Signatures of Axion Monodromy Inflation

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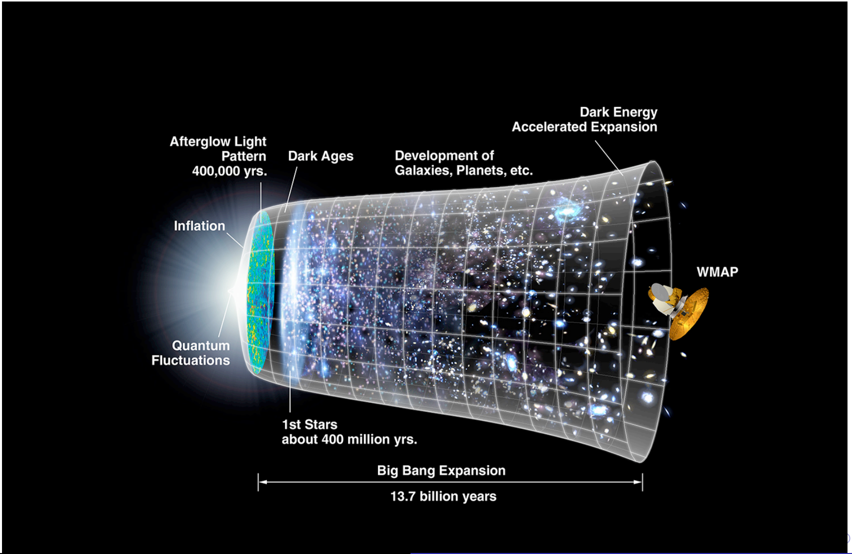
based on arXiv:0907.2916
with Flauger, McAllister, Pajer and Westphal

McGill University
December 2009

Outline

Inflation


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Brief Introduction to Inflation

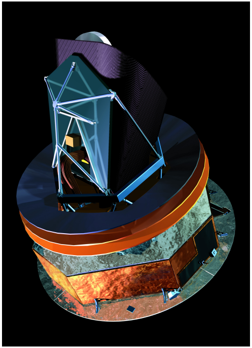
A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2 \qquad H \approx const$$

Generic Predictions:

- Scalar perturbations are approximately scale-invariant: $n_s \approx 1$
- Tensor to scalar ratio $r = 16\epsilon$, where $\epsilon \equiv -\frac{\dot{H}}{H^2}$.
- Scalar perturbations are approximately Gaussian.

Cosmological Data



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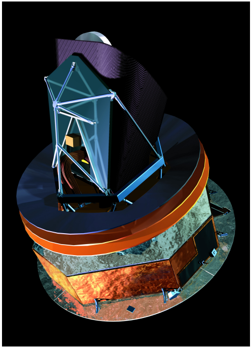

- Planck was launched on May 14th 2009 and started collecting data since August
- Planck is able to detect $r > 0.05$ and constrain $f_{NL}^{loc} < 6$

r and the Field Excursion

- $\mathcal{L} = 1/2(\partial\phi)^2 - V(\phi)$

[1] Lyth, 1996

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- $\mathcal{L} = 1/2(\partial\phi)^2 - V(\phi)$
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  $\frac{\Delta\phi}{M_p} = \int_{N_{CMB}}^{N_{end}} dN\sqrt{\frac{r(N)}{8}}$

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  $\frac{\Delta\phi}{M_p} \geq O(1)\left(\frac{r}{0.01}\right)^{1/2}$
- Detectable gravitational waves suggests superplanckian field variation:$\Delta\phi > M_p$ [1]

[1] Lyth, 1996

UV Sensitivity

- An inflaton potential in EFT:
  $V = 1/2m^2\phi^2 + 1/4\lambda\phi^4 + \phi^4\Sigma_{p=1}^{\infty}\lambda_p\left(\frac{\phi}{\Lambda}\right)^{2p}$

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- Still not satisfactory b/c EFT is ignorant about Planck scale.
- We need a candidate UV completed theory, string theory.

Shift symmetry of axions

- Axions are pseudoscalar fields with only derivative couplings. Continuous shift symmetry: $S(a) = S(a + \text{const})$.

