fitting with Weinberg's picture of the small but nonzero late-time acceleration

Note: The landscape does not mean "anything goes".

Lots of structure.

...

- $f_{axion} << M_p$ — Banks Dine Gorbatov

- no hard cosmological constant (metastable)

- Extreme limits of moduli space $\rightarrow$ light degrees of freedom — Ooguri Vafa

- We might expect a "discretuum" of UV complete r, n_s

Monodromy generates symmetry-controlled large field range and observable B mode signal. (Other inflation mechanisms can yield low r.)

$$\int d^D x \sqrt{G} \sum_q \Big| \overbrace{F_q - C_{q-3} \wedge H + F_{q\cdots} B \wedge \cdots \wedge B}^{\tilde{F}_q \text{ Gauge-invar.}} \Big|^2$$

fluxes

$$\int_{\Sigma_q} F_q = Q_q$$

axions $b = \int_{\Sigma_2} B$

(Direct Dependence)

This generalizes Stueckelburg couplings in electromagnetism (spontaneously broken in a superconductor)

$$S = \int d^4x \left\{ F^2 - \rho^2 (\partial\theta - A)^2 \right\}$$

Gauge symmetry $A_\mu \to A_\mu + \partial_\mu \Lambda$
$\theta \to \theta - \Lambda$

In string theory, the string sources a <u>2-index</u> gauge potential B_{MN} analogously to how a charged particle sources A_μ in Electromagnetism

axions $= B_{MN}$-modes
(and duals)

$$\int d^D x \sqrt{G} \sum_q \left| F_q - C_{q-3} \wedge H + F_{q-\dots} B \wedge \dots \wedge B \right|^2$$

In a nutshell, we reduce this to 4 dimensions and compute the inflaton potential $V(\phi)$, taking into account the back reaction on other degrees of freedom while (meta-)stabilizing the extra dimensions.

e.g. $D=10$ IIA

$$H = dB\,, \quad \tilde{F}_2 = dC_1 + F_0 B$$

$$\tilde{F}_4 = dC_3 + C_1 \wedge H_3 + \tfrac{1}{2} F_0 B \wedge B$$

This, its reductions & T-duals lead to

$$|\tilde{F}_q|^2 \sim |Q B^n|^2$$

for various $n \equiv \frac{p_0}{2}$ ← fiducial power of b

Corrections

$$\sum_{k>1} g_s^{2k} \left| \tilde{F}_q \right|^{2k} \sim \sum_k g_s^{2k} \frac{Q_m^2}{L^{2m}} b^{2nk}$$

Suppression

In general,
Work at large(-ish) radii & weak g_s for control, with or without low-energy SUSY.

$$\ldots \quad |\tilde{F}_q|^2 \sim |QB^n|^2$$

for various $n \equiv \frac{p_0}{2}$ ← fiducial power of b

Back reaction on "moduli" (shape & size of extra dimensions) reduce the power to $V \sim \phi^{p < p_0}$

To be systematic, we will later try to push p_0 (& p) high, to see if the theory allows that

$$V = V_0(\chi) + V_1(\chi)\left(\sum_n Q^{(2n)} b^n\right)^2 + \dots$$

axion

Moduli

- Whole structure periodic

$$b \to b+1 \Longleftrightarrow Q \to Q + \Delta Q$$

e.g. brane spectrum on Σ_2

- Each branch (fixed Q) has large range b

$$-b_{uv} < b < b_{uv}$$

$V(b_{uv} \gg 1) = V_{uv}$ (density at which lose control)

$$V = V_0(\chi) + V_1(\chi)\left(\sum_n Q^{(2n)} b^n\right)^2 + \dots$$

Moduli

$$\mathcal{L}_{kin} = \int d^4x \sqrt{-g}\, M_p^2 f(\chi)^2 \dot{b}^2$$

- Moduli adjust, flatten V [Dong et al '10]
- $\int db\, M_p f[\chi(b)] = \phi_b$ Canonically Normalized

e.g. $\frac{b}{L^2} \sim \frac{\phi_b}{M_p}$ (one scale)

