Recent Progress in String Cosmology

(mainly large-field inflation; mainly potential no-go results)

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(including work with A. Knochel, S. Kraus, D. Lüst, P. Mangat, J. Moritz, F. Rompineve, T. Weigand, A. Westphal, L. Witkowski, ...)

Outline

- Large-field inflation: Non-stringy basics
- Large-field inflation: Issues in string theory

  In particular: Weak Gravity Conjecture;
  Gravitational instantons

- Small-field Inflation; Dark Radiation; α' corrections

Slow-roll inflation and perturbations

Starobinsky '80; Guth '81
Mukhanov/Chibisov '81; Linde '82

- The simplest relevant action is

$$S = \int d^4x \sqrt{g} \left[\frac{1}{2} R[g_{\mu\nu}] + \frac{1}{2} (\partial\varphi)^2 - V(\varphi) \right] .$$

(We use $\overline{M}_P \equiv 1$ here and below.)

- Assume homogeneity and let $H \equiv \dot{a}/a$. This implies

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0 \qquad \text{and} \qquad 3H^2 = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) .$$

- Slow-roll inflation (i.e. $\dot{\varphi}^2 \ll V$ and $\ddot{\varphi} \ll 3H\dot{\varphi}$) needs

$$\epsilon = \frac{1}{2} \left(\frac{V'}{V} \right)^2 \ll 1 \quad \text{and} \quad |\eta| = \left| \frac{V''}{V} \right| \ll 1 .$$

- To gain some intuition, assume that

$$V \quad \sim \quad \varphi^n \quad \text{or} \quad \ln(\varphi) \qquad \text{(or some combination thereof).}$$

- This implies

$$\epsilon \sim \eta \sim 1/\varphi^2 \,,$$

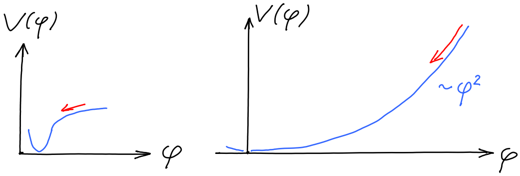
such that inflation is generic if $\varphi \gg 1$.

To summarize:

- Inflation is realized if $V(\varphi)$ has a sufficiently flat region.
- This is generic for $\varphi \gg 1$,
  or it can be ensured by tuning several simple terms at $\varphi \ll 1$.

- As a result, one can roughly distinguish

Small- and Large-Field Models



- Small field: $V(\varphi)$ has some tuned very flat region
  (one can think of the tuning as $V'(\varphi_0) \simeq V''(\varphi_0) \simeq 0$).

- Large field: 'Generic' potentials (e.g. $V(\varphi) \sim \varphi^2$),
  but the requirement $\Delta\varphi \gg 1$ may lead to problems with quantum gravity.

Tensor and Scalar Perturbations

(very superficially)

- Start from the metric

$$ds^2 = -dt^2 + a^2(t)\, e^{2\zeta(x)} \left(e^{\gamma(x)}\right)_{ij} dx^i\, dx^j \,,$$

where $\mathrm{tr}\gamma = 0$ and $\partial_i \gamma_{ij} = 0$.

- On dimens. grounds (quantized graviton in dS space), one has

$$\gamma_{ij} \sim \delta h_{ij} \sim H \,.$$

These are the tensors.

- To understand the scalar part, note that

$$a(t) \sim e^{\int H(t)\, dt} \equiv e^{N(t)} \,,$$

with the number of e-foldings $N = \int H\, dt$.

- Thus, one has

$$N = \int H\,dt = -\int H\,\frac{d\varphi}{\dot{\varphi}} = -\int \frac{3H^2}{3H\dot{\varphi}}\,d\varphi = \int \frac{d\varphi}{\sqrt{2\epsilon}}\,.$$

- Now, fluctuations of φ during inflation lead to fluctuations of N and hence of ζ :

$$\zeta \sim \delta N \sim \frac{\delta\varphi}{\sqrt{\epsilon}} \sim \frac{H}{\sqrt{\epsilon}}\,.$$

- **Note:** This also leads to a very intuitive formula for ϵ :

$$\sqrt{\epsilon} \sim \frac{\delta\varphi}{\delta N}\,.$$

- **Finally:** We found the tensor-to-scalar-ratio $\gamma/\zeta \sim \sqrt{\epsilon}$.

