The Powers of Monodromy

and the range of r in string theory

Based on works (2008-**present**) with
Westphal; McAllister; Wrase
Flauger; Dong, Horn; Dodelson, Torroba,
Senatore, Zaldarriaga; Mirabayi
as well as 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 (next talk), 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,...Kallosh-Linde(sugra)
and the earlier N-flation scenario by
Dimopoulos, Kachru, McGreevy, Wacker;...
New Book: Baumann/McAllister;

BICEP2(+ input from BICEP1, Keck Array, 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,...]

3rd month

Primordial n-1 Dust

video highlights
YouTube
Caltech...

(n=2 to 10 depending on analysis)

Outline

* Inflaton Field Range and quantum gravity
* String theory: large field range with underlying periodicity (monodromy)
* New examples and phenomenological range

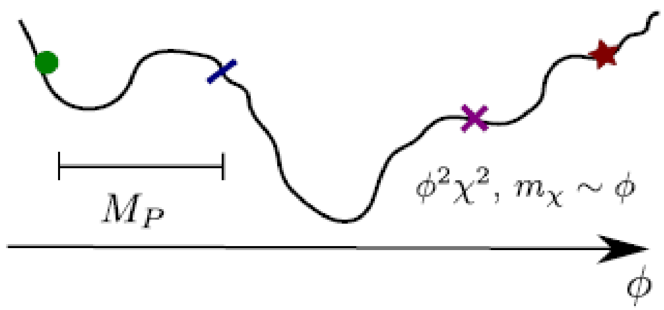
$$V \simeq \mu^{4-p}\phi^{p} + \Lambda^{4}(\phi)\sin\left(\frac{\phi}{f(\phi)} + \gamma\right)$$

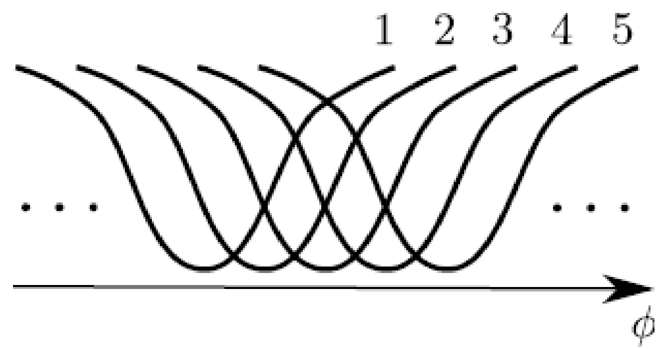
$p = 3, 2, 4/3, 2/3, \ldots$ (cf '08 $p = \cancel{2/3}, 1$; '10 $p \leq 2$)

*Ocillatory templates for Planck2014 [Flauger,McAllister,ES,Westphal in progress, cf Easther, Peiris, Planck2013, Meerburg, Spergel, Wandelt, Aich, Hazra, Sriramkumar, Souradeep,...]

Parameterized ignorance of quantum grav.

String Theory axions (and duals)





New degrees of freedom each $\Delta\Phi \sim M_P$

No continuous global symm. in QG

From ubiquitous Axion-Flux couplings

Discrete shift symm., f<<M_p

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

Inflation does not hinge on primordial B-modes, the TT power spectrum + E-mode polarization already provide a function's worth of evidence in favor of the paradigm. Despite interesting efforts, no consistent alternative theory is known (cf BH thermo, singularities).

What is at stake instead is a true observational lever to Quantum Gravity.

The particular ``model''

$$L_{Kinetic} - V(\phi)$$

is of interest insofar as it is connected to other physics. A tensor/scalar ratio r >.01 is strongly sensitive to quantum gravity via Lyth relation:

Lyth Relation

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

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

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

$\Delta\Phi > M_P$ <=> $r > .01$

implies sensitivity of

$$V(\phi) = V_0 + \sum_n c_n \frac{(\phi-\phi_0)^n}{M_p^n}$$

$$\epsilon \sim \frac{\dot{\phi}^2}{V} \sim \left(\frac{V' M_p}{V}\right)^2 \; ; \; \eta \sim \frac{\ddot{H}}{H^2} \sim \frac{V'' M_p^2}{V}$$

to infinite sequence of *dangerously irrelevant* Planck-suppressed operators, compelling a UV complete treatment (shift symmetry gives radiative stability, Wilsonian naturalness, but still large assumption about classical theory).

