String Cosmology - A Short Synopsis

- The temperature angular power spectrum of the CMB is shown, with a focus on the first acoustic peak and the Sachs-Wolfe effect.
- The measured spectrum is compared to the theoretical prediction of the CDM model, showing excellent agreement.
- The Planck Collaboration XVI have provided a comprehensive catalogue of compact sources, including Galactic and extragalactic objects.
- The catalogue is accurate to a $0.1^\circ$ arcminute, with an accuracy of $\pm 50\mu K$ at $1500\ GHz$.
- The catalogue includes a high angular resolution, with a resolution of $0.07^\circ$ at $1500\ GHz$ and $0.1^\circ$ at $>6000\ GHz$.
- The catalogue is suitable for quick follow-up, particularly with the short-lived BICEP2 experiment.
• **Why use string theory in cosmology?**

  • singularity at the beginning! — need quantum gravity to resolve
  
  • inflation is UV-sensitive — needs a high-scale theory
  
  • what are dark energy & dark matter?
  
• if we try to use string theory for cosmology — better build on *generic consequences* of string theory!

  • string vacuum structure seems to be a “landscape” of **extremely many vacua** — *this can accommodate a tiny C.C.*

  • false-vacuum eternal inflation & **tunneling** set cosmological initial conditions — hint from large-scale CMB anomalies?
• if we try to use string theory for cosmology — better build on *generic consequences* of string theory!

• *string compactification produces moduli*:
  - need moduli stabilization - spectrum of massive scalars
    e.g. [GKP '01; KKLT '03; LVS '05] … *see Joe’s talk*
  - modulated reheating from isocurvature fluct. of light moduli
    e.g. [Cicoli, Tasinato, Zavala, Burgess & Quevedo ‘12]
  - non-thermal DM & baryogenesis from moduli decay
    e.g. [Acharya, Kumar, Bobkov, Kane, Shao & Watson ’08; Allahverdi, Cicoli & Dutta ‘13] … *see talk*
  - inflation: many low-r models — inflection point & R+R2-like models

• *light axions*:
  - axion dark matter
    e.g. [Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell ‘09]
    [Acharya, Bobkov & Kumar ‘10] [Cicoli, Goodsell & Ringwald ‘12]
  - dark radiation: e.g. lightest volume modulus of LVS decays into volume $C_4$-axion — $O(0.5)$ extra eff. neutrino species in CMB
    e.g. [Cicoli, Conlon & Quevedo ‘12] [Higaki & Takahashi ‘12] … *see talks by Marsh, Rummel, Angus*
why so many causally disconnected regions with $\Delta T/T \sim 10^{-5}$? today: 13.7 billion years

CMB: 370,000 years

Big Bang: $t = 0$
• inflation: period quasi-exponential expansion of the very early universe

(solves horizon, flatness problems of hot big bang ...)

[Guth ‘80]

• driven by the vacuum energy of a slowly rolling light scalar field:

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

[Linde; Albrecht & Steinhardt ‘82]
• **slow-roll inflation:**

scale factor grows exponentially: \( a \sim e^{Ht} \) if:

\[
\begin{align*}
\dot{\phi}^2 &\ll V \\
|\ddot{\phi}| &\ll |3H \dot{\phi}|
\end{align*}
\]

\[
\Rightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{1}{2} \left( \frac{V'}{V} \right)^2 < 1, \quad \eta \equiv \frac{\dot{\epsilon}}{\epsilon H} \simeq \frac{V''}{V} \ll 1
\]

with the Hubble parameter:

\[
H^2 = \frac{\dot{a}^2}{a} \simeq \text{const.} \sim V
\]

e-folds \( N_e \) in \( a \sim e^{Ne} \):

\[
N_e = \int H \, dt = \int_{\phi_E}^{\phi_E + \Delta \phi} \frac{d\phi}{\sqrt{2\epsilon}}
\]

[Linde; Albrecht & Steinhardt '82]
• inflation generates metric perturbations: scalar (us) & tensor

\[ \mathcal{P}_S \sim \frac{H^2}{\epsilon} \sim \left( \frac{\delta \rho}{\rho} \right)^2 \]

\[ \sim \ k^{n_S - 1} \]

\[ \text{and} \quad \mathcal{P}_T \sim H^2 \sim V \]

window to GUT scale &
direct measurement of inflation scale

• scalar spectral index:

\[ n_S = 1 - 6\epsilon + 2\eta \]

• tensor-to-scalar ratio:

\[ r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S} = 16\epsilon \]
shades of difficulty ... 