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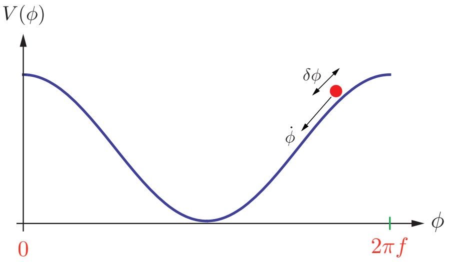
- Natural Inflation[2] with potential $V(\phi) = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$



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Axion inflation

- Problem with Natural Inflation: Axions with super-Planckian decay constant[3] are elusive in controllable string theory setup.

[3] Banks, Dine, Fox and Gorbatov, 2003; Svrcek and Witten, 2006
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- Our proposal: recycle an axion N times via monodromy

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Real-life Monodromy: Waterride

A waterride I have taken when I was young

Real-life Monodromy: Spiral Stairs

or the spiral stairs once walked on

Summary of Motivations

- Large field inflation is both interesting for observations and theoretical concerns.

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- Our model= An axion from string theory with shift symmetry
  + Its non-periodic potential from monodromy
  + Modulations computed with string theory setup

Axions in String Theory

- String theory provides many axions:

$$b(x) = \int_{\Sigma_2} B_2,\ c(x) = \int_{\Sigma_p} C_p$$

[5] Wen and Witten, 1986

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- Worldsheet vertex operator[5]:

$$V(k) = \int_{WS} d^2\xi exp(ik \cdot X(\xi))\epsilon^{\alpha\beta}\partial_\alpha X^\mu \partial_\beta X^\nu B_{\mu\nu}(X)$$

$V(k=0) = \int_{\Sigma_2} B_2 = 0$ indicates axion b can only have derivative couplings.

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Shift Symmetry Breaking

We need to break shift symmetry to obtain an inflaton potential.

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From D-branes

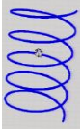
The presence of worldsheet boundaries such as D-branes.
We use wrapped branes to create a monodromy.

From instantons

Worldsheet instantons, or D-brane instantons introduce sinusoidal modulations.

Monodromy from a Five Brane

Consider a D5-brane wrapping on a two cycle[6],



$S_{DBI} = -T_5 \int d^4x \sqrt{g_4} \int d^2\xi \sqrt{det(G^{ind} + B^{ind})}$
$V(b) = T_5 \sqrt{l^4 + b^2}$
Take large b limit: $V(\phi) = \mu^3 \phi$

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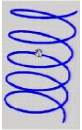

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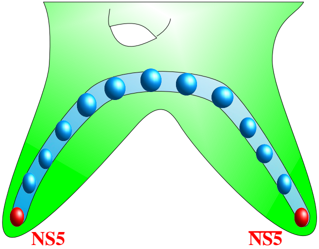

Fixing Parameters

A linear potential

$V = \mu^3 \phi$ with $\epsilon = \frac{1}{2\phi^2}$, $\eta = 0$

- $N(\phi) = \int_{\phi_{end}}^{\phi} \frac{d\phi}{\sqrt{2\epsilon}}$ 60 efolds indicates $\phi_* = 11Mp$
- COBE normalization: $P_s = \frac{1}{24\pi^2}\frac{V}{\epsilon} = (5.4 \times 10^{-5})^2$ fixes $\mu = 6 \times 10^{-4} Mp$

Predictions of the Linear Potential

$V = \mu^3 \phi$

- Tensor mode: $r = 0.07$. We will soon know!
- Tilt: $n_s = 0.975$

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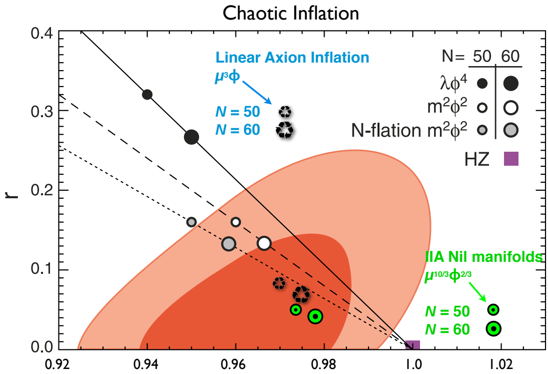
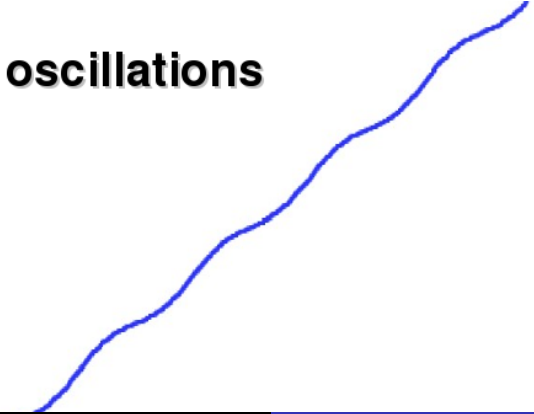