String theory is a good candidate for QG

*Recover S=A/(4G)(special cases)

*AdS/CFT...

*UV finite amplitudes, singularity resolutions, dimensionality and topology changing transitions,...

*Intricate connections among different limits --->**Landscape of vacua, fitting with Weinberg et al's picture of late-time acceleration

**Not anything goes: f_axion <M_p; No hard Λ; Light d.o.f. at limits of moduli space [Ooguri/Vafa],...).

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

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

fluxes

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

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

(Direct Dependence)

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

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

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

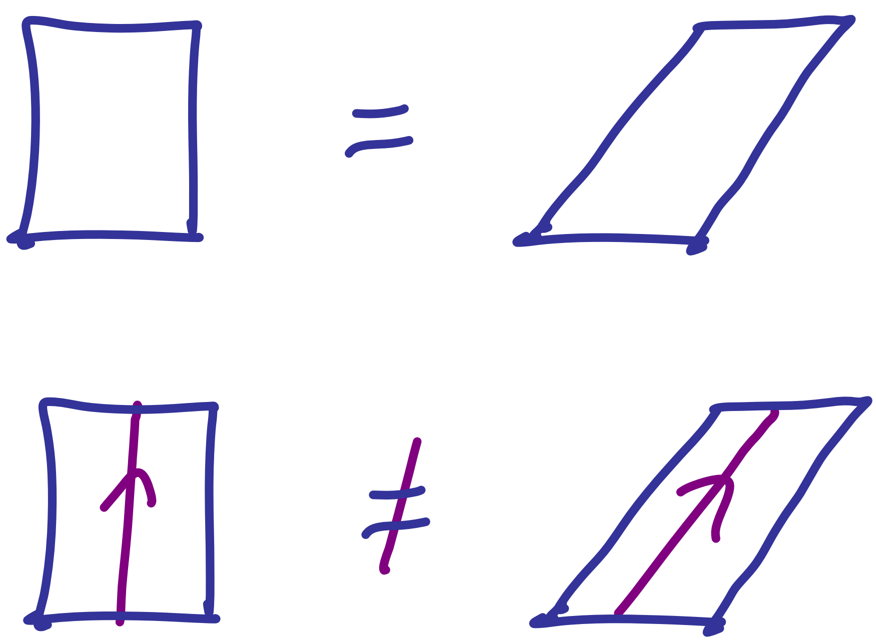
Corrections

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

suppression

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

Similarly, $\tau \to \tau + 1$ generically lifted by fluxes



axion

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

Moduli

- Whole structure periodic

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

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)

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

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. $\dfrac{b}{L^2} \sim \dfrac{\phi_b}{M_p}$ (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

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

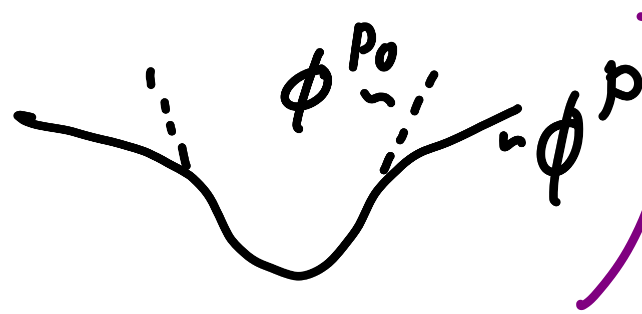
$$\simeq \mu^{4-p} \phi^p + \Lambda^4(\phi) \cos\left(\frac{\phi}{f(\phi)} + \gamma \right)$$

