Quantum Gravity Observables and CMB/LSS Observations

Based on works (2008-**present**) with
Westphal, McAllister; Flauger;
Senatore, Zaldarriaga;
Dong, Horn; Dodelson, Torroba,Wrase...
as well as related works by Kaloper, Sorbo,
Lawrence, Pajer, Easther, Peiris, Xu, Roberts,
Dubovsky, D'Amico, Gobbetti, Kleban, Schillo,
Gur-Ari; Palti, Weigand, Wenren,Berg, Sjors,
and MANY others
and the earlier N-flation scenario by
Dimopoulos, Kachru, McGreevy, Wacker;...
cf recent reviews -- Burgess Planck Paris mting
talk, Baumann/McAllister book, ES Les
Houches '13, Comptes Rendus '15, TASI '15,...

Outline

*Brief review of UV sensitivity of (large-field) inflation observables, other IR connections
*Brief update on data (recent releases, current upgrades and near future forecasts)
--BKP effectively discovered a new parameter! good for UV
*Improving theory constraints
--Systematics of axion monodromy
--`Weak gravity conjecture' as a constraint on multifield Natural Inflation?
*Other phenomenological opportunities (or, numerology w/Planck data)

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

$$\boxed{\frac{\Delta\varphi}{M_p} \sim \frac{r^{\frac{1}{2}}}{\sqrt{8}} N_e \sim \left(\frac{r}{.01}\right)^{\frac{1}{2}}}$$

highly UV sensitive if $\gtrsim 1$

$\to$ • 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)

$\to$ Determined by Quantum Gravity theory

$\to$ B-modes test string-theoretic large-field inflation in particular.

*Inflation not the thing at stake. Strong connection to QG is (among other implications)

UV/IR

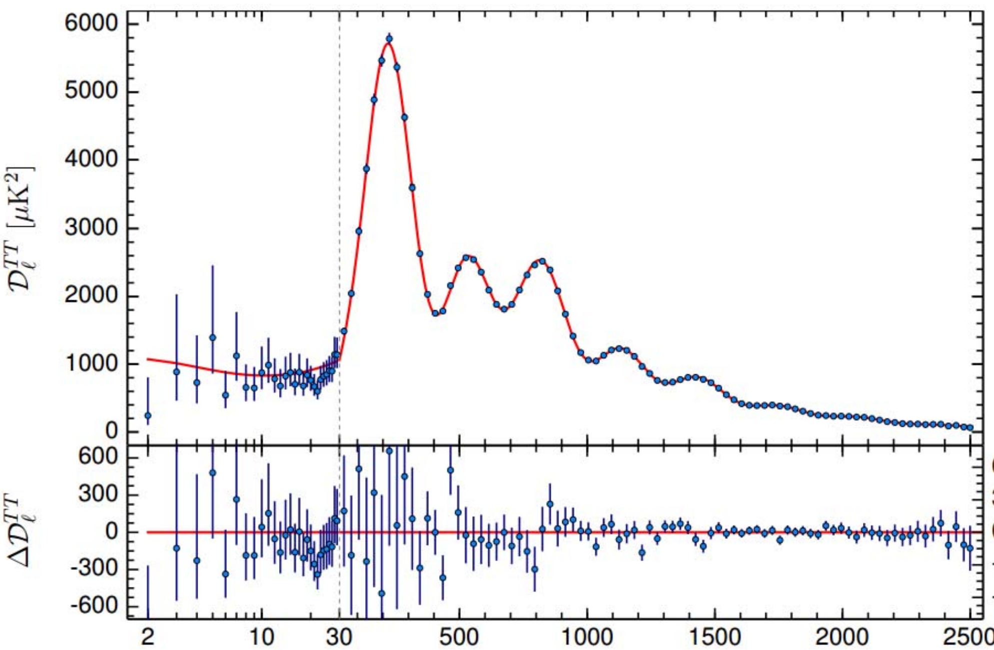
QG (string theory) mechanisms (UV)
fed into more systematic EFT (IR)
& data analysis

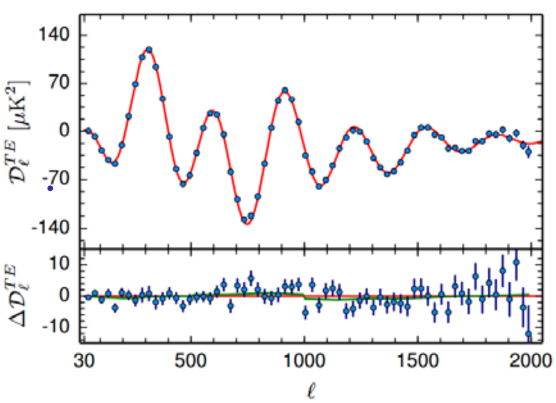
- NG at single-field level
- discrete shift symmetries
- dissipative processes
- exotic sources

Big Picture

Power spectrum function → 2 parameters

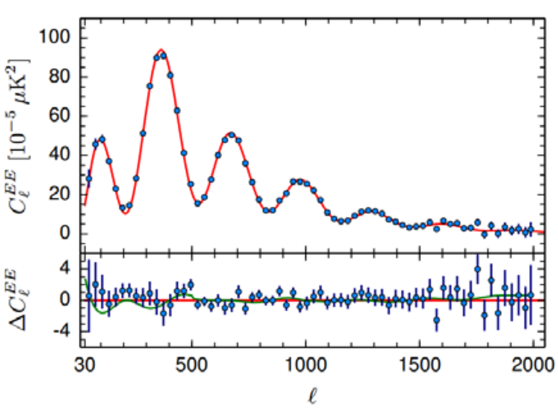
Planck Collaboration: Cosmological parameters





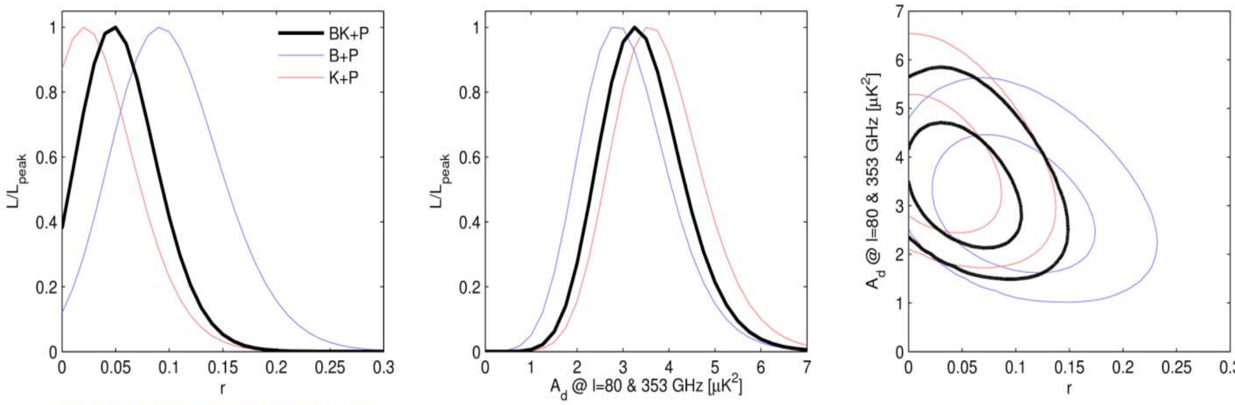
ℓ ≥ 30 we show the maximum likelihood frequency averaged
kelihood with foreground and other nuisance parameters deter-
the multipole range $2 \le \ell \le 29$, we plot the power spectrum
puted over 94% of the sky. The best-fit base ΛCDM theoretical
pper panel. Residuals with respect to this model are shown in