$D = 10$ Type II at $\phi_b \gg M_p$

$$V \sim M_p^4 \frac{g_s^4}{L^6} \frac{Q_n^2}{L^{2n}} \left(\frac{\phi^2}{M_p^2} + \frac{\phi^4}{M_p^4} + \mathcal{O}\left(\frac{g_s^2 Q_n^2 \phi^8}{L^{2n} M_p^8} \right) \right)$$

$$+ V_0 \left(\chi = g_s, L, \ldots \right)$$

In specific models, find

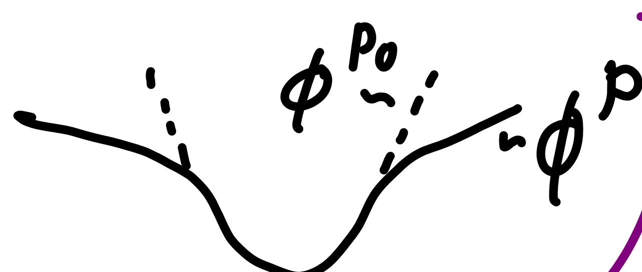
$$V \sim \hat{V}_1(\chi) \phi^{p_0} + V_0(\chi) \Big|_{\chi_{min}}$$

$$\simeq \mu^{4-p} \phi^p + \Lambda^4(\phi) \cos\left(\frac{\phi}{f(\phi)} + \gamma \right)$$

With $p < p_0$; $p = 3, 2, 4/3,$
$1, 2/3$

- $V_{\text{inflation}}$ helps stabilize moduli $\mathcal{X}$ in 2-term structure: Flux quanta → Q b

$$\left(\frac{L_2}{L_1}\right)^{n} Q_1^2 + \left(\frac{L_1}{L_2}\right)^{\tilde{n}} (b Q_2)^2 \, \hat{V}$$

(Backreaction flattens V in such cases: 

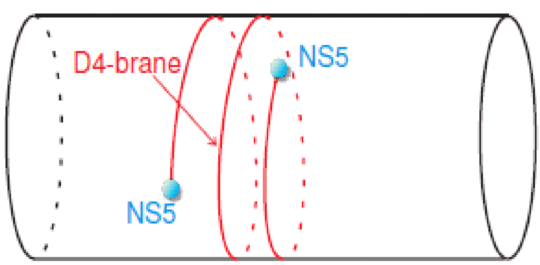
)

On each branch:

$\simeq \mu^{4-p}\phi^{p} + \Lambda^{4}\cos\frac{\phi}{f}$

$p \neq$ integer: other fields adjust

Large $\Delta\phi \gg M_p$,
but conditions similar each time around



(T-dual of) specific example '08
$p_0 = 2 \rightarrow p = 1$

Large field, $\Delta\Phi_{infl} \gg M_p$

$\Longrightarrow r \gg .01$ cf chaotic inflation
A.Linde '83

+ residual, model-dependent oscillations

cf Natural Inflation
Adams Bond Freese Frieman Olinto

Phenomenology

1. r

2. oscillations

- detectability highly model-dependent
- more like a "smoking gun"
- period drift (New templates)

3. Was it a coincidence that $\{r, n_s\}$ landed in the right ballpark?

- Try to push theory to extremes to see if $\{r, n_s\}$ robust

Oscillation Templates for Planck 2014

[Flauger McAllister ES Westphal + Peiris]

$$V = V_0(\phi) + \Lambda^4(\phi)\cos\left(\frac{\phi}{f(\phi)} + \gamma\right)$$

[previous: Easther Flauger Peiris, Pajer
Planck 2013, Meerburg Spergel Wandelt
Aich et al]

low-ℓ anomalies & slow oscillation '14

$\Lambda^4 \cos(\cdots)$ generated by periodic effects such as worldsheet instantons (Large L_{Σ_2}) or particle/string production

Highly model-dependent, but interesting to search for

↳ Challenge: getting $f(\phi)$ wrong can wash out signal over $l_{min} \leq l \leq 2500$

$$\cos\left[\frac{\phi_k}{f(\phi_k)}\right]$$

$$\phi_k \simeq \sqrt{2p\left(N_* - \log\left(\frac{k}{k_*}\right)\right)}\, M_p$$

Template including effects described above (moduli drift)

