

## String Cosmology

### Assumptions

- 1) "Dark energy is due to a cosmological constant"  $DE = CC$   
 Planck 2018  $\omega_0 = -1.03 \pm .03$ ; we take  $\omega_\Lambda = -1$
  - 2) "There was an early phase of slow-roll inflation which set the initial conditions for structure growth"  $SR$  inflation set IC
  - 3) "String theory describes the correct high energy completion of quantum gravity"  
 $QG = str$  thy
- $\Rightarrow$  we should be able to find 1) & 2) in soln of str thy.

caveat : we actually only study a tiny lamppost of weakly coupled str thy ( $g_s \ll 1, l_s \ll$  all scales)

- Specifically IIB w/
- RR gauge fields + D branes
  - NS gauge field
  - 10d metric
  - dilaton (fixes  $g_s$ )

i.e. a string-inspired EFT w/o strings

### Outline

- 1) The Landscape: the vision • solving the CC problem w/ a flux landscape
- 2) The Landscape: the reality • The details of KKLT solutions
- 3) Models: Inflation + DE • ~~brane~~ inflation, unwinding inflation  
 • brane-world DE

### The CC problem (Weinberg 1989)

$$\rho_{vac} = \langle \rho \rangle + M_4^2 \Lambda_{bare} = M_4^2 \Lambda = 10^{-120} M_4^4 \quad \left( M_d^{d-2} = \frac{1}{8\pi G_N} \right)$$

Zero-point energies:  $\langle \rho \rangle = \int_0^{\Lambda_{EFT}} \frac{4\pi d^3k}{(2\pi)^3} \frac{\sqrt{k^2 + m^2}}{2} \approx \frac{\Lambda_{EFT}^4}{16\pi^2}$

This can't be solved by a single fine tuning w/ the framework of EFT  
 Tune @  $\Lambda_{QCD}$ ; then later decide to integrate out electron

$$\Lambda_{EFT} = .5 \text{ MeV} \left( \frac{10^{-3} \text{ GeV}}{1 \text{ MeV}} \right) \left( \frac{M_4}{10^{18} \text{ GeV}} \right) = 5 \cdot 10^{-22} M_4 \quad M_4 = 10^{18} \text{ GeV}$$

$$\rho_{vac} \approx 4 \cdot 10^{-88} M_4^4 : \text{ 30 orders of magnitude off}$$

Even if  $\exists$  a miracle in perturbation thy, non-pert eg. QCD instantons still give huge contrib

Anthropics: use our presence as a selection mechanism

- $1 < \Lambda_{\text{Max}} \stackrel{\text{lg } \Lambda}{\sim}$  prevents growth of structure  
 structure had started to form @  $z_s \geq 4$  at which time  $\rho_v < \rho_{\text{mat}}$   
 $\rho_{\text{mat}}(z_s) \approx \rho_{\text{mat},0} a^3(z_s) = \rho_{\text{mat},0} (1+z_s)^3 \quad \rho_v \lesssim 100 \rho_{\text{mat},0}$
- Maximum  $\rho_v$  and flatness:  $\Omega_v + \Omega_{\text{mat}} = 1$ ; given  $H_0 = 70 \frac{\text{km}}{\text{s Mpc}}$   
 $\rho_v \approx \rho_{\text{mat},0} = 3M_{\text{pl}}^2 H_0^2 = \mathcal{O}(1) 10^{-120} M_{\text{pl}}^4$

When is anthropic reasoning valid (e.g. Banks 2000)

- 1) You have a thy w/ a huge number of soln
- 2) You have a mechanism for populating/exploring soln space
- 3) You have reasonable assumptions about what it takes to get life  
 (e.g. curvature  $\neq 0$ ,  $H_0 \neq$  our value  $\rightarrow$  effect answer by order of mag.)