Small perturbations from ΛCDM allowed (tensors, features/oscillations, non-Gaussianity), but wildly dramatic effects highly constrained



BICEP/Keck - Planck

Multi-component Likelihood Analysis



r constraint consistent with zero (For BK+P L_0/L_{peak} is 0.4, which happens 8% of the time in a dust only model.)

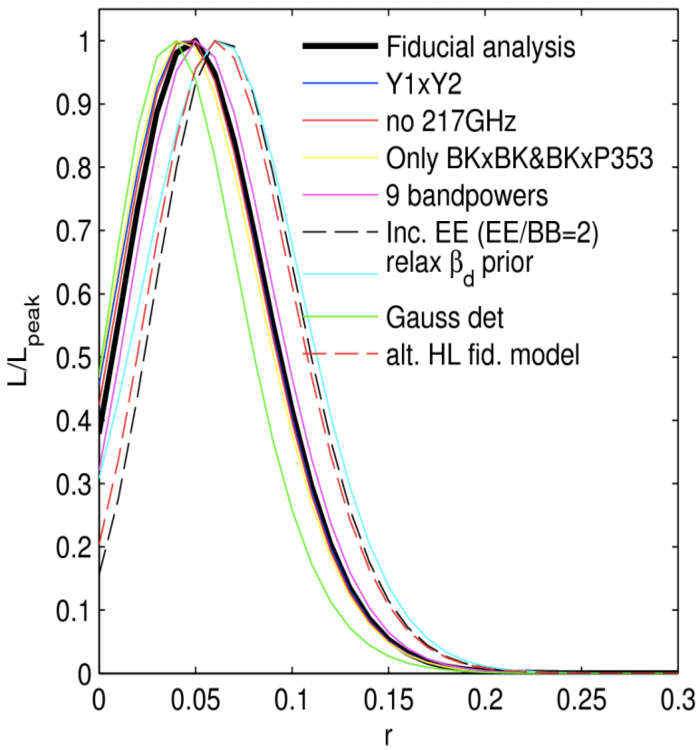
Dust is detected with 5.1 σ significance

As expected, dust and r are anticorrelated

- Use single and cross-frequency spectra between BK 150 GHz and Planck 217 & 353 GHz channels
- Try including:
  - Gravitational wave signal with amplitude r
  - Dust signal with amplitude A_d (specified at ℓ =80 and 353 GHz)

Major advance experimentally: direct bound competitive with indirect (TT) bound. Planck-BICEP/Keck reduced viable n_s-r region by 29 percent. Primed for key range of r down to Planck field range

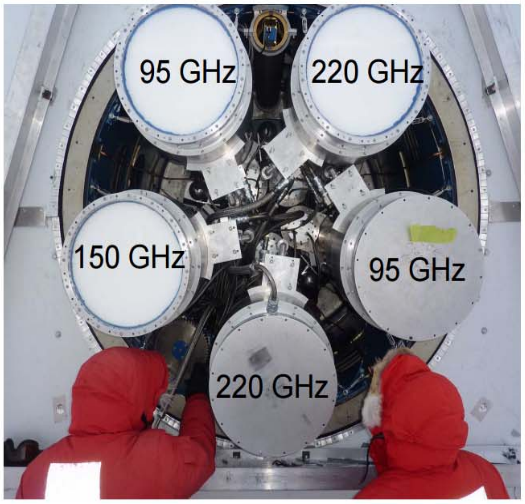
Variations on fiducial analysis



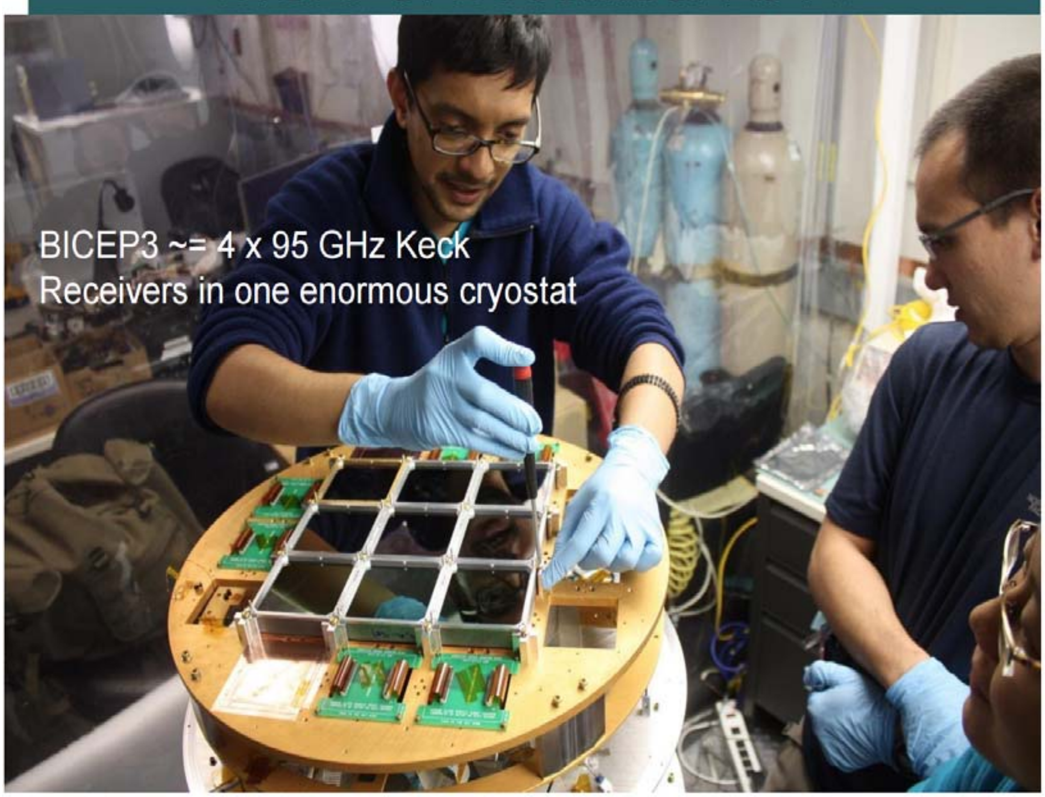
- We consider a range of variations on the fiducial analysis
- Most make little difference - see paper for details
- Excluding 353x353 makes little difference - this spectrum has little statistical weight
- The data "wants" a steeper dust SED - relaxing the β_d prior it pulls to the top end of the range and hence more of the 150x150 signal is interpreted as *r*. However β_d appears to be pretty well known so this should not be over interpreted.