- tensor-to-scalar ratio links levels of difficulty:

\[ r \equiv \frac{P_T}{P_S} = 16\epsilon \leq 0.003 \left( \frac{50}{N_e} \right)^2 \left( \frac{\Delta \phi}{M_P} \right)^2 \] [Lyth ’97]

- \( r \ll O(1/N_e^2) \) models:
  
  \( \Delta \phi \ll O(M_P) \) \( \Rightarrow \) \text{Small-Field inflation} ... needs control of leading \text{dim-6 operators} 

  \( \Rightarrow \) \text{enumeration & fine-tuning reasonable}

- \( r = O(1/N_e^2) \) models:

  \( \Delta \phi \sim O(M_P) \) \( \Rightarrow \) \text{needs severe fine-tuning of all dim-6 operators, or accidental cancellations}

- \( r = O(1/N_e) \) models:

  \( \Delta \phi \sim \sqrt{N_e M_P} \gg M_P \) \( \Rightarrow \) \text{Large-Field inflation} ... needs suppression of all-order corrections 

  \( \Rightarrow \) symmetry is essential!
single field models ...

- monomial — large-field, $r \sim 0.1$ ($n = 2, 3, 4$):

$$V(\phi) = \lambda M_{\text{pl}}^4 \left( \frac{\phi}{M_{\text{pl}}} \right)^n$$

$$n_s = 1 - \frac{n + 2}{2N_e}, \quad r = \frac{4n}{N_e}$$

$$\Delta \phi(N_e) = \sqrt{2nN_e} M_{\text{P}}$$

- natural (axion) inflation — large field, $r = 0.01 \ldots 0.1$:

$$V(\phi) = \Lambda^4 \left[ 1 + \cos \left( \frac{\phi}{f} \right) \right]$$

$$f \gtrsim 10 \ M_{\text{P}} : \text{large-field} \ (m^2 \phi^2) : \quad n_s = 1 - \frac{2}{N_e}, \quad r = \frac{8}{N_e}$$

$$4.5 \ M_{\text{P}} \lesssim f \lesssim 10 \ M_{\text{P}} : \text{small-field} : \quad n_s \approx 1 - \frac{M_{\text{P}}^2}{f^2}, \quad r \to 0$$
• We need to understand generic \( \text{dim} \geq 6 \) operators

\[
\mathcal{O}_{p \geq 6} \sim V(\phi) \left( \frac{\phi}{M_P} \right)^{p-4}
\]

\[
\Rightarrow \quad \Delta \eta \sim \left( \frac{\phi}{M_P} \right)^{p-6} \geq 1 \quad \forall p \geq 6 \quad \text{if} \quad \phi > M_P
\]

• requires **UV-completion**, e.g. string theory: need to know string and \( \alpha' \)-corrections, backreaction effects, ...

• typical approximations (tree-level, large-volume/non-compact, probe ...) often insufficient

• detailed information about moduli stabilization necessary!

• string theory manifestation of the supergravity eta problem
• effective theory of large-field inflation:

\[ \mathcal{L} = \frac{1}{2} R + \frac{1}{2} (\partial_{\mu} \phi)^2 - \mu^{4-p} \phi^p \]

• the last term — the potential — spoils the shift symmetry …

• However, if:

\[ V_0 = \mu^{4-p} \phi^p \ll M_P^4 \]

• quantum GR only couples to \( T_{\mu\nu} \):

\[ \delta V^{(n)} \sim V_0 \left( \frac{V_0}{M_P^4} \right)^n, \quad V_0 \left( \frac{V_0''}{M_P^2} \right)^n \ll V_0 \quad \text{not} \quad \delta V^{(n)} \sim c_n \frac{\phi^n}{M_P^n} \]
• while field fluctuation interactions:

\[ \mu^{4-p}(\phi_* + \delta\phi)^p \sim \mu^{4-p}\phi_*^p \left( 1 + \sum_n c_n \frac{\delta\phi^n}{\phi_*^n} \right) \]

die out with increasing field displacement …

• if the inflaton potential breaks the shift symmetry \textbf{weakly} & \textbf{smoothly} (means: with falling derivatives) —

it does \textbf{not} matter, whether the shift symmetry is periodically broken, or secularly

• a shift symmetry itself does not guarantee \textbf{smoothness} of breaking — need UV theory as input, for all models!
shades of difficulty ...