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

- $V_{\text{inflation}}$ helps stabilize moduli χ in 2-term structure: Flux quanta $\to Q\, b$

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

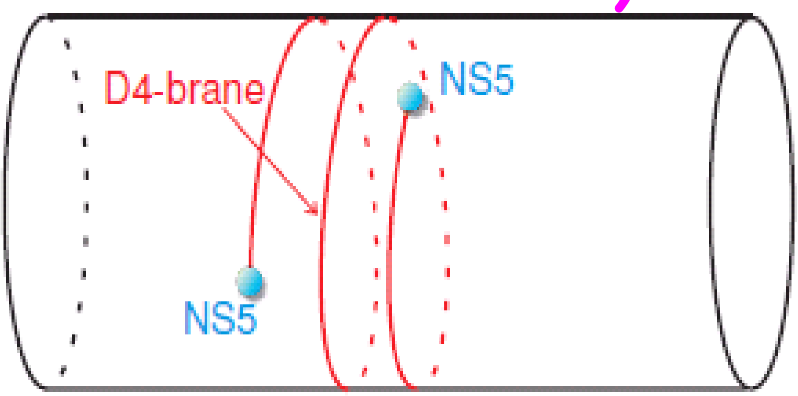
(Backreaction flattens V in such cases:



)

The specific example '08

(in GKP/KKLT)



(T-dual)

[McAllister, ES Westphal; Flauger et al]

$$V \sim \mu^3 \phi + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

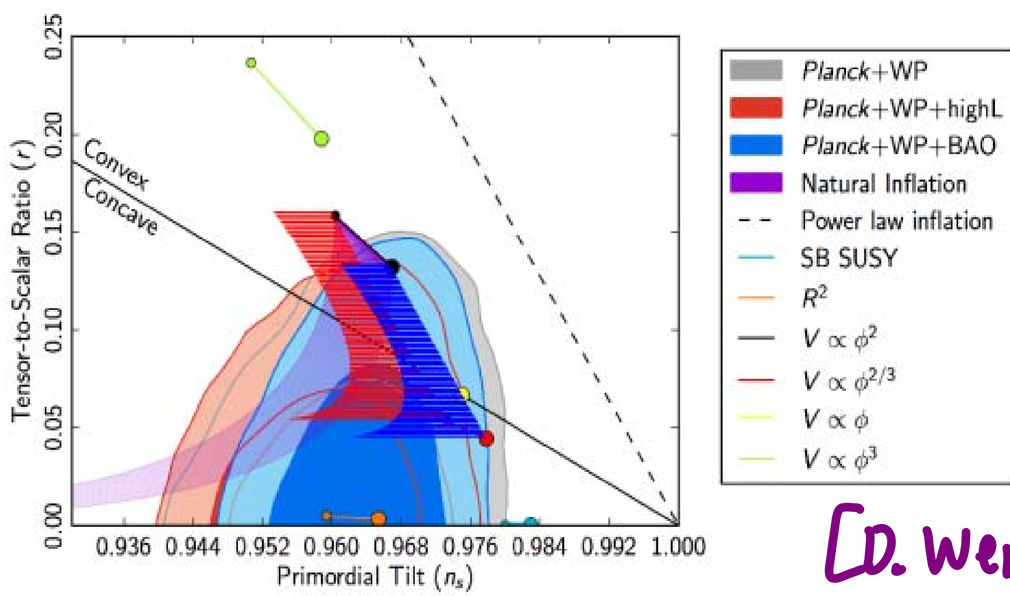
can be understood in this framework via AdS/CFT

as $p_0 = 2 \rightarrow p = 1$

[Dong Horn ES Westphal '10]

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

This centralizes n_s



[D. Wenren]

Now to new UV complete examples:

$$S_{II} = \int \frac{d^D x \sqrt{-G}}{\alpha'^{\frac{D-2}{2}}} \left\{ R + \frac{|dB|^2}{g_s^2} + \sum_q |\tilde{F}_q|^2 + \ldots \right\}$$