BICEP/Keck/Planck Joint analysis; slide from G. Efstathiou, March 2015 Eurostrings.

- Two Keck Array receivers switched to 220 GHz
- First light February 2015

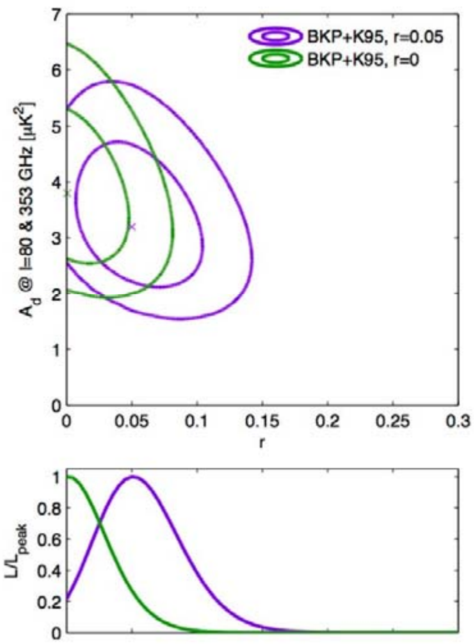


BICEP3: December 2014



Near Future Projections (+K95 2014)

Victor Buza
B2/ K /B3 collab.



Data Included:
— BK150
— Planck, 30 - 353 GHz
— Keck (2014), 95 GHz – data in the can!

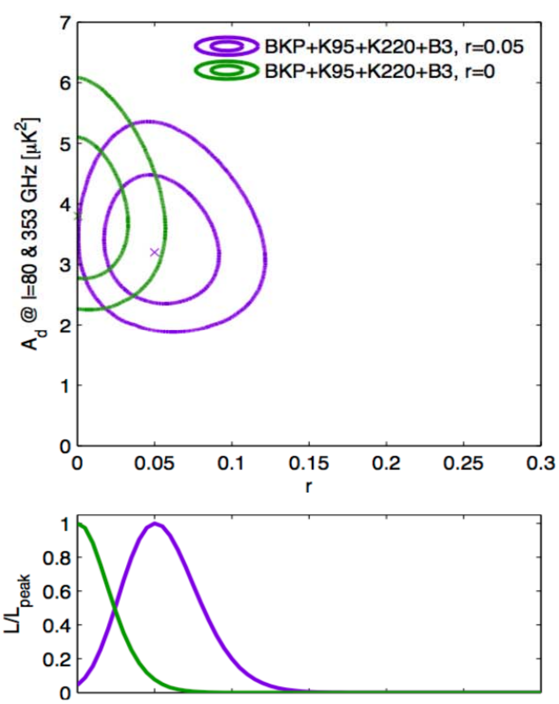
Contours are projected likelihood contours centered on different expectation values:
$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)
$r = 0$, $A_d = 3.8\ \mu K^2_{CMB}$

Of course we can't predict how the actual data will shift.

Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit).

$r < 0.060$ (95%) [0.062 if β_s=-3.0]
— or —
Foregrounds only PTE = 4.0% [4.3% if β_s=-3.0]

Farther Future Projections (+K95, 220, B3 2015)



Data Included:
— BK150
— Planck, 30 - 353 GHz
— Keck (2014 + 2015), 95 GHz – this year's data!
— Keck (2015), 220 GHz – this year's data!
— BICEP3 (2015), 95 GHz – this year's data!

Contours are projected likelihood contours centered on different expectation values:
$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)
$r = 0$, $A_d = 3.8\ \mu K^2_{CMB}$

Of course we can't predict how the actual data will shift.

Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit).
$r < 0.041$ (95%) [0.043 if β_s=-3.0]
— or —
Foregrounds only PTE = 0.6% [0.9% if β_s=-3.0]

- Lensing B-modes (non-Q. gravity)
  SPT ...
- SPIDER : flew Jan '15
  w/2 frequencies, more sky
  including cleaner patches
  next flight w/additional frequency
- ACT upgrades going after r
  w/multiple frequencies
- US CMB S4 $\to$ $\mathcal{O}(10^5)$ detectors
  (ground)
- Litebird Satellite (Japan et al)