Recently, the focus has been on large-field models
for two reasons....

1) Observations

- The tensor-to-scalar ratio ('primordial gravity waves') is

$$r \equiv \frac{\Delta_T^2}{\Delta_R^2} = 16\epsilon \simeq 8\left|\frac{d\varphi}{dN}\right|^2 \quad \Rightarrow \quad \Delta\varphi \simeq 20\sqrt{r}$$

(assuming $N \simeq 60$). This is known as the Lyth bound.

- Thus, even though the BICEP 'discovery' of $r \simeq 0.15$ went away, the need to consider large-field models may return.

- Note: The Planck/BICEP analysis still sees a ($\sim 1.8\sigma$) hint for $r \simeq 0.05$.

- Much better values/bounds are expected soon.

...reasons for interest in large-field models...

2) Fundamental

- On the one hand, large-field models are more 'robust'
- On the other hand, there are generic arguments against large-field models in consistent quantum gravity theories

  see e.g. Arkani-Hamed/Motl/Nicolis/Vafa '06 .... Conlon '12
  ....
  Kaloper/Kleban/Lawrence/Sloth '15

- This goes hand in hand with persistent problems in constructing large-field models in (the known part of) the string theory landscape

Jumping somewhat ahead:

- Basic obstacle: Moduli spaces of string compactifications are 'essentially' compact

  (Note: Of course, specific non-compact directions exist, e.g. large-volume or large-complex-structure. However, in these directions the potential tends to decay too quickly.)

‘Fundamental reasoning’ continued...

- However, triggered by BICEP, new promising classes of stringy large-field models have been constructed (e.g. F-term axion monodromy)

  Kim, Nilles, Peloso ’07
  McAllister, Silverstein, Westphal ’08
  .....
  Marchesano, Shiu, Uranga ’14
  Blumenhagen, Plauschinn ’14
  AH, Kraus, Witkowski ’14

- At the same time, there are ongoing efforts to sharpen the ‘no-go arguments’ as well as to refute them

  Rudelius ’14...’15
  Ibanez, Montero, Uranga, Valenzuela ’15
  Brown, Cottrell, Shiu, Soler ’15
  AH, Mangat, Rompineve, Witkowski ’15
  . . .

- I will try to explain some aspects of this debate....

Natural (axionic) inflation in string theory

Freese/Frieman/Olinto '90; Banks/Dine/Fox/Gorbatov '03

- The ubiquitous axionic (pseudo-)scalars $(C_0, C_1, \ldots, B_2 \text{ etc.})$ appear to provide excellent inflaton candidates:

$$\mathcal{L} \supset -\frac{1}{2}(\partial\varphi)^2 - \frac{1}{32\pi^2}\left(\frac{\varphi}{f}\right)\text{tr}(F\tilde{F})\,.$$

- Crucially, in appropriate settings the shift symmetry may be broken (from $\mathbb{R}$ to $\mathbb{Z}$), but only non-perturbatively

$$V_{eff} \sim \cos(\varphi/f)\;, \qquad \varphi \equiv \varphi + 2\pi f\,.$$

- **Problem:** $f \ll 1$ in perturbatively controlled regimes.
- **Example:** Type-IIB axio-dilaton $S = i/g_s + C_0\,.$

- Indeed, the familiar Kahler potential

$$K = -\ln(-i(S-\overline{S})) \qquad \text{with} \qquad S = i/g_s + C_0$$

gives rise to

$$\mathcal{L} \supset K_{S\overline{S}}|\partial S|^2 \supset \left(\frac{g_s}{2}\right)^2 (\partial C_0)^2 \,.$$

- Thus, since $C_0 \equiv C_0 + 1$, the axion decay constant is

$$f = \frac{g_s}{\sqrt{2}\, 2\pi}\,,$$

which is much smaller than unity already at the self dual point $g_s = 1$.

- This appears to be a generic result (cf. Banks et al.)

- One can try to make (small-field) models with sub-planckian axions or venture into the non-perturbative regime....

  see e.g. AH/Kraus/Westphal '13; Blumenhagen/Plauschinn '14; Grimm '14

- However, the three most widely used approaches are

  (a) KNP Kim/Nilles/Peloso '04

  (b) N-flation Dimopoulos/Kachru/McGreevy/Wacker '05

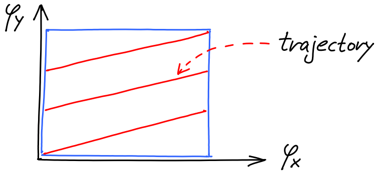
  (c) Axion-Monodromy McAllister/Silverstein/Westphal '08

- All three are distinct ideas about how to enlarge the axionic field range without losing calculational control.
- The No-Go arguments alluded to earlier challenge these possibilities.