Modulations

- $V(\phi) = \mu^3\phi + \mu^3 bf\cos(\frac{\phi}{f})$
- Monotonicity: $b < 1$
- Number of oscillations in CMB: $\frac{1}{10f}$



Background Evolution

Solve $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$ perturbatively in b

$\phi = \phi_0 + \phi_1$

Zeroth order solution: $\phi_0(t) = (\phi_*^{3/2} - \frac{\sqrt{3}}{2}\mu^{3/2}t)^{2/3}$

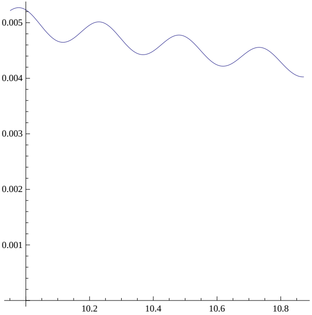
First order solution: $\phi_1 \approx -3bf^2\phi_0 \sin\left(\frac{\phi_0}{f}\right)$

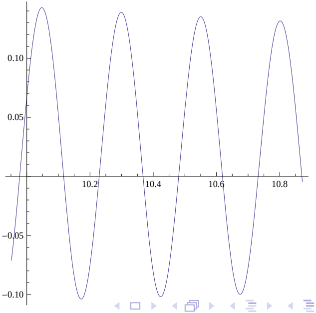
Background Evolution

Slow roll parameters

$$\epsilon = \epsilon_0 + \epsilon_{osci} \approx \frac{1}{2\phi_*^2} - \frac{3bf}{\phi_*} \cos\left(\frac{\phi_0}{f}\right)$$

$$\eta = \eta_0 + \eta_{osci} \approx 0 - 6b \sin\left(\frac{\phi_0}{f}\right)$$





Resonant Mechanism

- Background oscillates at frequency $\omega = \frac{\dot{\phi}}{f}$
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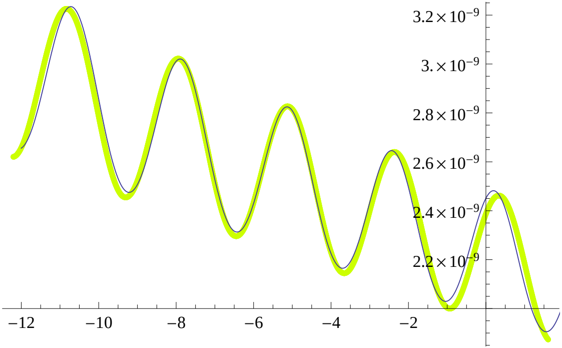
- Perturbation mode of comoving momentum k oscillates at frequency $\frac{k}{a}$ until freezes at $k = aH$
- So when $H < \omega < M_p$, every mode will resonate with the background at some time.

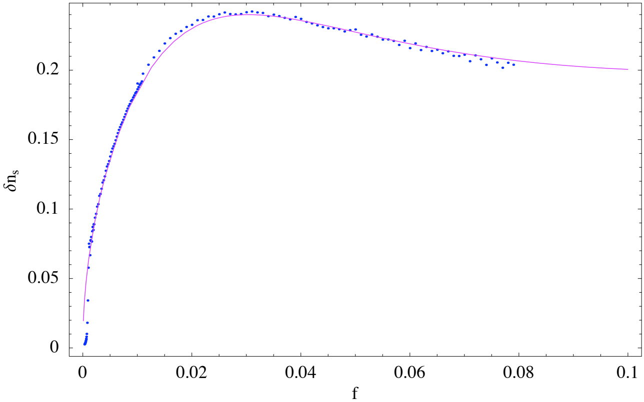
Postulated Power Spectrum

- Oscillations in the power spectrum
$P_s = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left(1 + \delta n_s \cos\left(\frac{\phi_k}{f}\right)\right)$ where $\phi_k \simeq \phi_* - \frac{\ln k/k_*}{\phi_*}$