Experimental Community Optimistic
about determining $r \gtrsim .01$

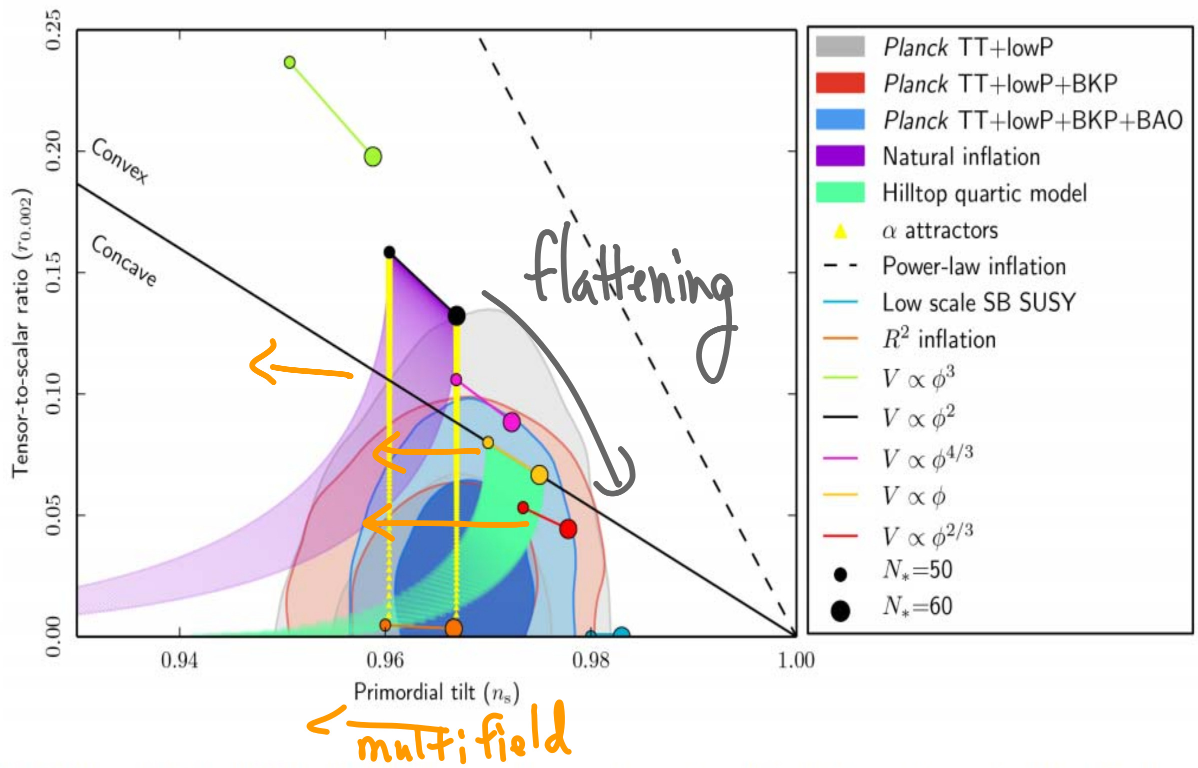


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

$V = \frac{1}{2} m^2 \phi^2$ 'strongly disfavo(u)red'

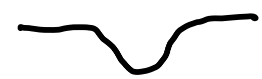
contains exit, 2 parameters $\leftrightarrow \langle \zeta\zeta \rangle$, N_e

Given that this minimal possibility is excluded, require additional parameter. ★ Expected from UV:

(mass > H) 'Dong et al '10 Flattening'

<u>Heavy</u> fields affect results:

they adjust in response to inflationary potential energy. QFT toy model

$$V(\varphi_L, \varphi_H) = g^2 \varphi_L^2 \varphi_H^2 + m^2 (\varphi_H - \varphi_0)^2$$ 

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2 \varphi_L^2}{g^2 \varphi_L^2 + m^2} m^2 \varphi_0^2$$

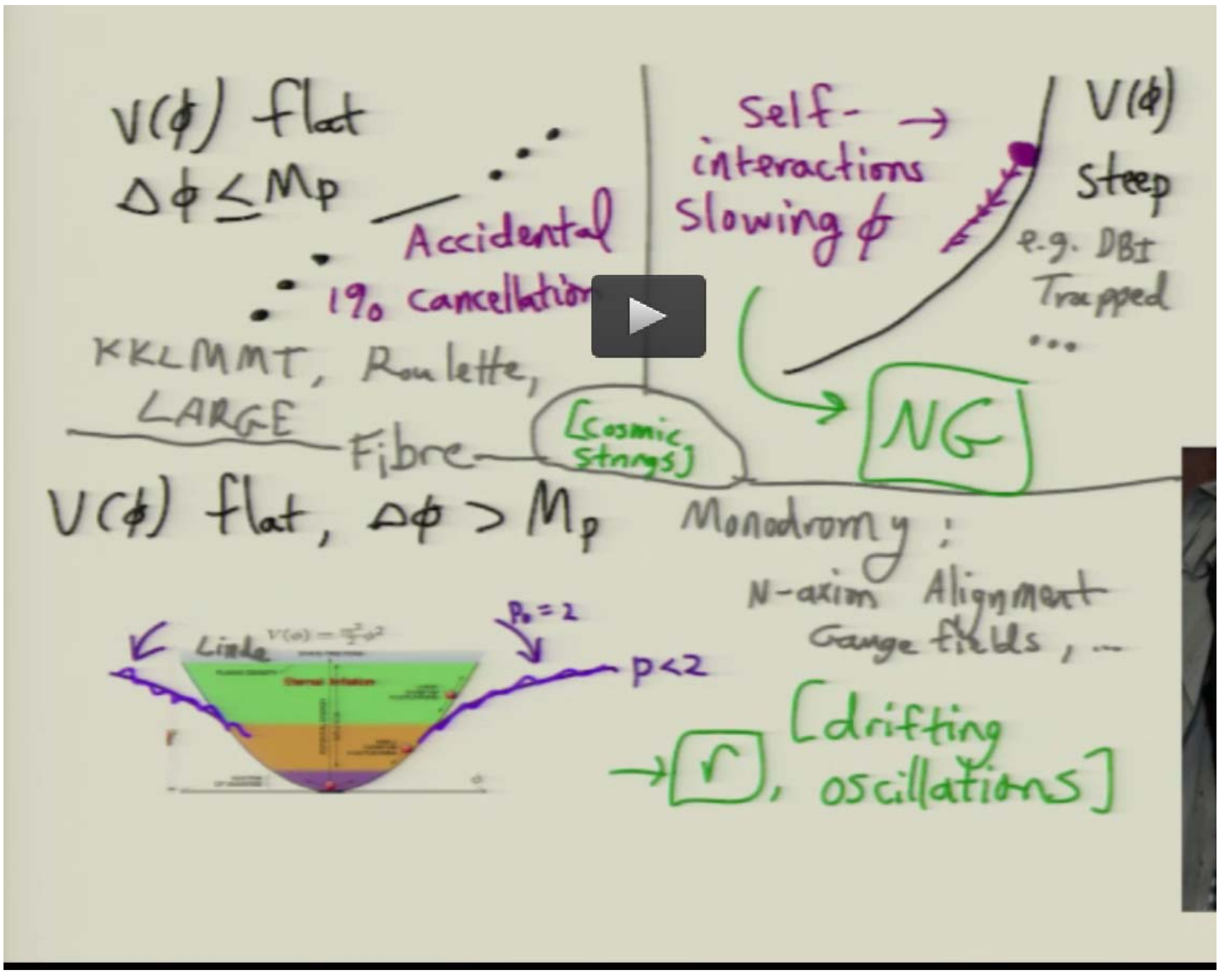
($\dot{\varphi}_H^2$ term subdominant)