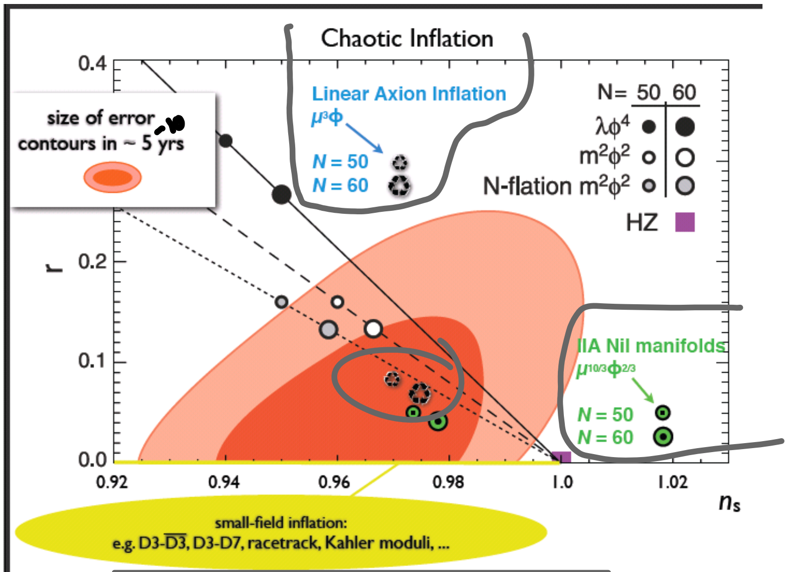
$$V = V_0 + \mu^{4-p}\phi^p + \Lambda_0^4 e^{-C_0\left(\frac{\phi}{\phi_0}\right)^{p_\Lambda}} \cos\left[\gamma_0 + \frac{\phi_0}{f_0}\left(\frac{\phi}{\phi_0}\right)^{p_f+1}\right] \tag{1}$$

e.g. $p = \frac{4}{3}$, $p_\Lambda = -\frac{1}{3}$, $p_f = -\frac{1}{3}$

- p_f & p_Λ similar to p: come from $\phi \leftrightarrow$ "moduli" interaction.

r, n_s

Result for '08 example



$r = 0.07$
$n_s \approx 0.98$

$V(\phi) = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{2\pi f}\right)$

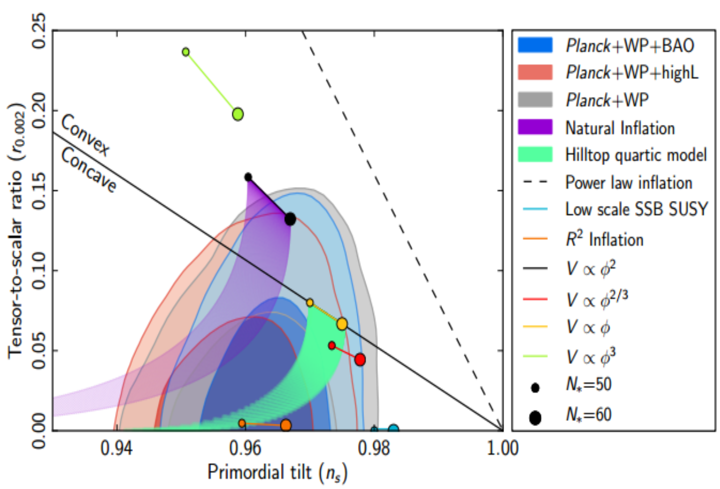
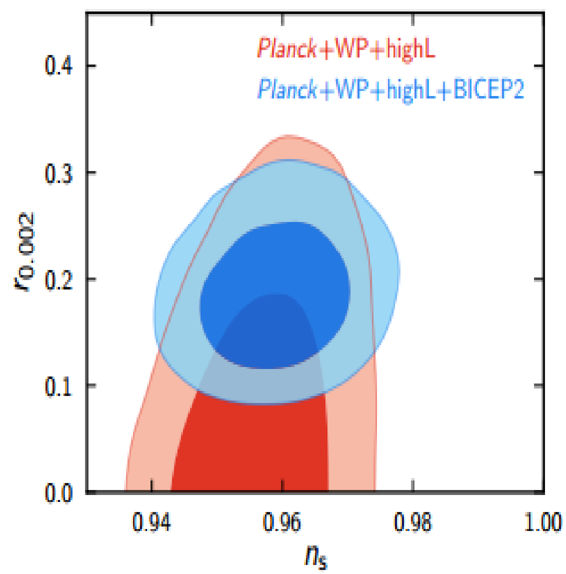


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared the theoretical predictions of selected inflationary models.



power law potentials with p=3,2,4/3, 1,2/3,...

r=.2, .13, .09, .07, .04,...

so far. We hope to get this understood more systematically in the B-mode era.