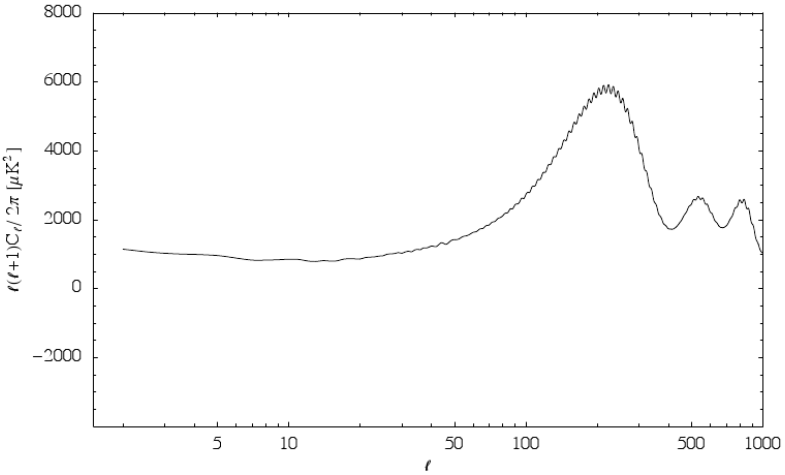


Analytical Power Spectrum

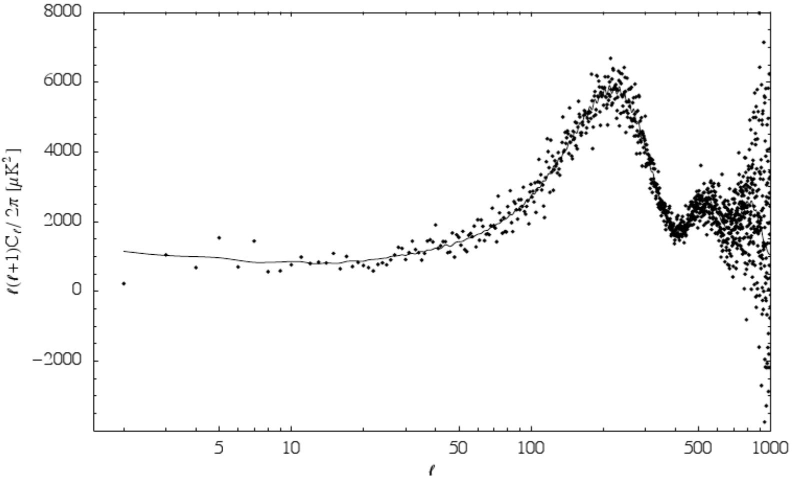
Solution: $\delta n_s = \frac{12b}{\sqrt{(1+(3f\phi_*)^2)}}\sqrt{\frac{\pi}{8}\coth\left(\frac{\pi}{2f\phi_*}\right)f\phi_*} \sim 24b\sqrt{f}$



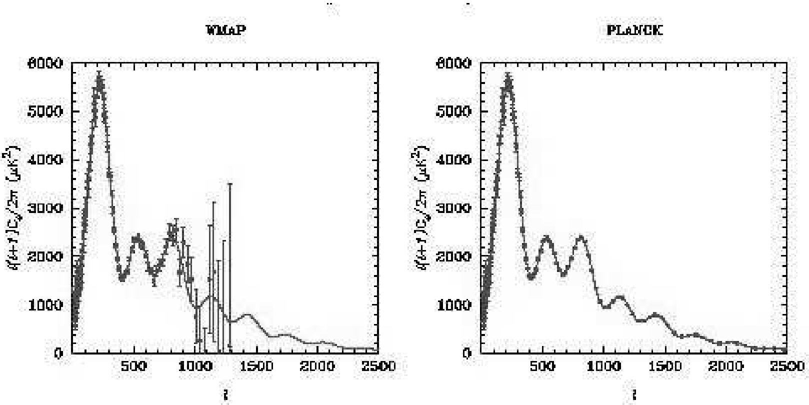
Predicted Angular Power Spectrum



Compare with Unbinned WMAP



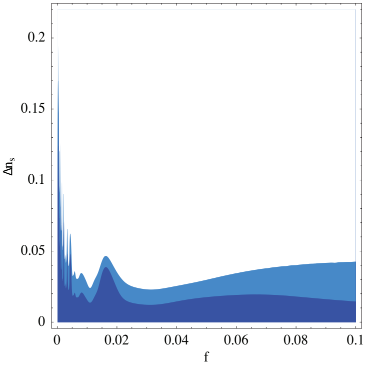
Improvement from Planck



[7]