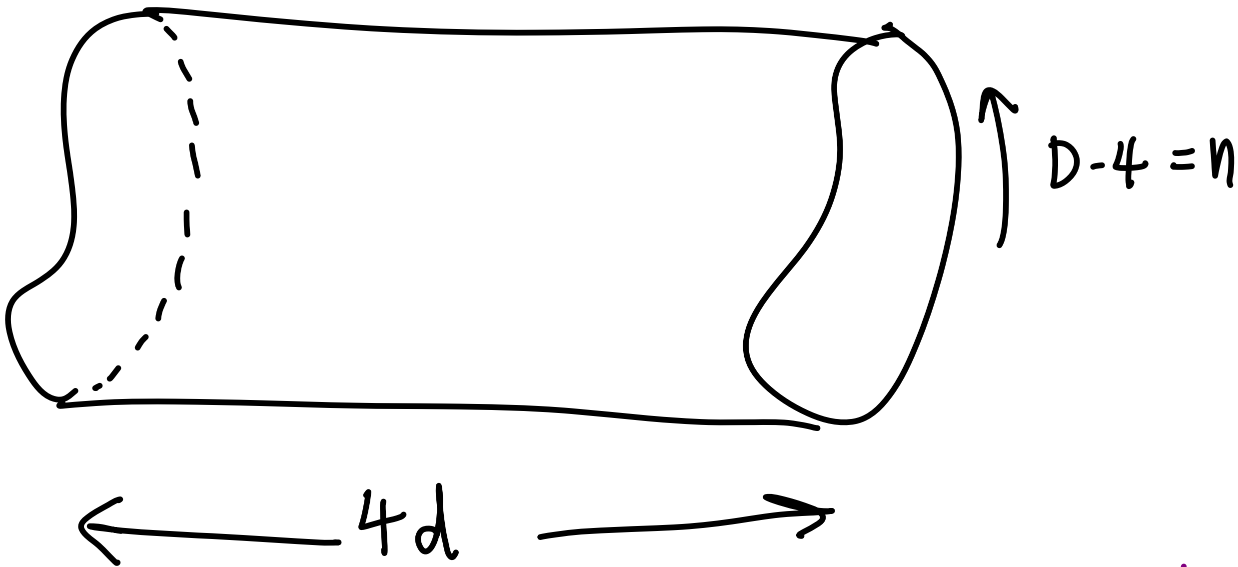
flatter: energetically favorable.

- UV completion of gravity (e.g. string theory) can introduce ϕ_H (e.g. 'moduli' scalar fields).

$\hookrightarrow V \propto \phi^n \longrightarrow V \propto \phi^{p<n}$ in examples.

Variety of inflationary mechanisms in string theory





scalar fields include string coupling

$$e^{(d-2)\hat{D}} = \frac{g_s^2}{L^n} \quad \text{and size} \quad L\sqrt{\alpha'} = e^{\phi}\sqrt{\alpha'}$$

$$S_{eff} = \frac{1}{2} M_p^2 \int d^4x \sqrt{g} \left\{ R - \sum_{i=1}^{n} (\partial \phi_i)^2 - 2(\partial \hat{D})^2 - V_{eff} + h.d. \right\}$$

Valid near appropriate weakly coupled, weakly curved solutions

Potential V_{eff} has structure

$$V(\tilde{D}, \phi; \theta, \ldots) \sim \sum_i \hat{V}_i(\theta \ldots) e^{\alpha_i \tilde{D} + \beta_i \phi}$$

bulk

dilaton size other geometry deformations, axions θ, brane positions, ...

+ warping effects (cf constraints)
Douglas ...

+ quantum, non-perturbative

with some terms

$$\hat{V}_i(\theta) \sim \begin{cases} \mu^4 (\theta - 2\pi N)^2 \\ \mu^4 \sqrt{1 + (\theta - 2\pi N)^2} \end{cases}$$

(axion monodromy)

Axions :

- ubiquitons (~half the fields in $D=10$ $\sim 2^D$ more generally)

- (discrete) symmetry protection

  but couple to 'moduli' $\Rightarrow$ back reaction

- Single axion period $f < M_p$

  Banks et al

- Multifield version less constrained

  $\leftrightarrow$ weak gravity conjecture ?

In string theory, the basic period $f_\theta (2\pi)^2$ a priori turns out $\ll M_p$ at weak curvature + coupling

Banks/Dine/Fox/Gorbatov
Svrcek/Witten

cf Arkani-Hamed et al

<u>Axions</u> $\hat{a} = \int_{\Sigma_p} \underbrace{A_{i_1 \cdots i_p}}_{\text{potential field (higher-dim'l analogue of Maxwell } A_\mu)} dx^{i_1} \wedge \cdots \wedge dx^{i_p}$

Σ_p: p-dim'l closed submanifold

$f_{\hat{a}}$ comes from kinetic term:

$$\int d^D x \sqrt{G_{(D)}}\, F_{i_1 \cdots i_{p+1}} G_{(D)}^{i_1 i_1'} \cdots G_{(D)}^{i_p i_p'} F_{i_1' \cdots i_{p+1}'}$$

$$= \int d^4 x \sqrt{g_4}\, f_{\hat{a}}^2 (\partial \hat{a})^2 = \int d^4 x \sqrt{g_4}\, (\partial \theta_{\hat{a}})^2$$

$\Rightarrow$ for all sizes $\sim R$, this yields

$$f_{\hat{a}} \sim M_p \left(\frac{\sqrt{\alpha'}}{R}\right)^p \ll M_p$$

$\sqrt{\alpha'}$ = string length

$$S = \frac{1}{2\alpha'^{\frac{D-2}{2}}} \int d^D x \sqrt{-G}\, e^{-2\phi_s} \left(R - \frac{D-10}{\alpha'} + 4(\partial\phi_s)^2 \right) + S_{matter}\,. \tag{3.1}$$

$$S_{matter} = \int d^D x \sqrt{-G}\Big\{ - \sum_{n_B} \tau_{n_B} \frac{\delta^{(D-1-n_B)}(x_\perp)}{\sqrt{G_\perp}} + \sum_{n_O} \tau_{n_O} \frac{\delta^{(D-1-n_O)}(x_\perp)}{\sqrt{G_\perp}} + e^{-2\phi_s}|H_3|^2 + \sum_p |\tilde{F}_p|^2 + C.S. + h.d.\Big\} \tag{3.2}$$

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

fluxes

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

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

(Direct Dependence)

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

This generalizes Stueckelburg couplings in electromagnetism

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

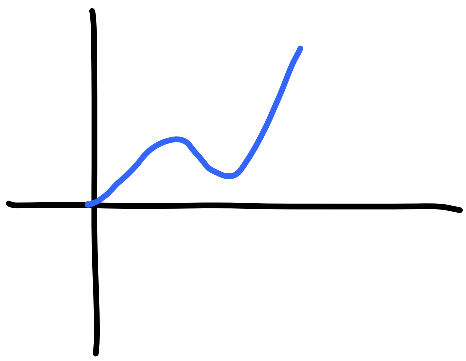
Gauge symmetry $A_\mu \to A_\mu + \partial_\mu \Lambda$
$\theta \to \theta - \Lambda$

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

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

Is there a corresponding unbroken phase?