(a) KNP / Winding inflation

Kim/Nilles/Peloso '04; Berg/Pajer/Sjors '09; Ben-Dayan/Pedro/Westphal '14

- Consider a 'winding' trajectory on a 2d periodic field space:



- Clearly, such a trajectory can be much longer than the (naive) field range

- The technical challenge is the realization of the required potential in concrete string models

- Thus, even getting only an effective trans-planckian axion appears to be difficult. Is there a fundamental reason?

No-go argument I: Weak gravity conjecture

Arkani-Hamed/Motl/Nicolis/Vafa '06

- Some recent papers developing this in (more or less close) relation to large-field inflation:

  Cheung/Remmen; de la Fuente/Saraswat/Sundrum . . . '14
  Rudelius; Ibanez/Montero/Uranga/Valenzuela; Brown/Cottrell/Shiu/Soler; Bachlechner/Long/McAllister; AH/Mangat/Rompineve/Witkowski; Junghans; Heidenreich/Reece/Rudelius; Kooner/Parameswaran/Zavala; Harlow; AH/Rompineve/Westphal; . . . '15
  Conlon/Krippendorf . . . '16

Weak gravity conjecture

- Roughly speaking: 'Gravity is always the weakest force.'
- More concretely (mild form):
  For any U(1) gauge theory there exists a charged particle with
  $$q/m > 1\,.$$
- Strong form:
  The above relation holds for the lightest charged particle.

Weak gravity conjecture (continued)

- One supporting argument:

  Quantum gravity forbids global symmetries. We should not be able to take the limit of small gauge couplings.

  The WGC quantifies this on the basis of stringy examples.

- Another supporting argument:

  In the absence of sufficiently light, charged particles, extremal BHs are stable. Such remnants are believed to cause inconsistencies.

  see e.g. Susskind '95

  The boundary of stability of extremal black holes is precisely $q/m = 1$ for the decay products.

Generalizations of the weak gravity conjecture

- The basic lagrangian underlying the above is

$$S \sim \int (F_2)^2 + m \int_{1-dim.} d\ell + q \int_{1-dim.} A_1 \, .$$

- This generalizes to charged strings, domain walls etc. Crucially, the degree of the corresponding form-field (gauge-field) changes:

$$S \sim \int (F_{p+1})^2 + m \int_{p-dim.} dV + q \int_{p-dim.} A_p$$

with

$$F_{p+1} = dA_p \, .$$

Generalizations to instantons

- One can also lower the dimension of the charged object, making it a point a in space-time:

$$S \sim \int (d\varphi)^2 \; + m + q\,\varphi(x_{inst.})\,.$$

- One easily recognizes that this is just a more general way of talking about instantons and axions:

$$m \;\Leftrightarrow\; S_{inst.} \qquad , \qquad q\,\varphi(x_{inst.}) \;\Leftrightarrow\; \frac{1}{f}\int \varphi F\tilde{F}\,.$$

WGC for instantons and inflation

- The consequences for inflation are easy to derive.
- First, recall that the instantons induce a potential

$$V(\varphi) \sim e^{-m} \cos(\varphi/f) .$$

- Since, for instantons, $q \equiv 1/f$, we have

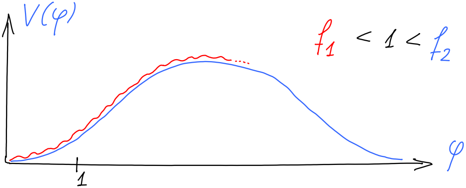
$$q/m > 1 \qquad \Rightarrow \qquad \boxed{m f < 1} .$$

- Theoretical control (dilute instanton gas) requires $m > 1$.
- This implies $f < 1$ and hence
large-field 'natural' inflation is in trouble.

A Loophole

Rudelius '15

- Suppose that only the mild form of the WGC holds.
- In this case, we can have one 'sub-planckian' instanton maintaining the WGC, together with a lighter 'super-planckian' instanton realizing inflation:



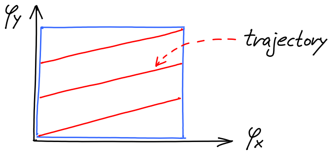
For other arguments and loopholes see e.g.
de la Fuente, Saraswat, Sundrum '14
Bachlechner, Long, McAllister '15.