- tensor-to-scalar ratio links levels of difficulty:
  \[ r \equiv \frac{P_T}{P_R} = 16\epsilon \leq 0.003 \left( \frac{50}{N_e} \right)^2 \left( \frac{\Delta\phi}{M_P} \right)^2 \] [Lyth '97]

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warped D-brane inflation & DBI; varieties of Kahler moduli inflation

\[ \begin{align*}
V(X,Y) & = 16 \times 10^{-10} \times (10^{10} X + 10^{10} Y) \\
V(X,Y) & = 5 \times 10^{-10} \times (10^{10} X + 10^{10} Y) \\
V(X,Y) & = 10 \times 10^{-10} \times (10^{10} X + 10^{10} Y) \\
\end{align*} \]
shades of difficulty ...

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warped D-brane inflation & DBI; varieties of Kahler moduli inflation

fibre inflation in LARGE volume scenarios (LVS)
[Cicoli, Burgess & Quevedo '08]
shades of difficulty ...

- tensor-to-scalar ratio links levels of difficulty:
  \[ r \equiv \frac{P_T}{P_R} = 16\epsilon \leq 0.003 \left( \frac{50}{N_e} \right)^2 \left( \frac{\Delta \phi}{M_P} \right)^2 \]  
  
  observable tensors: \[ r > 0.01 \]

- \( r = O(1/N_e) \) models:
  - axion monodromy inflation
  - 2-axion inflation
  - \( N \)-flation

\[ \Delta \phi \sim \sqrt{N_e} M_P \gg M_P \]
small-field string inflation...

- Brane-Antibrane Dvali & Tye; Alexander; Dvali, Shafi & Solganik; Burgess, Majumdar, Nolte, Quevedo, Rajesh & Zhang.
- D3-D7 Dasgupta, Herdeiro, Hirano & Kallosh; Hsu, Kallosh & Prokushkin; Hsu & Kallosh; Aspinwall & Kallosh; Haack, Kallosh, Krause, Linde, Lüst & Zagermann; ...
- warped brane-antibrane Kachru, Kallosh, Linde, Maldacena, McAllister & Trivedi; Firouzjahi & Tye; Burgess, Cline, Stoica & Quevedo; Iizuka & Trivedi; Krause & Pajer; Baumann, Dymarsky, Klebanov, McAllister & Steinhardt; Baumann, Dymarsky, Kachru, Klebanov & McAllister; ...
- DBI Silverstein & Tong; Alishahiha, Silverstein & Tong; Chen; Chen; Shiu & Underwood; Leblond & Shandera; ...
- Racetrack Blanco-Pillado, Burgess, Cline, Escoda, Gomez-Reino, Kallosh, Linde & Quevedo; Linde & AW; ...
- Kähler moduli Conlon & Quevedo; AW; Bond, Kofman, Prokushkin & Vaudrevange; Ben-Dayan, Jing, AW & Zarate ...

large-field string inflation...

- Fibre inflation (r < 0.01) Cicoli, Burgess & Quevedo

- Single-Axion inflation with f > $M_P$ Grimm; Blumenhagen & Plauschinn;
- 2-Axion inflation Kim, Nilles & Peloso; Berg, Pajer & Sjors; Kappl, Krippendorf & Nilles; Long, McAllister & McGuirk; Tye & Wong; Ben-Dayan, Pedro & AW; Gao, Li & Shukla ...
- N-flation Dimopoulos, Kachru, McGreevy, Wacker; Easther & McAllister; Grimm; Cicoli, Dutta & Maharana; Choi, Kim & Yun; Bachlechner, Dias, Frazer & McAllister
- axion monodromy Silverstein & AW; McAllister, Silverstein & AW; Flauger, McAllister, Pajer, AW & Xu; Dong, Horn, Silverstein & AW; Shlaer; Palti & Weigand; Marchesano, Shiu & Uranga; Blumenhagen & Plauschinn; Hebecker, Kraus & Witkowski; Ibanez & Valenzuela; Kaloper, Lawrence & Sorbo; McAllister, Silverstein, AW & Wrase; Franco, Galloni, Retolaza & Uranga;
• string theory axions:
  