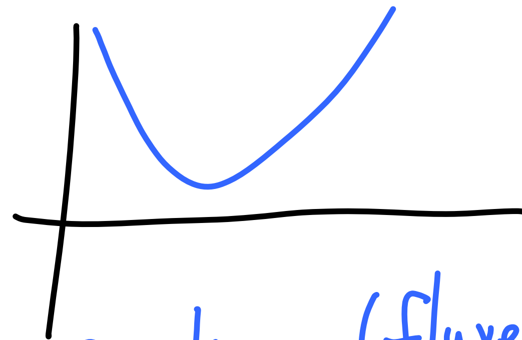
• Moduli: Two basic structures



3-term

$$\hat{a}x - \hat{b}x^2 + \hat{c}x^4$$

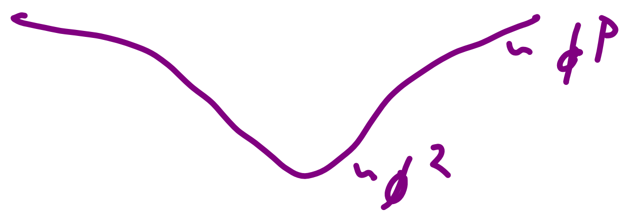
Need $\frac{\hat{a}\hat{c}}{\hat{b}^2}$ to stay w/in $O(1)$ window for minimum



2-term (fluxes)

$$\left(\frac{L_1}{L_2}\right)^n Q_1^2 + \left(\frac{L_1}{L_2}\right)^{\tilde{n}} (bQ_2)^2$$

$$\Rightarrow V \propto b^{\frac{2n}{n+\tilde{n}}} < 2$$



In specific models, find

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

$$\simeq \mu^{4-p}\phi^p + \Lambda^4(\phi)\cos\left(\underline{\underline{b(\phi)}}\right)$$

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

Role of Symmetry?

- $\breve{F}_q$'s gauge-invariant (Stuckelberg)

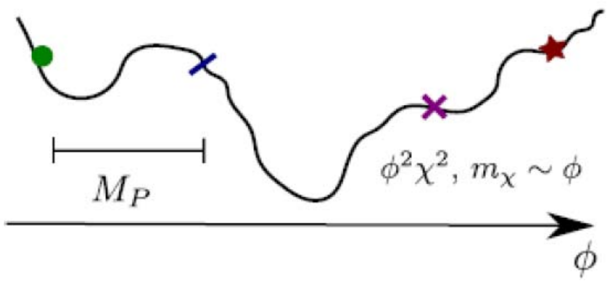
- The sector of the spectrum arising from higher-codimension branes wrapping the axion cycle is periodic, each individual element undergoing monodromy.

(This sector produces oscillatory features, at a model-dependent level.

- Other sectors (cf $\breve{u}$, L above) not protected by this symmetry. We take this into account ($\to$ flattening, when stable)

- Bottom-up radiative stability as in $m^2\phi^2$ etc.

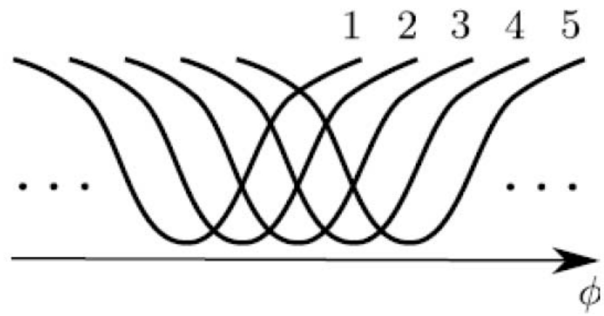
Parameterized ignorance of quantum grav.



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

No continuous global symm. in QG

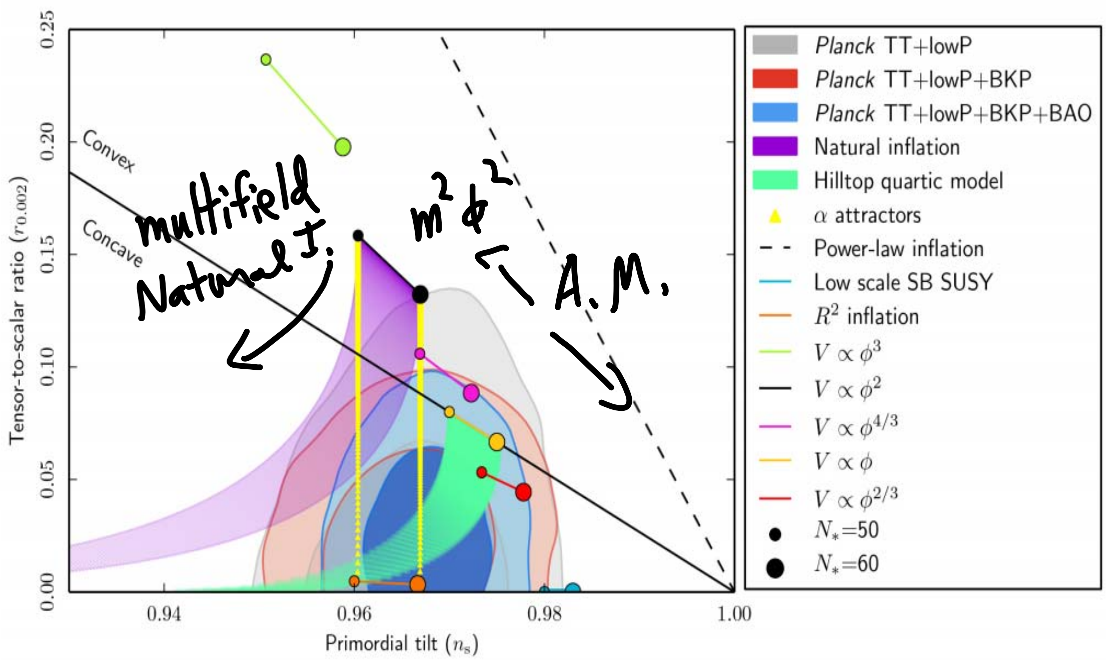
String Theory axions (and duals)



From ubiquitous Axion-Flux couplings

Discrete shift symm., f<<M_p

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



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Are there theoretical constraints to compare to data constraints?

- Multifield Natural Inflation & WGC
  - Kim Nilles Peloso (axion alignment) – N-flation
- Axion Monodromy parameter ranges

Weak Gravity conjecture $\overset{?}{\leftrightarrow}$ axion inflation

- Harvard Arkani-Hamed et al '06
  Rudelius
- Cornell Bachlechner, Long, McAllister
- Michigan Brown, Cottrell, Shiu, Soler
- Maryland Saraswat, Sundrum

...

Rough idea(s)

- QG $\Rightarrow$ ~~global symmetry~~

  so $g_{u(1)} \to 0$ should be problematic

- To avoid remnants, need light stable charged particles with $\frac{Q}{M} > 1$. Repulsion beats attraction so BH can decay.