$\mathcal{O}(g_s^2 \tilde{F}^4)$

$D = 10$ IIA

Gauge-invariant generalized field strengths

$H = dB \quad F_0 = Q_0$

$\tilde{F}_2 = dC_1 + F_0 B$

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

e.g. $\delta B = d\Lambda_1, \ \delta C_1 = -F_0 \Lambda_1, \ \delta C_3 = -F_0 \Lambda_1 \wedge B$

IIB $\quad H = dB \quad , \quad F_1 = dC_0$

$\tilde{F}_3 = dC_2 - C_0 H, \ \tilde{F}_5 = dC_4 - \frac{1}{2} C_2 \wedge H + \frac{1}{2} B \wedge dC_2$

IIB $\hat{=}$ IIA on circle: (T-duality)

$C_0 = X^9 Q_0 + \hat{C}_0$

$C_2 = X^9 Q_0 B + \hat{C}_2$

$\Rightarrow |\tilde{F}_5|^2 \supset |F_1 \wedge B \wedge B|^2$

[Bergshoeff et al]

New class of examples with larger range of r

Type IIB $\mathcal{L} \supset |F_1 \wedge B \wedge B|^2$

(T-dual of $F_0 \, B \wedge B$ in IIA)

Warmup:

To exhibit flattening effect, consider

e.g. $T^6 = T^2 \times T^2 \times T^2$

$$F_1 = \frac{Q_1}{L_1} \sum_{i=1}^{3} dy_1^{(i)}, \quad B = \sum_{i=1}^{3} \frac{b^{(i)}}{L^2} dy_1^{(i)} \wedge dy_2^{(i)}$$

fluxes

2-form potential field → axion $b = \int_{\Sigma_2} B$

$$F_3 = Q_{31} dy_1^{(1)} \wedge dy_1^{(2)} \wedge dy_1^{(3)} + Q_{32} dy_2^{(1)} \wedge dy_2^{(2)} \wedge dy_2^{(3)}$$

Basic Effect:

$$V \sim M_p^4 \frac{g_s^4}{L^{12}} \left(\frac{Q_1^2}{L^4} u b^4 + Q_{31}^2 u^3 + \frac{Q_{32}^2}{u^3} \right)$$

Inflationary potential & Q_{32} flux stabilize u during inflation

Fluxes stabilize u after inflation

$$u \sim 3^{\frac{1}{4}} L \sqrt{\frac{Q_{32}}{Q_1}} \cdot \frac{1}{b} \qquad \propto \quad V_{eff} \propto b^3$$

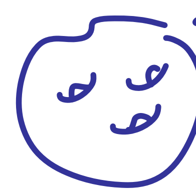
$$p_0 = 4, \quad p = 3$$

Checks:

- Kinetic terms negligible
- u does not go to extreme values with light degrees of freedom cf Ooguri-Vafa
- Asymmetric axion directions Stable ($|m^2| \ll H^2$, $\partial_{\phi_+} V \gg \partial_{\phi_-} V$)

The above mechanism (and generalizations) arises in string compactification on a product of Riemann Surfaces

(Saltman, ES '04) Classical, High-Scale.