Winding inflation (continued)

- The fields φ_x and φ_y are two 'string theory axions', both with $f < 1$ (obeying the WGC).
- They are also moduli. Hence, fluxes (e.g. $\langle F_3 \rangle \neq 0$ on the compact space) can be used to stabilize them.
- A judicious flux choice allows for stabilizing just one linear combination, forcing the remaining light field on the winding trajectory:

$$V \supset (\varphi_x - N\varphi_y)^2 + e^{-M} \cos(\varphi_x/f) + e^{-m} \cos(\varphi_y/F)$$

with $N \gg 1$.



- This realizes inflation and avoids the (mild) WGC!

AH/Mangat/Rompineve/Witkowski '15

- To be more precise, let's change variables:

$$\varphi \equiv \varphi_x \,, \qquad \psi \equiv \varphi_x - N\varphi_y$$

- While ψ is 'frozen', our inflaton φ 'sees' both the instantons belonging to φ_x as well as those belonging to φ_y:

$$V \supset \psi^2 + e^{-M} \cos(\varphi/f) + e^{-m} \cos[(\varphi - \psi)/NF]$$

- Crucially, in our proposal the quantities M and m are precisely the type of variables that can be tuned.

- Indeed, consider complex structure moduli $z_1, \ldots, z_n, u, v$. Let $\varphi_x = \text{Im}(u)\,,\ \varphi_y = \text{Im}(v)$ and

$$\begin{aligned} K &= K(z, \overline{z}, u - \overline{u}, v - \overline{v}) \\ W &= w(z) + f(z)(u - Nv) + g(z)e^{2\pi i v}\,. \end{aligned}$$

- Much more could be said concerning recent work on

KNP / Winding inflation / Aligned natural inflation

- See, for example...

Kappl/Krippendorf/Nilles; Ben-Dayan/Pedro/Westphal;
Long/McAllister/McGuirk; Abe/Kobayashi/Otsuka '14
Rühle/Wieck; Choi/Kim; Kappl/Nilles/Winkler '15
Parameswaran/Tasinato/Zavala '16

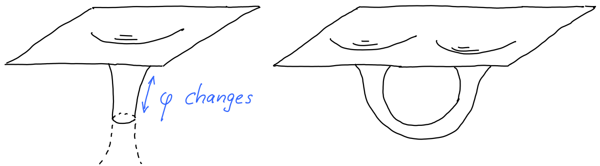
- Critical issues in moduli stabilization have e.g. been raised in...

Buchmüller/Dudas/Heurtier/Westphal/Wieck/Winkler;
Palti '15

No-go argument II: (Gravitational) instantons
(Giddings-Strominger wormholes)

- In Euclidean Einstein gravity, supplemented with an axionic scalar φ $(\varphi \equiv \varphi + 2\pi f)$, instantonic solutions exist:

Giddings/Strominger '88
...



- The 'throat' is supported by the kinetic energy of $\varphi = \varphi(r)$, with r the radial coordinate of the throat/instanton.

- The relevance for inflation arises through the induced instanton-potential for the originally shift-symmetric field φ.

Montero/Uranga/Valenzuela '15

Caveats:

- a) Euclidean quantum gravity has its own fundamental problems
- b) It is not completely clear 'where the throat should connect' (our world, another world, 'crunch', 'baby universe' ......)
- Hence the interpetation of these instanton solutions still has issues...

Gravitational instantons (continued)

- The underlying lagrangian is simply

$$\mathcal{L} \sim \mathcal{R} + f^2 |d\varphi|^2 \,, \quad \text{now with} \quad \varphi \equiv \varphi + 2\pi \,.$$

- This can be dualized $(dB_2 \equiv f^2 * d\varphi)$ to give

$$\mathcal{L} \sim \mathcal{R} + \frac{1}{f^2} |dB_2|^2 \,.$$

- The 'throat' exists due the compensation of these two terms. Reinstating M_P, allowing n units of flux (of $H_3 = dB_2$) on the transverse S^3, and calling the typical radius R, we have

$$M_P^2 \, R^{-2} \sim \frac{n^2}{f^2} R^{-6} \quad \Rightarrow \quad M_P \, R^2 \sim \frac{n}{f} \,.$$