  - $B_2$, $C_2$, and $C_4$-axions on type IIB CYs with O7s

  $$T_a = \frac{1}{2} \kappa_{abc} v^b v^c + i \int_{\Sigma_4^a} C_4 - i \frac{1}{2(\tau - \bar{\tau})} \kappa_{a\beta\gamma} G^\beta (G^\gamma - \bar{G}^\gamma)$$

  $$G^\alpha = c^\alpha - \tau b^\alpha \quad c^\alpha = \int_{\Sigma_2^\alpha} C_2 \quad \text{and} \quad b^\alpha = \int_{\Sigma_2^\alpha} B_2$$

  $$K = -3 \ln \left[ T + \bar{T} - i \frac{1}{2(\tau - \bar{\tau})} \kappa_{1\beta\gamma} (G - \bar{G})^\beta (G^\gamma - \bar{G}^\gamma) \right]$$

  - complex structure axions & D7-brane position moduli

  - T-dual in IIA: Wilson lines

  e.g. Wilson Line Inflation [Avgoustidis, Cremades & Quevedo '06]
N-inflation in string theory ...
N-inflation ...

• many fields in lockstep: 
  \[ \mathcal{L} = \frac{1}{2} K_{ij} \partial^i \partial^j - \sum_i \Lambda_i^4 [1 - \cos(\theta_i)] \]
  \[ \Downarrow \]
  \[ \mathcal{L} = \frac{1}{2} (\partial \phi_i)^2 - \sum_i \Lambda_i^4 [1 - \cos(\phi_i / f_i)] \]

  \[ \Delta \phi_{diag.} \sim \sqrt{\sum_{i=1}^N \Delta \phi_i^2} \gg 1 \quad \text{with} \quad |\Delta \phi_i| < 1 \]

  called "N-flation"

  [Dimopoulos, Kachru, McGreevy & Wacker '05]
  [Easther & McAllister '05]

• string theory embedding is challenging, due to need for large number of fields w/ instanton potentials ...
  see: [Grimm '07] and: [Cicoli, Dutta & Maharana '14]
  for coming very close

  LVS with \[ \mathcal{V} = \sum_i \tau_{b_i}^{3/2} - \tau_s^{3/2} \Rightarrow h^{1,1} - 1 \quad C_4 - \text{axions} \]

  ... see talk
N-inflation in string theory ...

- if kinetic matrix: \[ \mathcal{L} = \frac{1}{2} K_{ij} \partial^i \partial^j - \sum_i \Lambda_i^4 [1 - \cos(\theta_i)] \]

drawn from a Wishart random matrix ensemble

- can have: \[ f_1 \cdots f_{N-1} \ll f_N \lesssim 0.1 \, M_P \]

- but: \[ f_{\text{eff.}} \approx \sqrt{N} f_N \quad \text{“kinetically aligned } N\text{-flation”} \]

[Bachlechner, Dias, Frazer & McAllister ‘14]
2-axion monodromy inflation in string theory ...
2-axion alignment ...

2-axion field theory action:
\[
\mathcal{L}(\theta, \rho) = (\partial \theta)^2 + (\partial \rho)^2 - V(\rho, \theta),
\]
\[
V(\theta, \rho) = \Lambda^4 \left( 2 - \cos \left( \frac{\theta}{f_1} + \frac{\rho}{g_1} \right) - \cos \left( \frac{\theta}{f_2} + \frac{\rho}{g_2} \right) \right)
\]

flat direction — alignment condition:
\[
\frac{f_1}{g_1} = \frac{f_2}{g_2} \implies \det V_{ij} = 0
\]

lifting flatness - method I:
\[
g_2 = \frac{f_2}{f_1} g_1 + \alpha, \quad \alpha < 1
\]

tuned "alignment" produces enhanced field range:
\[
f_{\text{eff}} = \frac{f_2 g_1 \sqrt{(f_1^2 + f_2^2)(f_1^2 + g_1^2)}}{f_1^2 \alpha}
\]
2-axion alignment — type IIB string embedding

[Long, McAllister & McGuirk '14]