[7]Planck Collaboration, 2006

Power Spectrum: Likelihood Analysis



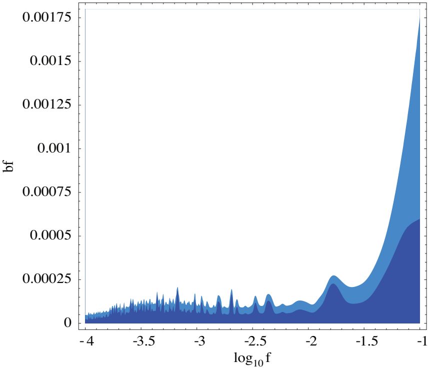
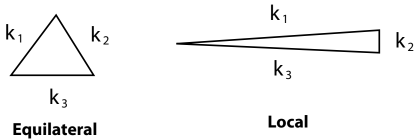


Figure of merit:

$$bf < 10^{-4} \text{ for } f < 0.01$$

Lightning review of non-Gaussianity

- Simple case: $\phi(x) = \phi_G(x) + f_{NL}^{local}\, \phi_G^2(x)$ [8]
- f_{NL}, amplitude of bispectrum, is usually a function of three momenta



[8] Komatsu and Spergel,2001
[9] Komatsu et. al. WMAP5 2008

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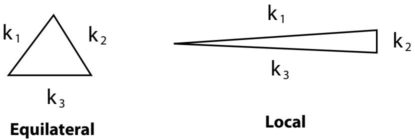


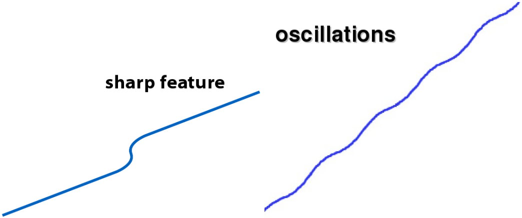
- WMAP5 data gives: $-9 < f_{NL}^{local} < 111, \; -151 < f_{NL}^{equil} < 253$ [9]

  Planck will constraint $f_{NL}^{local} < 6$

[8] Komatsu and Spergel,2001
[9] Komatsu et. al. WMAP5 2008

f_{NL} from Inflation Models

- Canonical single-field slow-roll[10] : $f_{NL} \sim O(\epsilon), \quad \epsilon \sim 10^{-2}$
- Curvaton, non-canonical kinetic terms(k-inflation, DBI) or features in the potential:



[10] Maldacena, 2003

Non-Gaussianity: Oscillatory

- Resonant non-Gaussianity condition[11]: $H < \omega < M_p$ for linear potential: $2.4 \times 10^{-6} < f < 0.09$.

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- $\langle \mathcal{R}(\tau, \mathbf{k}_1)\mathcal{R}(\tau, \mathbf{k}_2)\mathcal{R}(\tau, \mathbf{k}_3)\rangle = \frac{P_s^2}{(\mathrm{k}_1\mathrm{k}_2\mathrm{k}_3)^2} f_{res} \sin\left(\frac{1}{\phi f} \ln \mathrm{K} + \mathrm{phase}\right) \delta^3(\mathbf{K})\,(2\pi)^7$, [12]
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- $f_{res} \simeq \frac{3\,\dot{\eta}_{osci}}{8H\sqrt{\phi f}}$,
- Our model:

$$f_{res} \simeq \frac{9b}{4\phi_0^{3/2} f^{3/2}} = \frac{9}{4} b \left(\frac{\omega}{H}\right)^{3/2}$$