Gravitational instantons (continued)

- Returning to units with $M_P = 1$, their instanton action is

$$S \sim n/f \qquad \text{(with } n \text{ the instanton number).}$$

- Their maximal curvature scale is $\sqrt{f/n}$, which should not exceed the UV cutoff:

$$f/n < \Lambda^2$$

- This fixes the lowest n that we can trust and hence the minimal size of the instanton correction to the potential $V(\varphi)$:

$$\boxed{\delta V \sim e^{-S} \sim e^{-n/f} \sim e^{-1/\Lambda^2}}$$

Gravitational instantons (continued)

- For gravitational instantons not to prevent inflation, the relative correction must remain small:

$$\frac{\delta V}{V} \sim \frac{e^{-1/\Lambda^2}}{H^2} \ll 1$$

- For a Planck-scale cutoff, $\Lambda \sim 1$, this is never possible
- However, the UV cutoff can in principle be as low as H
- Then, if also $H \ll 1$, everything might be fine....

$$\frac{\delta V}{V} \sim \frac{e^{-1/H^2}}{H^2}$$

AH, Mangat, Rompineve, Witkowski '15

Gravitational instantons (continued)

- Now, most string models of inflation do indeed have a low cutoff (e.g. compactification scale)
- However, it may be too naive to assume that 'uncalculable' gravitational instantons can simply be ignored
- They may find their 'continuation' in the gauge or D-brane instantons of the concrete string model
- The closely related issue of (singular) 'core instantons' has been brought up
  Heidenreich, Reece, Rudelius '15
- UV completion and moduli stabilization are crucial open issues
  ...ongoing work w/ Mangat/Rompineve/Theisen/Witkowski

(b) N-flation

Dimopoulos/Kachru/McGreevy/Wacker '05

- The basic idea is that, in the 'string axiverse', the available field range is naturally enlarged by the N-dimensional pythagorean theorem:

$$\Delta\varphi^2 = \Delta\varphi_1^2 + \cdots + \Delta\varphi_N^2 \qquad \Rightarrow \qquad \Delta\varphi_{max} \sim \sqrt{N}\,.$$

- Recent issues involve the both (the difficulties of) the technical realization

  Bachlechner/Long/McGuirk/McAllister '14..'15
  Cicoli/Dutta/Maharana '14

  as well as the question of constraints from the multi-field version of the WGC.

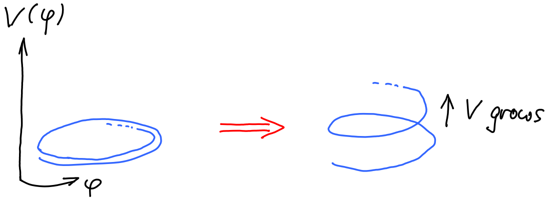
  Cheung/Remmen; Rudelius; McAllister et al.; Junghans '14..'15

(c) Monodromy inflation

Silverstein/Westphal/McAllister '08

Very general but simple-minded definition:

- Start with a single, shift-symmetric, periodic inflaton φ
- Break the periodicity weakly by the scalar potential



The 'classical' model

Silverstein/Westphal, McAllister/Silverstein/Westphal '08

- For 'landscape reasons', focus on IIB models w/ D7 branes
- (One) natural idea: Use 'axion' $\varphi = \int_{S^2} B_2$,

  with monodromy introduced by pullback to D7-brane:

$$S_{\rm DBI} \sim \int \sqrt{-\det(g_{\mu\nu} + F_{\mu\nu} + B_{\mu\nu})}$$

- Unfortunately, this has a supergravity η-problem since,

  symbolically, $K \supset |G - \overline{G}|^2$; $G \sim C_2 + iB_2$

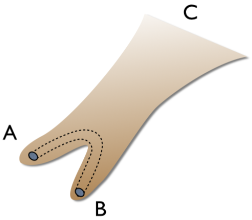
- By contrast, the crucial shift symmetry can be maintained if

$$\varphi = \int_{S^2} C_2 \ ,$$

  But this requires D7 $\rightarrow$ NS5,
  which in turn requires an anti-NS5 (for tadpole cancellation).

- As a result, SUSY is broken explicitly and the desired 4d effective supergravity description of moduli stabilization is lost.