Flux Landscape: Bousso Polchinski 2000

a toy example of how str thy gives a huge # of soln with some  
in anthropic window

To illustrate the point take a fixed 7-torus in 11D

$$S_{11} = M_{11}^9 \int d^{11}x \sqrt{-g_{11}} \left( R - \frac{1}{2} |F_4|^2 \right) \quad |F_n|^2 = \frac{1}{n!} F_{\mu_1 \dots \mu_n} F^{\mu_1 \dots \mu_n}$$

• Fluxes,  $F_n$ , are  $n$ -forms  $F_n = \underbrace{F_{\mu_1 \dots \mu_n}}_{\text{totally antisym}} dx^{\mu_1} \wedge \dots \wedge dx^{\mu_n}$

• They are higher-dim analogs of electric + magnetic fields

$$F_n = dA_{n-1} \quad F_{\mu_1 \dots \mu_n} = d_{[\mu_1} A_{\mu_2 \dots \mu_n]}$$

gauge field

•  $(n-2)$ -branes are the electrically charged objects.

Higher-dim analogy of Dirac quantization  $T_p \int F_{p+2} = 2\pi n$   
 where  $T_p$  is the tension of a  $p$ -brane and the flux fills a compact space

• Electric/Magnetic duality:  $F_7 = * F_4$   $F_4 = f_4 \sqrt{-g_4} dx^0 \wedge \dots \wedge dx^3$   
 direct products  $ds_{11}^2 = ds_4^2 + ds_7^2$ :  $F_7 = f_4 \sqrt{g_7} dy^1 \wedge \dots \wedge dy^7$

For an internal flux  $F_7 = f_4 \sqrt{g_7} dy^1 \dots dy^7$  we can dimensionally reduce the action

$$S_4 = M_{11}^9 V_7 \int d^4x \sqrt{-g_4} (R - \frac{1}{2} F_4^2 - \Lambda_b) \text{ but quantization } M_{11}^6 \int F_7 = M_{11}^6 f_4 V_7 = 2\pi n$$

$$= \underbrace{M_{11}^9 V_7}_{M_4^2} \int d^4x \sqrt{-g_4} (R - \frac{1}{2} \underbrace{\left(\frac{2\pi n}{M_{11}^6 V_7}\right)^2}_{\left(\frac{2\pi n M_{11}^3}{M_4^2}\right)^2} - \Lambda_b)$$

$\approx 0 \rightarrow \Lambda = \Lambda_b + \frac{1}{2} C^2 n^2$

$$\sqrt{|2\Lambda_b|} = C n \quad \frac{d\Lambda}{dn} = C^2 n \Big|_{n_*} \approx \frac{|\Lambda_b|^{1/2} M_{11}^3}{M_4^2} < 10^{-120} M_4^2$$

↑ if cancellation can work

making  $M_{11}$  as small as possible  $M_{11} \sim \text{TeV}$  implies  $|\Lambda_b|^{1/2} \sim \text{TeV}$

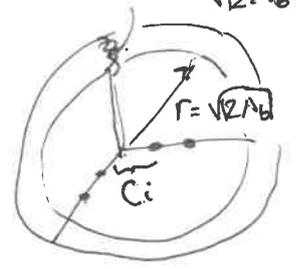
$$\left(\frac{\text{TeV}}{M_4}\right)^4 \sim 10^{-60} \Rightarrow 10^{-120}$$

$$|\Lambda_b| \approx \frac{2\pi n M_{KK}^7}{M_{11}^6} \quad \Delta r = \frac{\Delta \Lambda_{\text{obs}}}{\sqrt{|2\Lambda_b|}}$$

Need multiple fluxes:  $\Lambda = \Lambda_b + \frac{1}{2} \sum C_i^2 n_i^2$

$$2\Lambda_b < \sum n_i^2 C_i^2 < 2\Lambda_b + \Delta \Lambda_{\text{obs}}$$

$10^{-120}$



$$\text{Vol}_{\text{cell}} = \prod C_i < \text{Vol}_{\text{shell}} = \int \sum_{N-1} r^{N-1} \Delta r$$

$$= \int \sum_{N-1} |2\Lambda_b|^{N/2-1} \Delta \Lambda_{\text{obs}}$$

large  $\Lambda_b$  helps

What are  $C_i$ ?