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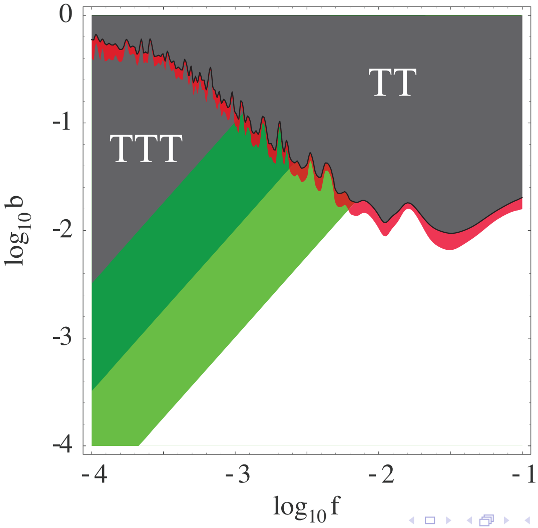
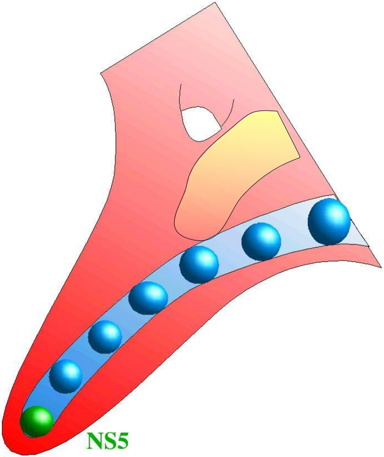
Summary of the Phenomenology

- r=0.07: Gravitational waves detectable by Planck.
- Potentially detectable oscillations in scalar power spectrum.
- Potentially detectable resonantly enhanced non-Gaussianity.

Parameter Space



Cartoon of Embedding



The Plan

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Decay constant f

Calculate the decay constant from the kinetic term: $-\frac{1}{2}f^2(\partial c)^2$
Recall in SUSY we have $\mathcal{L} = K_{a\bar{a}}\partial\Phi^a\partial\bar{\Phi}^{\bar{a}}$ for superfields

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Size of the modulation

Stabilize the moduli following KKLT
Scalar potential: $V = e^K(|DW|^2 - 3|W|^2)$

Need to know D=4 $\mathcal{N} = 1$ data.

$D = 4, \mathcal{N} = 1$ data from Type IIB O3/O7 orientifolds

Under orientifold action, cohomology classes split,$H^{r,s} = H_+^{r,s} + H_-^{r,s}$
Corresponding two cycle bases ω_A also split into ω_a, $a = 1, \cdots, h_-^{1,1}$,and ω_α, $\alpha = 1, \cdots, h_+^{1,1}$ [13]

[13]Grimm and Louis,2004

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Chiral multiplet

$$G^a \equiv \frac{1}{2\pi}(c^a - i\frac{b^a}{g_s})$$

$$T_\alpha \equiv i\rho_\alpha + \frac{1}{2}c_{\alpha\beta\gamma}v^\beta v^\gamma + \frac{g_s}{4}c_{\alpha bc}G^b(G - \bar{G})^c$$

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- $K = log\left(\frac{g_s}{2}\right) - 2log\mathcal{V}_E$
- $\mathcal{V}_E = \frac{1}{6}c_{\alpha\beta\gamma}v^\alpha(T,G)v^\beta(T,G)v^\gamma(T,G)$, note specifically $v = v(\mathrm{Re}\,T, \mathrm{Im}\,G)$

[13] Grimm and Louis,2004

Calculation of Axion Decay Constant

- $-\frac{1}{2}f^2(\partial c)^2 \subset K_{G\bar{G}}\partial G\partial\bar{G}$

$$\frac{f^2}{M_p^2} = \frac{g_s}{8\pi^2}\frac{c_{\alpha--}v^\alpha}{\mathcal{V}_E}$$

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- Validity of α' expansion: use worldsheet instanton to estimate: $e^{-S_{WS}} < e^{-2}$

$$2 < \frac{1}{2\pi\alpha'}\int \sqrt{g_{string}} = \sqrt{g_s}v^{\alpha}2\pi$$

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$$\frac{f^2}{M_p^2} = \frac{g_s}{8\pi^2}\frac{c_{\alpha--}v^\alpha}{\mathcal{V}_E}$$