• In full stabilization (on  ^{3})
g_s & L also adjust

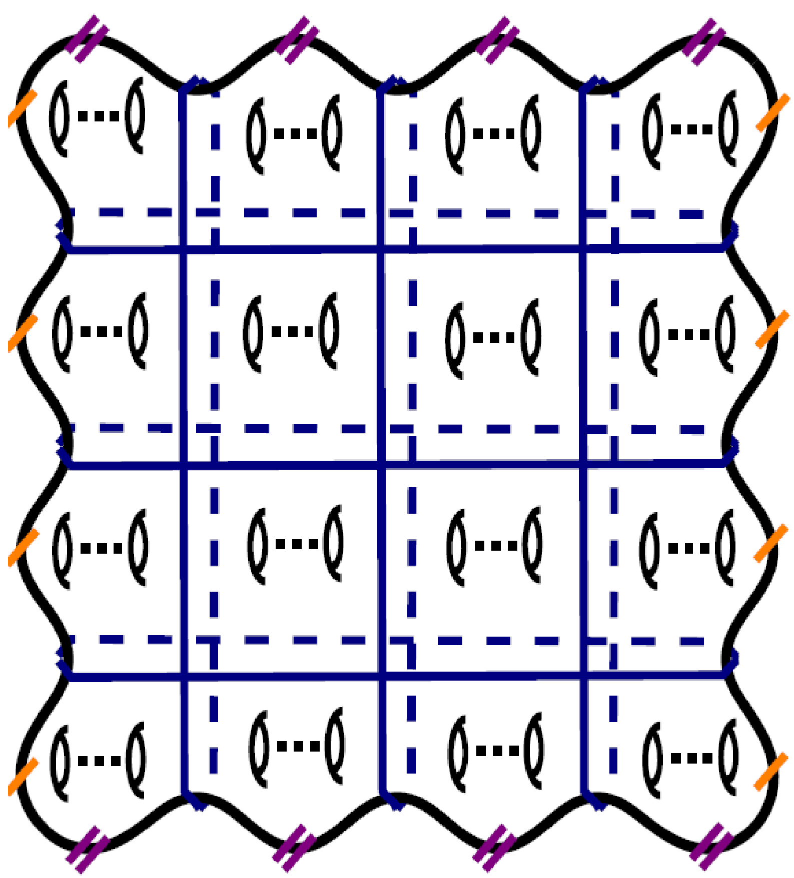
$$\to V \sim \phi^3, \phi^2, \phi^{4/3}, \phi^{2/3}$$

Microphysical constraints to satisfy (proofs of principle)

	Σ_1		Σ_2		Σ_3	
	1	2	3	4	5	6
7-brane	x		x		x	x
7’-brane	x	x		x	x	
7’’-brane		x	x	x		x
e.g. F_1						x
e.g. B		x	x	x	x	

7-brane, 7’-brane, 7’’-brane rows: trivial cycles

e.g. B row: nontrivial cycles; combinations that vanish on 7-branes: $B^{(1)}$ (columns 2, 3), $B^{(2)}$ (columns 4, 5)



$\eta = g_s / \mathcal{V}^{2/3}$ $\qquad \mathcal{V}$ = volume, g_s = coupling

$$U \sim M_p^4 \Big\{ (h + n_7 - 1)\eta^2 - N_7 \eta^3 + \tilde{q}_5^2 \eta^4 + n_3^2 \eta^2 + \tilde{q}_3^2 \mathcal{V}^{2/3} \eta^4 + q_1^2 \mathcal{V}^{4/3} \eta^4 \Big\}$$

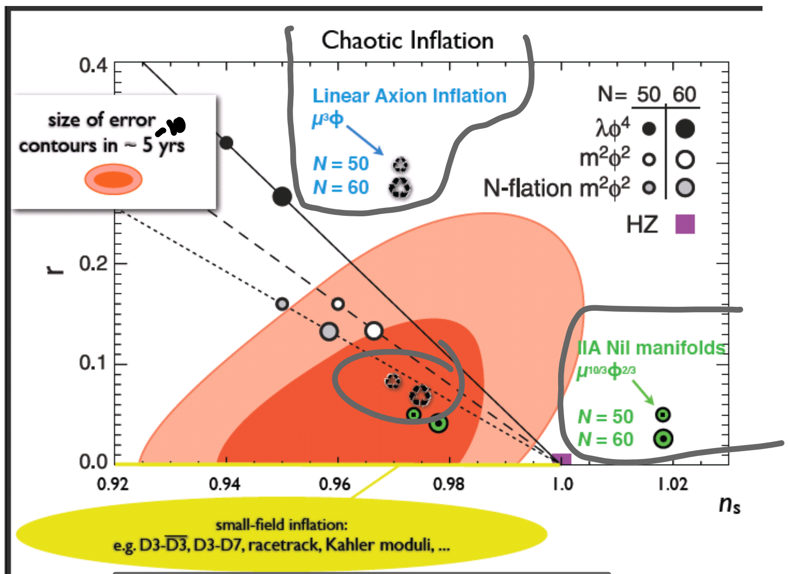
[Saltman - ES]