$$F_7 = f_{4,i} \sqrt{-g_4} dx^1 \dots dx^3 \wedge \sqrt{g_{3,i}} dy^1 \dots dy^3$$

$$*F_7 = f_{4,i} \sqrt{g_{4,i}} dy^1 \dots dy^4 \quad M_{11}^3 \int *F_7 = f_{4,i} V_{4,i} = 2\pi n \quad f_{4,i} = \frac{2\pi n V_{3,i}}{M_{11}^3 V_7}$$

$$M_{11}^9 \int d^{11}x \sqrt{-g_{11}} (R - \frac{1}{2} \sum |F_4|^2)$$

$$= V_7 M_{11}^9 \int d^4x \sqrt{-g_4} (R - \Lambda_b - \frac{1}{2} \sum \left(\frac{2\pi n V_{3,i}}{M_{11}^3 V_7}\right)^2)$$

$$C_i = 2\pi V_{3,i} M_{11}^3 \frac{M_{11}^3}{M_4^2} = 2\pi \frac{V_{3,i} M_{11}^3}{V_7 M_{11}^7} M_{11}$$

Possible  $\Lambda_b \sim M_4^2$

$N=100 \quad C_i \sim \frac{1}{6} \checkmark$

$N=6 \quad C_i \sim 10^{-10} \checkmark$

dependent on manifold and degeneracies

In "Lecture 2" we will see how KKLT realizes this program in a setting of a dynamical warped (not direct product) CY compactification in  $\mathbb{H}^4$ . It is somewhat amazing that the general "vision" still works once you get rid of the drastic simplifications.

First let's talk about pt 2: populating the landscape

External inflation: in any gridpoint outside the  $\Delta\Lambda_{obs}$  shell, there will be an inflating dS that is meta-stable. If the decay rate  $\frac{\Gamma}{V} \propto e^{-\Delta S_E} = e^{-(S_{inst} - S_{false})} < H^4$  some region of space will remain in that vacuum (although every world line exits w/ Prob=1)

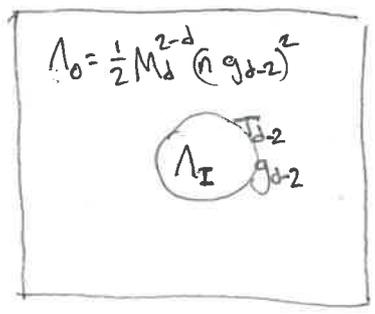
Brown - Teitelbaum (1987)

$$S = \int d^d x \sqrt{-g} (M_d^{2-d} R + |F_d|^2) + T_{d-2} \int d^{d-1} y \sqrt{g_{ind}} + g_{d-2} \int A_{d-1}$$

$$F_d = E \epsilon_{\mu_1 \dots \mu_d} \quad \begin{matrix} \uparrow \\ \text{coord + induced metric on brane} \end{matrix}$$

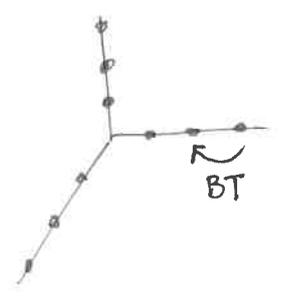
$$\Lambda = \frac{1}{2} M_d^{2-d} E^2$$

$$E = n g_{d-2} \quad [g_{d-2}] = m^{d/2}$$



$$\Lambda_I = \frac{1}{2} M_d^{2-d} ((n-1)g_{d-2})^2 \leftarrow \text{Gauss's Law}$$

Conservation of energy fixes size of bubble when it appears



one bubble moves along 1 axis in the landscape

For every 3 cycle in  $F_7 = f_{4,1i} \sqrt{g_4} dx^1 \dots dx^3 \wedge \sqrt{g_{3i}} dy^1 \wedge \dots \wedge dy^3$  the  $T_{2i1} = M_{11}^6 V_{3,1i}$  for the 5-brane that wraps  $dy^1 \dots dy^3$  corresp. to one inst. per axis

# Jordita Winterschool on Theoretical Cosmology II

(1)

How do we realize the flux landscape as solns of IIB str thy?

KKL: Kachru, Kallosh, Linde, Trivedi hep-th/0301240

"3 step process" <sup>shape of internal manifold</sup>

1) Stabilize complex structure and axio-dilaton @ high  $E < M_{\text{KK}}$

GKP: Giddings Kachru Polchinski hep-th/0105097

Find 4D Minkowski x 6D CY with unstabilized Kähler moduli

2) Add a stack of D7 wrapping a 4-cycle: world vol. gauge <sup>size of internal manifold</sup>  
 thy has gaugino condensation at low energy. This depends on the volume of the 4-cycle - fixes Kähler modulus in SUSY AdS