What is the UV-complete theory blob in $r, n_s, \ldots$?

[cf Dodelson, Creminelli et al '14...]

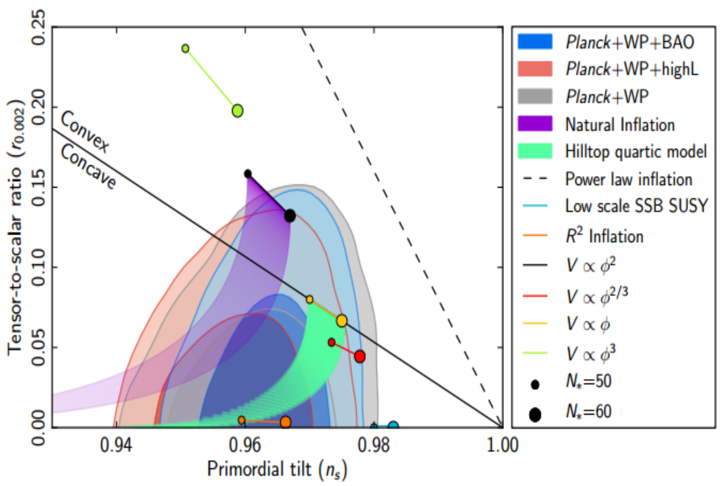
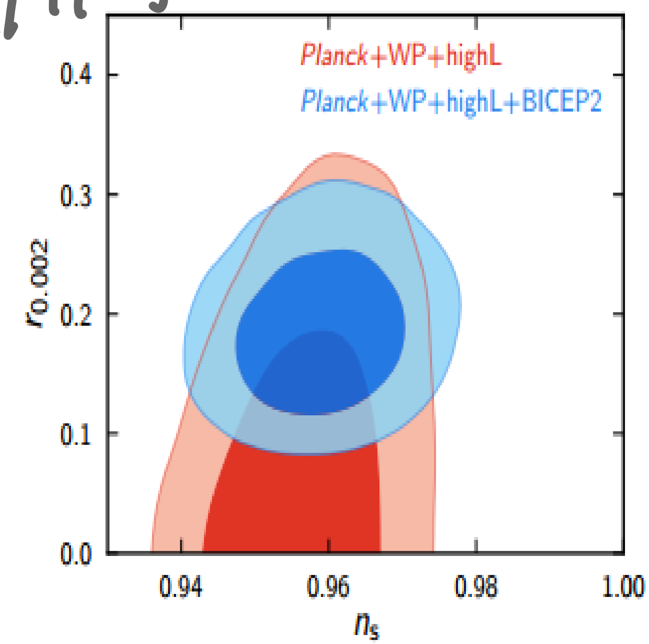


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared the theoretical predictions of selected inflationary models.



Are there theorems about range, rational values of $p \leftrightarrow n_s, r,$ etc.? cf EFT of perturbations but at $\Delta\Phi > M_p$

[Senatore et al]

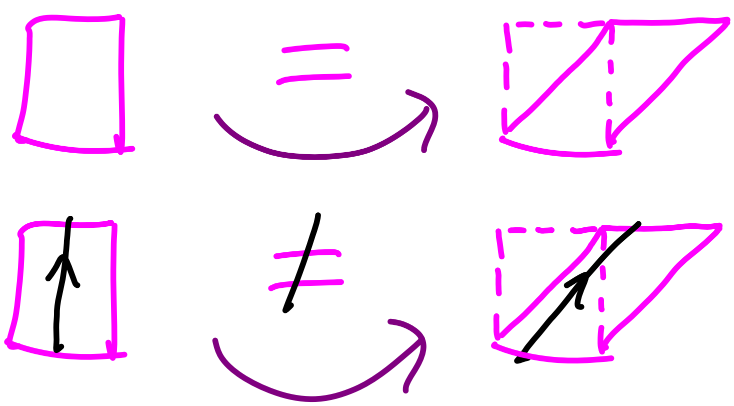
Dual Axions:

This structure is ubiquitous

B_{MN} $\longleftrightarrow$ C_q

(sourced by fundamental string) (sourced by branes)

$\Longleftrightarrow$ complex structure moduli



$\Longleftrightarrow$ brane positions

...