$$\tilde{q}_3^2 = q_3^2(u) + q_1^2(u) b^2$$

$$\tilde{q}_5^2 \sim \begin{cases} q_5^2(u) + 2 q_5(u) q_1(u) b^2 + q_1^2(u) b^4 & \text{(i)} \\ q_5^2(u) + q_1^2(u) b^4 & \text{(ii)} \end{cases}$$

Results depend on choices of flux & B ratios & distribution among cycles and Riemann Surfaces

Result for '08 example



$r = 0.07$
$n_s \approx 0.98$

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

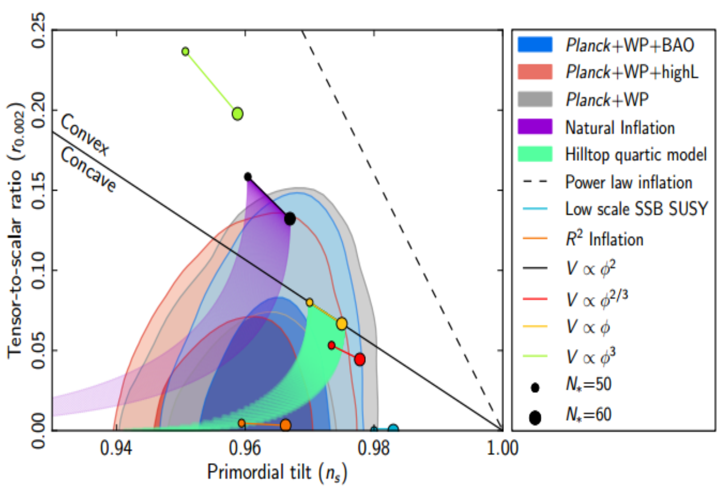
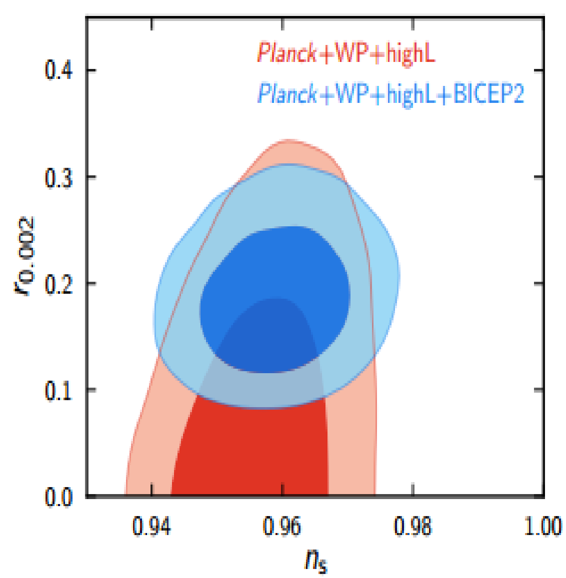


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets comparec he theoretical predictions of selected inflationary models.



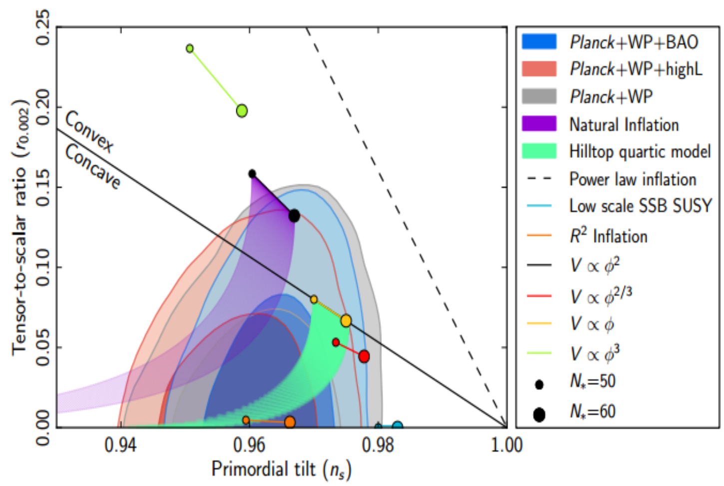
power law potentials with p=3,2,4/3, 1,2/3,...