- The 'canonical' way out is to appeal to special types of warped throats (the existence of which is difficult to establish) to control the anti-NS5 backreaction



Bifid throat with shared 2-cycle
(figure from Retolaza et al. '15)

- Crucial recent progress: The modifications of the 2-conifold geometry required for such 'bifid throats' have recently been constructed

Retolaza/Uranga/Westphal '15

F-term axion monodromy

- Alternative suggestions have emerged how this could be realized in a quantitatively controlled way

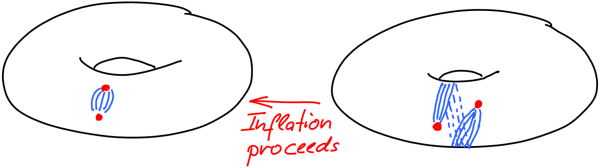
  (i.e. in a 4d supergravity description, with a stabilized compact space)

  Marchesano/Shiu/Uranga '14
  Blumenhagen/Plauschinn '14
  AH/Kraus/Witkowski '14

- One option is that inflation corresponds to brane-motion

  Dvali/Tye '98....Dasgupta et al. '02....Lüst et al. '11

- The monodromy arises from a flux sourced by the brane



Recent issues in F-term axion monodromy

- The difficulties of getting a small monodromy effect, especially moduli-backreaction were initially underestimated

$$\varphi = \text{Re}(u)\ , \qquad K = K(z, \bar{z}, u - \bar{u})\ , \qquad W = w(z) + f(z)u\ .$$

- Possible way's out include landscape tuning, appropriate hierarchical flux choice and high-scale non-geometric moduli-stabilization.

Blumenhagen/Damian/Font/Fuchs/Herrschmann/Plauschinn/Sekiguchi/Sun/Wolf '14-15; Hassler/Lüst/Massai '14

AH/Mangat/Rompineve/Witkowski '14 Palti '15 Andriot '15

- Flattening ($\varphi^2 \rightarrow \varphi$ etc.) is investigated, e.g., in the context of α' corrections to brane actions.

Bielleman/Ibanez/Marchesano/Pedro/Valenzuela/Wieck '14-'16

(cf. also Dong/Horn/Silverstein/Westphal '10 McAllister/Silverstein/Westphal/Wrase '14)

More precise but also constraining monodromy definition:

Kaloper/Lawrence/Sorbo '08..'11 (see also Dvali '05)

- Start with axion φ and 3-form C_3:
  (ignore all $\mathcal{O}(1)$ factors and couplings for now)

$$\mathcal{L} \sim |d\varphi|^2 + |dC_3|^2 \,.$$

- Note: Since $dC_3 = F_4 = *F_0$ is quantized, the 3-form theory corresponds to a discrete set of cosmolgical constants. The only dynamics is in the connecting domain walls
  (cf. 'Bousso-Polchinski landscape').

- Dualize by writing $d\varphi = *dB_2$, i.e.

$$\mathcal{L} \sim |dB_2|^2 + |dC_3|^2 \,.$$

- Finally, gauge B_2 by C_3: $\qquad dB_2 \to dB_2 + C_3 \,.$

Note: This gauging is the just the straightforward generalization of the familiar gauging of a U(1)-symmetry,

$$|\partial\Phi|^2 \rightarrow |(\partial + iA_1)\Phi|^2$$

or a corresponding scalar shift symmetry ($\varphi \equiv \arg(\Phi)$),

$$d\varphi \wedge *d\varphi \rightarrow (d\varphi + A_1) \wedge *(d\varphi + A_1).$$

- The result in our case is

$$\mathcal{L} \sim |dB_2 + C_3|^2 + |dC_3|^2$$

- In dualising back to φ, one now has to be very careful: One writes $dB_2 \equiv H_3$ and imposes the Bianchi identity through the lagrange multiplier φ:

$$\begin{aligned} \mathcal{L} &\sim |H_3 + C_3|^2 + \varphi\, dH_3 + |dC_3|^2 \\ &\sim |H_3|^2 + \varphi(dH_3 - dC_3) + |dC_3|^2 \end{aligned}$$

- After integrating out H_3 and writing $dC_3 = F_4$:

$$\mathcal{L} \sim |d\varphi|^2 - \varphi\, F_4 + |F_4|^2\,.$$

- Finally, after also integrating out F_4 ,

$$\mathcal{L} \sim |d\varphi|^2 - \frac{1}{2}\varphi^2\,.$$

one obtains the desired monodromy potential for φ.