- Validity of α' expansion: use worldsheet instanton to estimate: $e^{-S_{WS}} < e^{-2}$

$$2 < \frac{1}{2\pi\alpha'}\int \sqrt{g_{string}} = \sqrt{g_s}v^\alpha 2\pi$$

- Lower bound on f:

$$\frac{f^2}{M_p^2} > \frac{\sqrt{g_s}}{(2\pi)^3\mathcal{V}_E}$$

Warmup: Review of KKLT

- Non-perturbative superpotential:

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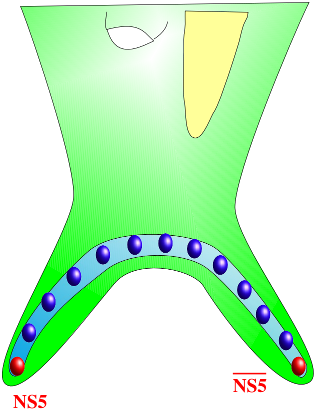
- $\mathcal{U}_{mod} = \frac{g_s}{2} \left(\frac{3|W|^2}{\mathcal{V}_E^2} \right)_{(0)}$ from AdS minimum+uplifting
- $bf < 2c_0 \cdot 10^7 \frac{g_s}{\mathcal{V}_E^2} e^{-2/g_s} \left(\frac{W}{0.1} \right)^2$

Consistency Conditions

- $g_s \ll 1$
- Euclidean instanton:$e^{-a_\alpha T_\alpha} < e^{-2} \rightarrow \tau_\alpha > \frac{N_\alpha}{\pi}$
- Back reaction on the throat $N_w = \frac{\phi}{2\pi f} \ll \frac{R_{perp}^4 X}{4\pi g_s} \rightarrow \frac{f}{M_p} > \frac{0.09}{X^{1/3}\mathcal{V}_E^{2/3}}$
- $V_{inf} \ll U_{mod} \rightarrow \tau_\alpha \ll 73 - 8\log\left(\frac{v^\alpha \pi\sqrt{g_s}}{2g_s}\right)$ where we used $N_\alpha < 50$
- Back reaction of the 4-cycle volume.
- Higher derivative terms

Backreaction of 4-cycle volume

Effect of N_w $D3$ branes[14]



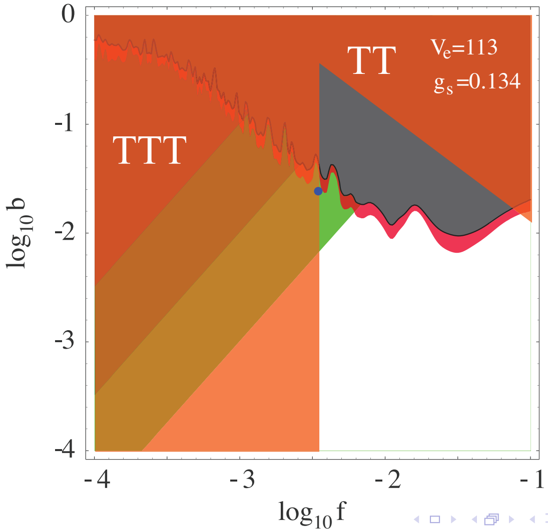
[14] Alternative: Berg, Pajer and Sjörs, to appear

Higher derivative terms

- $S_{10D,E} \supset \alpha'^3 \bar{R}^4$
- ${\bar{R}_{MN}}^{PQ} \supset \nabla_{[M} {H_{N]}}^{PQ}$ and ${H_{[M}}^{C[P} {H_{N]C}}^{Q]} + \ldots,$[15] where $H = dB$
- $S_{4D} = \int d^4x \left[-\frac{1}{2}\dot{\phi}^2 + \frac{\dot{\phi}^8}{M_I^{12}} + \frac{\ddot{\phi}^4}{M_{II}^8} \right],$
- $\frac{\omega}{M_I}, \frac{\omega}{M_{II}}$ at most a few percent.

[15] Gross and Sloan, 1987

A Toy Example



Conclusions

- Axion monodromy inflation is falsifiable by its prediction of $r = 0.07$.
- In addition: possible detectable oscillations in the power spectrum and resonantly enhanced non-Gaussianity.
- We study the microscopic constraints on specific class of models in string theory.

Future directions

- Study of oscillatory type non-Gaussianity with data.
- Study of reheating.
- Realization of chain inflation.
- Other compactification models.