Axions are $> \frac{1}{2}$ the scalar fields in string theory:

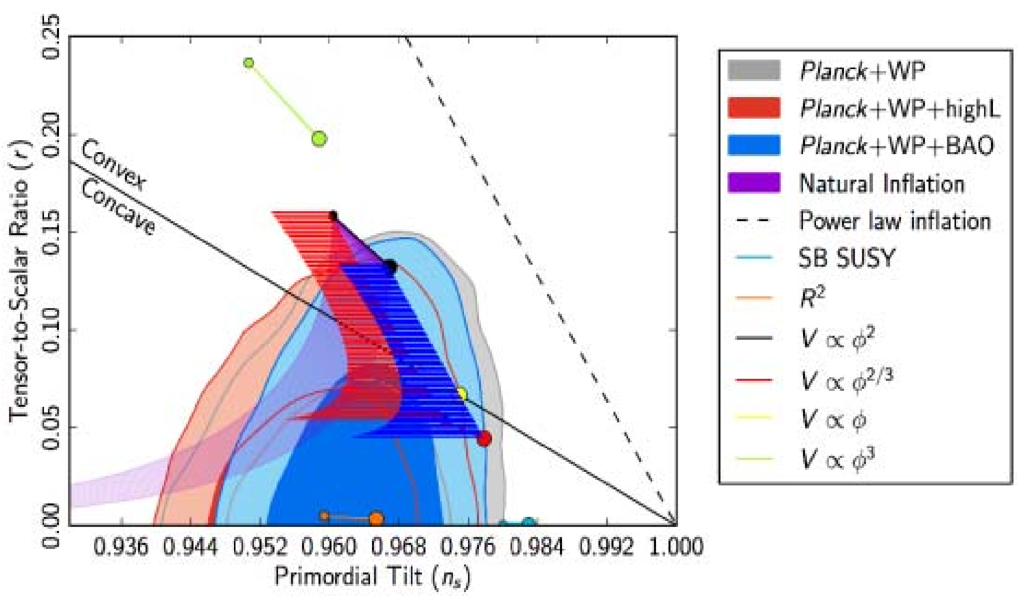
- SUSY case $\Phi = r + i\theta$
  (and duals)
- ~~SUSY~~ limits $N_{axion} \sim 2^D$
  $N_{\substack{\text{other}\\\text{moduli}}} \sim D^2$

It was a myth that string theory prefers small r, or that "most models" have that property — at least no credible argument for that.

Multiple Axions (N-flation), each with monodromy, may be the generic case.

This centralizes n_s

D. Wenren '14



Axion monodromy systematics

[Dodelson Dong ES Torroba '13 & in progress w/ McCandlish, Wenren]

$$V \sim \hat{V}(\chi)\,\phi^{p_0} + \cdots$$

$$\downarrow$$

$$V \sim \mu^{4-p}\,\phi^{p}$$

Strategy: look in theory space for extreme values of $p^0 \to p$ to see if phenomenological viability is robust.

In $D>10$, P_0 can naively be huge

$$|\tilde{F}_q|^2 = |F_q + B\wedge F_{q-2} + \cdots + F_0 B^{\frac{q}{2}}|^2$$

- But e.g. in product space we find that in appropriate field range, the $B^{\frac{q}{2}}$ is subdominant (cf N-flation).
- More generally, even for large P_0 there is room for strong 'flattening' by many adjusting fields.

Similarly, we can go back to twisted tori

ES Westphal '08

Gur-Ari '13

$$(z, \xi^a) \simeq (z-1, M^a{}_b\, \xi^b)$$

$$\in SL(n,\mathbb{Z})$$

but in $D > 10$ again to see if the theory will generate extreme values of $p_0 \to p$, or not.

So far, even for extreme topology, D, etc. we don't (yet) find parametrically large p (or even p_0).

Goal (in progress): find exceptions or prove theorem

low ℓ ?

There is a theoretical tension between the Wilsonian-natural shift-symmetry control of large-field inflation, and the low-ℓ anomalies if they become significant.

→ worth revisiting examples with flux hierarchies determining field range.

Broad Goal: more systematic understanding of large-field inflation, based on ubiquitous couplings between fluxes and axions (& their duals)

cf bottom up EFT (Senatore et al)

Maybe a good job for the Post-BICEP, pre-Planck/Keck100 era. Exciting (if uncertain) times...