- In summary: One can define axion monodromy as arising from the gauging of the dual 2-form by a 3-form.
- As an advantage, one can argue more systematically about protection by from higher-order potential terms
- Furthermore: The WGC can be applied to this construction...

Brown/Cottrell/Shiu/Soler; Ibanez/Montero/Uranga/Valenzuela '15

- Indeed, reinstating couplings, one has

$$\mathcal{L} \sim (\partial\varphi)^2 - \frac{g^2}{2}\varphi^2 \, ,$$

where g is the coupling of C_3 to the domain walls.

- By the domain-wall WGC (if such a thing exists...), the domain walls become light if $g \ll 1$.

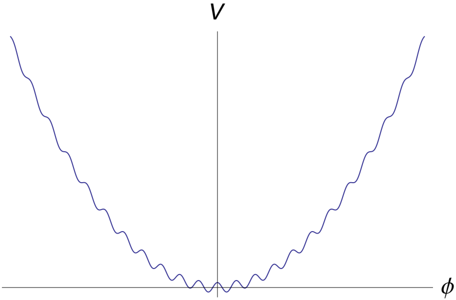
- Now, fast nucleation of these walls lowers the cosmological constant, which is equivalent to tunneling to $\varphi = 0$.

- This has been applied to bound monodromy models, in particular in the context of the 'Relaxion' (cf. Witkowski's talk)

Ibanez/Montero/Uranga/Valenzuela '15

- A more direct approach starts from the 'standard' monodromy potential (with 'instantontic wiggles') AH/Rompineve/Westphal '15

$$\mathcal{L} = (\partial\varphi)^2 - \frac{1}{2}m^2\varphi^2 - \alpha\cos(\varphi/f)\,.$$



$$T_{DW} \sim \sqrt{V}\Delta\varphi \sim \sqrt{\alpha}f$$

(Effective) domain walls are automatically present, but are too light to give any useful WGC constraint.

(In fact, this may even limit the relevance of the previously discussed constraint from Kaloper-Sorbo domain walls.)

- A constraint can nevertheless be derived from the

Magnetic Weak Gravity Conjecture:

Arkani-Hamed/Motl/Nicolis/Vafa '06

- Consider an A_1/F_2 gauge theory with coupling g $(\sim q)$.
- The dual $\tilde{A}_1/\tilde{F}_2$ theory has coupling $\tilde{g} \equiv 1/g$.
- The mass (field energy) of the smallest monopole is

$$M \sim \tilde{g}^2 \cdot \frac{1}{R_{min}} \sim \frac{1}{g^2} \cdot \Lambda \,.$$

- For this monopole to exist, i.e. not to be a black hole, one needs

$$1/\Lambda \sim R_{min} \, > \, R_{BH}(M) \sim M \,.$$

- Thus, at small g our theory must have a low cutoff: $\Lambda \sim g$.

- Applied to our setting this gives (reinstating M_P)

$$\Lambda^3 \sim m\, f\, M_P \qquad \text{and} \qquad \frac{\varphi_{max}}{M_P} \lesssim \left(\frac{M_P}{m}\right)^{2/3} \left(\frac{2\pi f}{M_P}\right)^{1/3} .$$

Please revisit Rompineve's talk for more details....

Other large and small-field models

- In spite of the recent 'axion-inflation-hype', many other string inflation models are as relevant as ever:

  KKLMMT — Kachru et al. '03
  Blow-up inflation — Conlon/Quevedo '05
  Fibre inflation — Cicoli/Burgess/Quevedo '08

  (The last two fall into the class of Kahler moduli inflation.)

  for recent work see e.g. Maharana/Rummel/Sumitomo '15

- Development/improvement of fibre inflation using recently derived new type of α' corrections

  Broy/Ciupke/Pedro/Westphal '15

- Development of volume modulus inflation to account for high-scale moduli-stabilization during inflation and low-scale SUSY

  Conlon/Kallosh/Linde/Quevedo '08
  Cicoli/Muia/Pedro '15

The calculation and (cosmological) application of α' corrections is receiving continuous attention...

- Higher-superspace-derivative terms in 4d SUGRA from 10d $\alpha'^2 R^4$ term....

  Possibility of achieving moderate field ranges and r-values....