- Connection to Natural inflation:

Basic idea:

$$\frac{Q}{M} \longleftrightarrow \frac{M_p}{f S}$$

S ← instanton action

f ← period in cosine $\Lambda^4 \cos\left(\frac{\phi}{f}\right)$

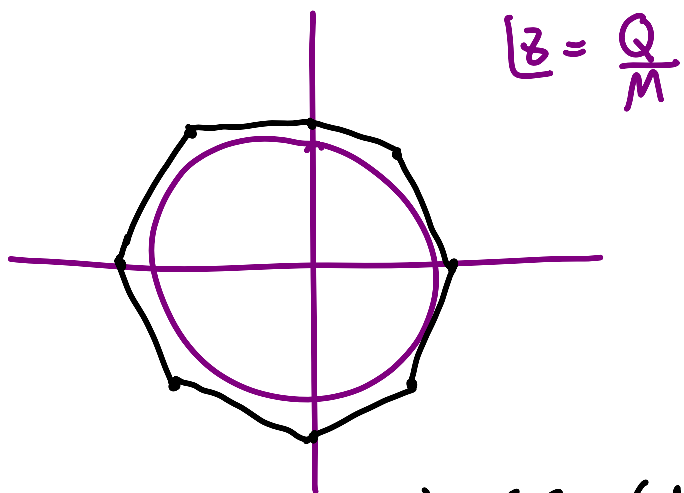
$$\frac{M_p}{f}\phi \sim Q\theta$$

from instanton effects

$$e^{-S + i\frac{\phi}{f}}$$

including multi-instantons?
If suppressed, these only add short-range wiggles in $V(\phi)$

- Multidimensional $\vec{Q}$ vectors
- Axion mixing, > 1 Instanton per axion



- Different forms of WGC (depending e.g. on if allow finite # remnants)
- Only a very strong form (beyond orig WGC paper) would exclude multifield Natural Inflation
- Disfavored in data (modulo flattening w/ additional d.o.f.)
- None of this applies if incorporate monodromy ($f < M_p$ fine!)

Axion monodromy systematics

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

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

$$\downarrow$$

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

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

In $D>10$, ρ_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 ρ_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

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

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

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

A Bound on Inflationary Potentials from Twisted Tori

Gur-Ari

September 26, 2014

Arbitrary D

$p \le 2$

e.g. $\dfrac{2s}{s+2}$

e.g. case $\underset{\substack{\cap \\ SL(n,\mathbb{Z})}}{M} = e^{X}$ ← real

$$ds^2 = L_z^2 dz^2 + d\tilde{\xi}^T (e^{zX})^T L^2 (e^{zX}) d\tilde{\xi}$$

wrap 4-brane on cycle $\sigma_a d\xi^a$

& compute DBI action →

$$S = -T_4 \int d^4x d\xi \left[V(z)\left(1 - \dot{z}^2 + \cdots\right)\right]$$

$$V(z)^2 = \sigma^T (e^{zX})^T e^{zX} \sigma$$

$$S = -T_4 \int d^4x\, d\varsigma \left[V(z)\left(1 - \dot{z}^2 + \cdots\right)\right]$$

$$V(z)^2 = \sigma^T \left(e^{zX}\right)^T e^{zX} \sigma$$

$\Rightarrow$ if σ an eigenvector of e^{X} with e-value $e^{\gamma} > 1$

will get $\partial\phi_{\text{canonical}} = e^{\gamma z}\partial z$

$$\Rightarrow \quad V(\phi) = \phi^2$$

More generally, will have

$$e^{zX} \sim \begin{pmatrix} 1 & z & \cdots & z^{D-5} \\ & \ddots & & \\ & & \ddots & \\ & & & 1 \end{pmatrix} \to p = \frac{2s}{s+2} < 2$$

$s = 1, \ldots, \mathcal{O}(D)$

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

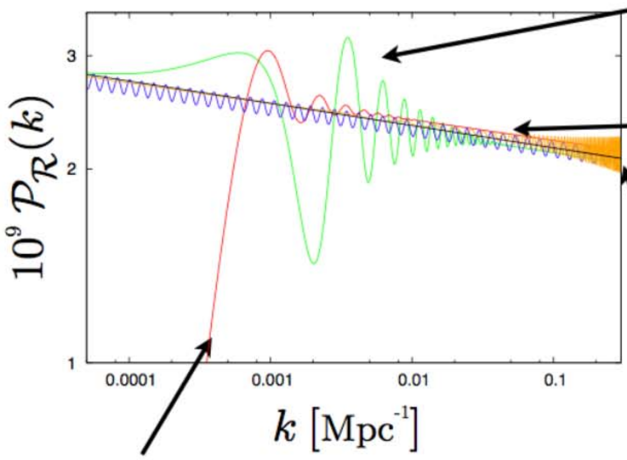
Additional Phenomenological directions

ΛCDM favored : $\chi_{\text{d.o.f.}} \sim 1.03\text{-}4$

1.04×2000 ℓ-modes in power spectrum $\sim$ Room for $\Delta\chi^2 \sim 80$ improvement, if $\exists$ additional structure

- Ongoing work in & out of Planck
  w/ Peiris et al   w/ Flanger et al
- Evidently polarization systematics still in progress, wait for final application to such searches

Searches for features:



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

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

$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

$$\mathcal{P}_\mathcal{R}^{\mathrm{lin}}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\mathrm{lin}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{lin}}}\cos\left(\omega_{\mathrm{lin}}\frac{k}{k_*} + \varphi_{\mathrm{lin}}\right)\right]$$

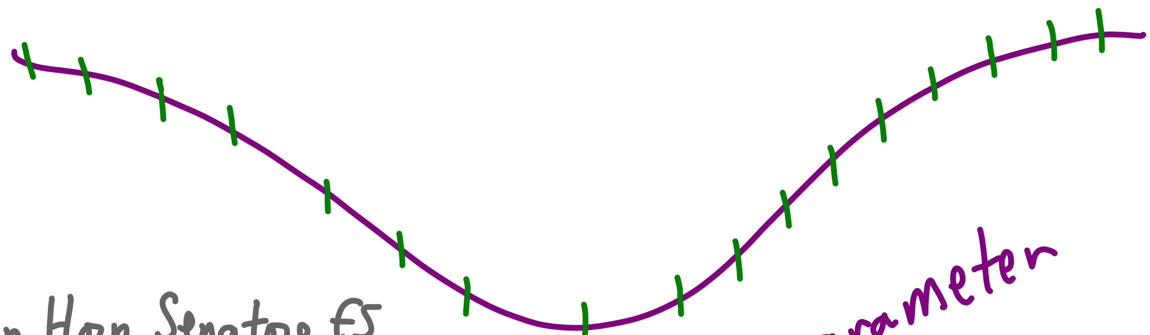
Just enough e-folds, i.e. inflation preceded by a kinetic stage

- No detection (G. Efstathiou/Planck)

(Instantons naturally suppressed in slow-roll AM, but interesting model-dep't signature.)