• use $C_2$-axions on magnetized D7-brane stacks:

$$ W_{np} = \sum_{\xi=A,B,C} A_{\xi} e^{-\frac{2\pi}{N_{\xi}} f_{\xi}}, \quad f_{\xi} = T^2 + i\kappa^2_{bc} F^{b}_{\xi} (G^{c}_{\xi} + \frac{T}{2} F^{c}_{\xi}) $$

magnetic $F_2$ - flux

• or $C_4$-axions on multiply wrapping D7-brane stacks:

$$ W_{np} = A_{A} e^{-\frac{2\pi}{N_{A}} (\bar{N}_{1}^{A} T^1 + \bar{N}_{2}^{A} T^2)} + A_{B} e^{-\frac{2\pi}{N_{B}} (\bar{N}_{1}^{B} T^1 + \bar{N}_{2}^{B} T^2)} $$

D7 wrapping numbers

produces 2-axion 2-cosine potential with tuned- alignment condition as in field theory

see also: [Ben-Dayan, Pedro & AW: work in progress]
2-axion hierarchy ...

- same action, same flatness condition, but $1/g_1=0$:

$$V(\theta, \rho) = \Lambda^4 \left(2 - \cos \left(\frac{\theta}{f_1}\right) - \cos \left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right)$$

- lifting flatness — method II:

$$\frac{\Lambda_2}{\Lambda_1} > \sqrt{\frac{f_2}{f_1}}, \quad f_2 \ll f_1, g_2 \quad \Rightarrow \quad f_{\text{eff}} = \frac{f_1 g_2}{f_2}$$

**hierarchy produces enhanced field range**

can do type IIB string models ...

[Tye & Wong '14]
[Ben-Dayan, Pedro & AW '14]

... see talk
single-axion monodromy ...
axion monodromy inflation with branes

- **$B_2$ (or $C_2$)** on 5-brane wrapping small $S^2$ with volume $v$:

$$S_{5\text{-brane}} \sim \frac{1}{g_s} \int_{\mathcal{M}_4 \times 2\text{-sphere}} d^6 \xi \sqrt{\det(G + B)}$$

$$= \frac{1}{g_s} \int_{\mathcal{M}_4} d^4 x \sqrt{-g} \sqrt{v^2 + b^2}$$

monodromy; breaks perturbative shift symmetry in $B_2$

$$\Rightarrow V(b) \sim b \text{, } b \text{ large, non-periodic}$$

- alternative — use a $B_2$ (or $C_2$) field on a 7-brane:

$$S \supset -\frac{2\pi}{\ell_s^8} \int d^4 x \ e^{-\phi} \sqrt{-g_4} \Gamma_i \quad \Gamma_i = \sqrt{(\text{Re}Z_i)^2 + (\text{Im}Z_i)^2}$$

$$\text{Re}Z_i = \frac{1}{2} \left( \int_{D_i} J \wedge J - \int_{D_i} (F_i + i B) \wedge (F_i + i B) \right)$$

$$\text{Im}Z_i = \int_{D_i} J \wedge (F_i + i B)$$

$$V(b) \sim b \text{ or } b^2$$
axion monodromy inflation - a 2nd example

“Dante’s Inferno”: [Berg, Pajer & Sjörs ’09]

- 2 axions, a 5-brane, and an EDI-instanton:

\[
V \sim m^2 r^2 + \Lambda^4 \left[ 1 - \cos \left( \frac{r}{f_r} + \frac{\theta}{f_\theta} \right) \right], \quad f_r \ll f_\theta < M_P
\]

\[
V_{\text{eff.}}(\tilde{\phi}) \sim m^2 \tilde{\phi}^2 \quad \text{for} \quad \tilde{\phi} \gg M_P \quad \text{while} \quad r, \theta < M_P
\]

picture taken from:
[Berg, Pajer, Sjörs ’09]

2-cosine variant - see earlier:
[Ben-Dayan, Pedro & AW ’14]
[Tye & Wong ’14]
where we have potential fields under the gauge transformation is directly analogous to the usual vector potential.