  Ciupke/Louis/Westphal '15; Broy/Ciupke/Pedro/Westphal '15

- SUGRA-description of DBI-action α' terms;
  Flattening effects in inflaton potentials

  Bielleman/Ibanez/Pedro/Valenzuela/Wieck '16

- Recent work on higher-derivative terms in M-/F-theory...

  Grimm/Keitel/Savelli/Weissenbacher '13
  Minasian/Pugh/Savelli '15

Dark Radiation

- conventional variable: N_{eff}

  (effective number of neutrino species; $N_{eff}^{SM} = 3.046$)

- Plank 2015:

  $$N_{eff} = 3.1 \pm 0.3 \quad (95\% \text{ CL})$$

  (Earlier hints at $\Delta N_{eff} \neq 0$ have so far not materialized)

- Crucial: Further improvement expected in the future;
  Potential to exclude models with $\Delta N_{eff} \neq 0$.

- Conventional picture of cosmological evolution with some extra light d.o.f. (DR) :

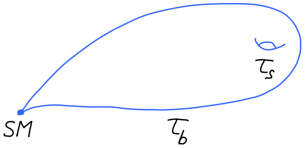
$$\text{Inflaton} \longrightarrow (\text{Modulus } \Phi) \longrightarrow \text{SM} + \text{DR}$$

$$\Delta N_{eff} \sim \frac{\Gamma_{\Phi \to DR}}{\Gamma_{\Phi \to SM}}$$

- In the LVS, the volume is the lightest moduls, Φ, and its imaginary part ('axion') unavoidably becomes DR

Dark radiation in the sequestered Large Volume scenario

Cicoli, Conlon, Quevedo '12
Higaki, Nakayama, Takahashi '12...'13



- sequestered Kähler potential:

$$K = -3\ln\left(T_b + \overline{T}_b - \frac{1}{3}\left[C^i\overline{C}^i + H_u\overline{H}_u + \{zH_uH_d + \text{h.c.}\} + \cdots\right]\right)$$

see e.g. Blumenhagen, Conlon, Krippendorf, Moster, Quevedo, '09

- A straightforward analysis gives:

$$\Gamma_{\Phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\Gamma_{\Phi \to H_u H_d} = \frac{2z^2}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

- Conclusion: Need either $z > 2$ or $n_H > 4$.

  (Here n_H counts Higgs doublets
  and one assumes the bound $N_{eff} < 4$.)

- Comment: Shift symmetry singles out $z = 1$,

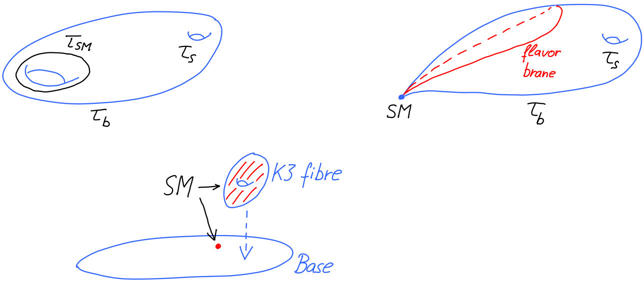
$$K_H \sim |H_u + \overline{H}_d|^2 \,.$$

  (It is unclear how to realize $z \gg 1$ at a fundamental level.
  Note that the Kähler metric becomes singular in this limit.)

Dark radiation in the general Large Volume scenarios

Angus '14
AH/Mangat/Rompineve/Witkowski '14

- We consider various settings (D-term-stabilized SM cycle in geometric regime, loop-stabilized fibred model, flavor branes)



- With the present 'dark radiation data' bounds, the sequestered LVS appears to be in trouble

  (Although this depends on $T_{reh.}$)

- The 'non-sequestered' or 'de-sequestered' (through flavor branes) LVS provides some more freedom, but still rather limited...

- Recent analysis: Cicoli/Muia '15

  Sequestered setting; String loop corrections included;
  Decay channel to SUSY scalars opens up
  $\Rightarrow$ dark radiation reduced.

Summary/Conclusions (for the inflation-part only)

- Quantum gravity (Instantons / Weak gravity conjecture) may be constraining large-field inflation at a very fundamental level

- Concrete problems with large-field inflation in string theory reflect these fundamental 'issues'

- Progress is being made both in understanding the generic constraints as well as in constructing counterexamples (i.e. models)

In primordial gravity waves / large-field inflation, fundamental quantum gravity problems may meet reality!

- Some of this discussion may also be relevant for relaxions