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...]



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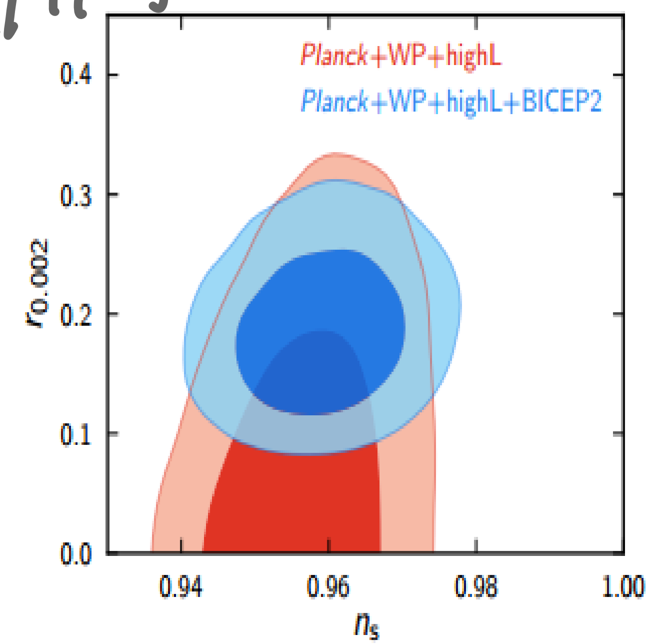

Are there theorems about range, rational values of $p \leftrightarrow n_s, r,$ etc.? cf EFT of perturbations but at $\Delta\Phi > M_p$

[Senatore et al]

it's <u>our</u> <u>job</u>!

Dual Axions

$$B_{MN} \leftrightarrow C_q$$

$\leftrightarrow$ Complex structure moduli

e.g. T^2

$$\rho = b + i\sqrt{G} \leftrightarrow \tau = \frac{G_{12}}{G_{22}} + i\frac{\sqrt{G}}{G_{22}}$$

$\leftrightarrow$ 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.

Axion monodromy systematics in $D > 10$

[Dodelson Dong ES Torroba '13 & in progress]

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

$$\downarrow$$

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

In $D > 10$, p_0 can be huge but many adjusting fields

So far in explicit family finding $1 < p < 4$ $(\ll D)$

Oscillation Templates for Planck 2014

[Flanagan McAllister ES Westphal]

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

[previous: Easther Flanagan 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 $\ell_{min} \le \ell \le 2500$

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

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

Template including effects described above (moduli drift)

$$V = V_0 + \mu^{4-p}\phi^{p}$$

$$+ \Lambda_0^4 e^{-C_0\left(\frac{\phi}{\phi_*}\right)^{\tilde{p}_1}} \cos\left[\gamma_0 + C_1\left(\frac{\phi}{\phi_*}\right)^{\tilde{p}_2}\right]$$

e.g. $p = \frac{4}{3}$, $\tilde{p}_1 = -\frac{1}{3}$, $\tilde{p}_2 = \frac{2}{3}$

Scan over $\tilde{p}_2$ as well as C_1 in the oscillatory part

More general effects such as multiple contribution to period-$f(\phi)$ effects, $\log(\phi)$ factors in $f(\phi)$ from non-perturbative stabilization mechanisms, etc may suggest additional templates (but can be degenerate).

Nth month

Primordial 3.5 million-1? All Dust component

It will be very exciting to see which way this goes. Either way we learn about inflation and the role or not of large field ranges. This is an unprecedented lever to QG and String Theory. Broad goal: develop systematic understanding based on structure of flux-axion couplings.