### 2.1 Axions from the two-form potential

\( V \) on moduli fields coming from the internal metric and the dynamical string coupling. In 

\[ \text{EM} \]

\[ 4 \]

\[ A_{\mu} \rightarrow A + \partial_{\mu} \Lambda_{0}, \quad \Rightarrow \quad C \rightarrow C - \Lambda_{0} \]

- string theory contains analogous gauge symmetries for NSNS and RR axions - e.g. IIA:

\[
H = dB, \\
F_{0} = Q_{0}, \\
\tilde{F}_{2} = dC_{1} + F_{0}B, \\
\tilde{F}_{4} = dC_{3} + C_{1} \wedge H_{3} + \frac{1}{2} F_{0}B \wedge B
\]

\[
\delta B = d\Lambda_{1}, \\
\delta C_{1} = -F_{0}\Lambda_{1}, \\
\delta C_{3} = -F_{0}\Lambda_{1} \wedge B
\]

- type IIB similar
• fluxes generate a potential for the axions:

\[- \frac{1}{\alpha'4} \int d^{10}x \sqrt{-G} \left\{ \frac{1}{g_s^2} |H|^2 + |Q_0 B|^2 + |Q_0 B \wedge B|^2 + \gamma_4 g_s^2 |Q_0 B \wedge B|^4 + \ldots \right\}\]

• produces periodically spaced set of multiple branches of large-field potentials:

\[f(\chi, \ldots) \left( \frac{Q^{(n)} a^n + Q^{(n-1)} a^{n-1} + \ldots + Q^{(0)}}{L^{2n'}} \right)^2 + \ldots \sim f(\chi, \ldots) a^{p_0} \quad \text{for } a \gg 1\]

→ for given flux quanta $Q^{(i)}$ potential is non-periodic – a given branch

→ $Q^{(i)}$ change by brane-flux tunneling – $Q^{(i)}$ shift absorbed by $a$-shift – many branches, full theory has periodicity
p-form axions get non-periodic potentials from coupling to branes or fluxes/field-strengths

produces periodically spaces set of multiple branches of large-field potentials:

$$V(\phi) \sim \mu^{4-p} \phi^p + \Lambda^4 \cos(\phi/f)$$
- **4D effective action: 4-form field strength, axion \( \phi \):**

\[
\mathcal{L} = \frac{1}{2} m_{pl}^2 R - \frac{1}{2} (\partial \phi)^2 - \frac{1}{48} F^{(4)^2} + \frac{\mu}{24} \phi^* F^{(4)}
\]

- **4D effective Hamiltonian:**

\[
H = \frac{1}{2} (p_\phi)^2 + \frac{1}{2} (\nabla \phi)^2 + \frac{1}{2} \left(n e^2 + \mu \phi\right)^2
\]

\[
\phi \rightarrow \phi + f \quad \Rightarrow \quad \mu f = e^2 , \quad n \rightarrow n + 1
\]

- again, axion **unwound into multiple branches**, \( n \) jumps by flux tunneling, periodicity by summing over branches
flux monodromy with F-term supergravity description

- flux-induces potentials for $B_2$- or $C_2$-axions & D7-brane position moduli, the T-duals of Wilson lines

- type IIA F-term description of $B_2$- or $C_2$-monodromy from fluxes, and Wilson line monodromy from flux
  - $\phi^2$, $\phi^4$ potentials

- type IIB F-term description of D7-position axion monodromy from F-theory $G_4$ flux
  - $\phi^2$ potential

- type IIB F-term description of dilaton-axion monodromy from type IIB $G_3$ flux
  - $\phi^2$ potential

beautiful F-term realizations — but open question: moduli stabilization!!

so far fully addressed only in the D7-position proposal

[Marchesano, Shiu & Uranga ’14]
[Hebecker, Kraus & Witkowski ’14]
[Blumenhagen & Plauschinn ’14]

... see talks
... see talk
• type IIB string theory:

\[
\int d^{10}x \left( \frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + |\tilde{F}_5|^2 \right)
\]

with: \( \tilde{F}_5 = dC_4 - B_2 \wedge F_3 + C_2 \wedge H_3 + F_1 \wedge B_2 \wedge B_2 \)

• \( \phi^2, \phi^3, \phi^4 \) terms …

- generically flattening of the potential from adjusting moduli and/or flux rearranging its distribution on its cycle - ‘sloshing’, while preserving flux quantization

[Marchesano, Shiu & Uranga ’14]
[Blumenhagen & Plauschinn ’14]
[Hebecker, Kraus & Witkowski ’14]
[McAllister, Silverstein, AW & Wrase ’14]

[Dong, Horn, Silverstein & AW ’10]
simple torus example: \[ ds^2 = \sum_{i=1}^{3} L_1^2(dy_1^{(i)})^2 + L_2^2(dy_2^{(i)})^2 \]

axion \[ B = \sum_{i=1}^{3} \frac{b}{L^2} dy_1^{(i)} \wedge dy_2^{(i)} \]