- A few interesting low-σ anomalies/'hints'
  e.g. multi-frequency log-spaced oscillations & equilateral NG
  $\gtrsim 3\sigma$ (enhanced w/polarization)
  still working

In above theory, oscillatory features more pronounced for regime with particle/string production



Green Horn Senatore ES '09

• Trapped Inflation $\xleftrightarrow{\text{parameter}}$ slow-roll AM (previously analyzed in continuum, leading to equilateral NG

Plan: Incorporate oscillations & analyze $\langle \zeta\zeta \rangle$, $\langle \zeta\zeta\zeta \rangle$. Check if ties above elements together (& effect on significance)

w/Senatore, Flauger,...

Final numerology :

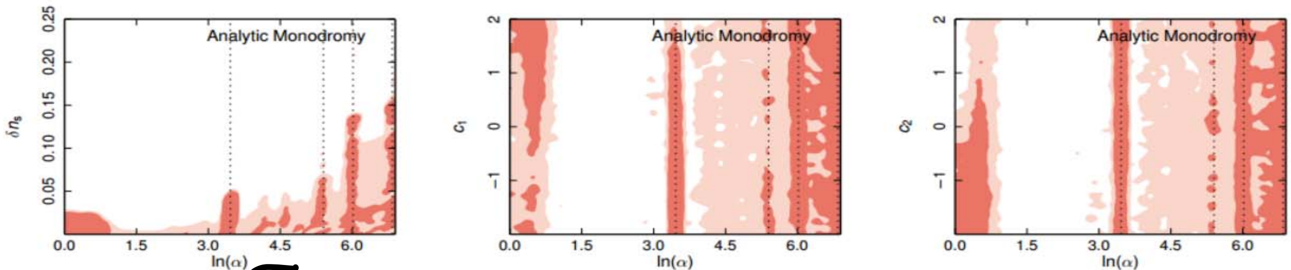


Fig. 37. Constraints on the parameters of the analytic template, showing joint 68 % and 95 % CL. The dotted lines correspond to the frequencies showing the highest likelihood improvements (see text).

$\log(35) \cong 3.5$

Planck Collaboration: *Planck* 2015 Results. Constraints on primordial NG

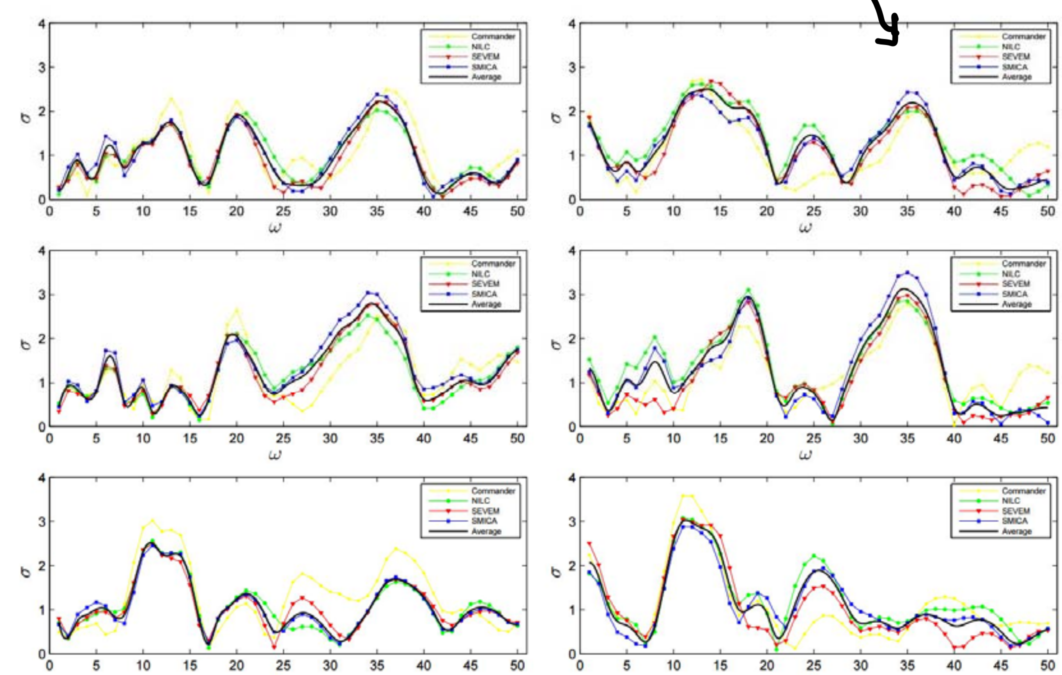
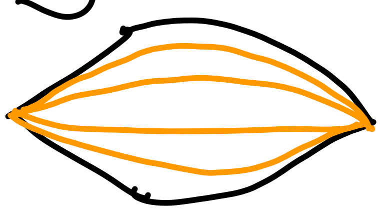


Fig. 19. Generalized resonance models analysed at $\ell_{\max} = 2000$ (E-modes $\ell_{\max} = 1500$) for the different *Planck* foreground separation methods, `SMICA` (blue), `SEVEM` (red), `NILC` (green), `Commander` (yellow), together with the SSN average (black). The upper panels apply to the constant resonance model (Eq. 10), with T-only (left) and $T+E$ (right), the middle panels give results for the equilateral resonance model (Eq. 13), and the lower panels for the flattened resonance model (Eq. 14). Both the equilateral and flattened resonance models produce broad peaks which are reinforced with polarization (middle and bottom right panels).

Structure of string compactification & thought-experimental cosmo

dS/dS duality



$$ds^2_{dS_d} = \cos^2\frac{w}{L}\, ds^2_{dS_{d-1}} + dw^2$$

$\leftarrow -dt^2 + e^{2Ht} d\vec{x}^2$

$\uparrow$ $g_{00} \to 0$ at $w = \pm \frac{\pi L}{2}$
Low energy regimes
each like AdS/CFT

This is reproduced by brane constructions Dong Horn ES Torroba

$\longrightarrow$ 2 large-N QFT_{d-1}
Coupled to GR_{d-1}

$M^{d-3}_{planck,\, d-1} \sim S \times \frac{1}{L^{d-3}}$ finite

Decay $\Rightarrow$ Entropy bound $\to \infty$, $M_{p,d-1} \to \infty$

Summary

- CMB data has interesting implications for QG in the early U.
  - Related to (e.g. symmetry) structures in string theory.
  - More to do to understand theory constraints as data comes in (& vice versa)
- Large-scale structure will go further on NG, other features

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- theory constraints also tie in to cosmo holography