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

effective 4d action gives \( \Phi^3 \)-potential: \[ u = \frac{L_2}{L_1} \, , \, \frac{\phi}{M_P} = \frac{b}{L^2} \]

\[ \mathcal{L} \sim M_P^2 \frac{b^2}{L^4} + M_P^4 \frac{g_s^4}{L^{12}} \left[ Q_{11}^2 L^4 \left( \frac{b}{L^2} \right)^4 u + Q_{31}^2 u^3 + \frac{Q_{32}^2}{u^3} \right] \sim \Phi^2 + \mu \Phi^3 \]

use Riemann surfaces: can fix \( Vol = L^6 \) as well & get \( m^2 \Phi^2 \)
Inflation with an exponential potential

Exponential potential and power law inflation

In another interesting class of potentials, the inflaton rolls away from an unstable equilibrium as in the first new inflationary model. Later on, an exponent of -1 is allowed only as a large field perturbation unmodified.

This class of models predicts such a mechanism exists and leaves predictions for cosmological perturbations unmodified. Therefore, there is no natural end to inflation, but if the exit mechanism leaves the inflationary predictions on cosmological perturbations unmodified, this leads to inflation with an exponential potential.

The hilltop potential with $V(\phi) = \phi^4$ is allowed only as a large field perturbation. Natural inflation is called power law inflation.

The theoretical predictions of selected inflationary models are discussed, and the constraints on the primordial perturbation parameters in the context of the Planck collaboration are presented.

Table 4. Constraints on the primordial perturbation parameters in the Planck collaboration.

- Tensor to Scalar Ratio $r$: 0.002
- Primordial Tilt $n_s$: $0.00 \leq n_s \leq 0.05$
- $r = 0.002$ is allowed only as a large field perturbation.

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Going down the rabbit hole ...

CMB large-angular scale anomalies & just enough inflation
PLANCK anomaly - a lack of power at large scales!!

\[
q = \frac{C_{\ell}^{\ell=2...50}}{C_{\ell}^{\ell>50}}
\]

[PLANCK Coll. XV ’13]

\[q = 0.9 \quad \text{at} \quad 2.5 - 3\sigma\]

[Bousso, Harlow, Senatore ’14]

\[q = 0.9 \quad \text{at} \quad 3.5 - 3.8\sigma \quad \text{with BICEP2}\]
• significance of the power suppression -- now:

\[ \frac{\sigma^2}{C^2} = \frac{2}{N} \]

\[ N_{\ell}^{(\text{CMB})} = 2\ell + 1 \]

⇒ significance of suppression measurement:

2 . . . 3 σ CMB + a bit of LSS

• the future:

\[ N_{\ell}^{(\text{CMB}+\text{LSS}+21\text{cm})} = 2\ell + 1 + 4\pi \frac{\ell^2}{\ell^3} \]

⇒ significance of suppression measurement:

3 . . . 4 σ CMB + LSS from EUCLID

5 . . . 6 σ CMB + LSS from EUCLID + 21cm data
an idea: rapid steeping potential can suppress power ...

- sudden growth change of $V'$ such that $\varepsilon$ grows much faster than $V$ in a narrow interval $\Delta \phi$

\[
\begin{align*}
\Delta_R^2 & \sim \frac{H^4}{\dot{\phi}^2} \sim \frac{V}{\varepsilon} \rightarrow \frac{1}{\beta} \Delta_R^2 < \Delta_R^2
\end{align*}
\]

- our claim: there is much more to this — different pre-inflation phases lead to a form of universality in the low-l deviations!

... see talk

[Contaldi, Peloso, Kofman, Linde '03]

[Pedro, AW '13; Cicoli, Downs, Dutta '13]

[Cicoli, Downs, Dutta, Pedro & AW '14]

also: [Bousso, Harlow, Senatore '13/'14]
• BICEP2 may provide evidence for primordial tensor modes with $r = 0.05 \ldots 0.16$ — if so, only large-field inflation survives …

• axion monodromy, with 1 or 2 axions, provides one avenue for large field inflation in string theory - technically natural & distinctive predictions …

• many powers $\phi^{2/3} \ldots \phi^4$ possible ; we need generalizations … harder look at universality, generic distinctiveness from field theory models & potential backreaction issues in string models