3) Add  $\overline{D3}$ , break SUSY and give "uplift" to dS

KPV: Kachru, Pearson, Verlinde hep-th/0112197

Alternatives: • LVS: Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058

include  $\alpha'$  correction as well as step 2: no fine tuning @ tree level  
 AdS is non-SUSY

• Time dependence: Dasgupta, Emelin, Mehedi Faruk, Tatar 1908.05288  
 - to get time dependent cosmology you should allow time dep. geomet + Flux  
 - dS is a coherent state in a (SUSY) AdS or Mink vacuum  
 - insisting time-ind destroys possibility of 4D EFT w/ finite d.o.f.

controversy: mostly in validity of step 2 in 10d description, some issues w/  $\mathbb{Z}_2$

step 1: GKP conventions: 1908.04788 Kachru, Kim, McAllister, Zimet

10D thy: assume warped CY compactification

$$ds^2 = e^{-6U(x)} e^{2A(y)} \underbrace{g_{\mu\nu} dx^\mu dx^\nu}_4 + e^{2U(x)} e^{-2A(y)} \underbrace{g_{ab} dy^a dy^b}_6 = G_{AB} dX^A dX^B$$

$$S_{\text{IIB}} = \frac{1}{2k_{10}^2} \int d^{10}X \sqrt{-G} \left( R_{10} - \frac{2A^2 T^2}{2(\text{Im}T)^2} - \frac{G_3 \cdot \overline{G}_3}{2\text{Im}T} - \frac{\widetilde{F}_5^2}{4} \right) + S_{\text{CS}} + \underbrace{S_{\text{local}}}_{D3, O3}$$

$$(2\pi\alpha')^2 = (2\pi l_s)^2 = 1 \quad G_3 = F_3 - TH_3 \quad T = C_0 + i e^{-\phi} \quad \widetilde{F}_5 = F_5 - \frac{1}{2} G_2 \wedge H_3 + \frac{1}{2} B_2 \wedge F_3$$

$$= G_3^+ + G_3^- \quad \text{ISD: } *_6 G_3 = i G_3 \Rightarrow G_3^- = 0$$

$$G_3^\pm = \frac{1}{2} (*_6 G_3 \pm i G_3) \quad \text{AISD: } G_3^\pm = 0$$



now integrate over  $M$ : LHS = 0

- 4D Minkowski if  $G_3 = 0$ ; SUSY only if  $(0,3)$  comp. vanishes allowed in  $G_3^+$

step 2: Gaugino Condensation

- Wrap  $N$  D7 branes on the 4-cycle whose volume is given by ReT

0408036  
 vrange

Reduce the DBI + CS brane action, in presence of ISD  $G_3$ , and find a 4D  $N=1$  pure SYM action at low energy below KK scale

vector gauge grp  $SU(N)$   
 matter gets mass given by vol  $\Sigma_4$  gauge coupling  $g_{YM}^{-2} \propto \text{ReT}$

04: Affleck, Dine, Seiberg

- Fermionic partner to gauge boson is gaugino,  $\lambda$
- at low energy the theory is confining (think quarks) and the gaugino bilinear gets a vev (think Higgs)
- This is non-perturbative and non-local from UV point of view
- $N=1$  potential reproduced by  $W_{np} = A e^{-\frac{2\pi T}{N}}$   
 $\langle \lambda\lambda \rangle = 16\pi e^{\frac{K^2 K}{2}} \frac{1}{d_T} W_{np}$

$W(T) = W_0 + A e^{-\frac{2\pi T}{N}}$  (assume axion is fixed  $\rightarrow$  let  $T = \bar{T}$  and shift  $A$ )

$V = e^{K^2 K(\text{not } T)} \frac{(2A e^{-2\pi T} (A(3+2T) + 3 e^{2\pi T} W_0))}{6T^2}$   $d = \frac{2\pi}{N}$

$d_T V = 0 \Rightarrow W_0 = -\frac{1}{2} A e^{-\frac{2\pi T}{N}} (3 + 2 \frac{2\pi}{N} T)$  also gives  $d_T W = 0$  SUSY

- $V_{\text{SUSY}} = -\frac{(\frac{2\pi}{N})^2 A^2 e^{-\frac{4\pi T}{N}}}{6T}$
- \* find a very shallow SUSY AdS vacuum
- \*  $W_0$  is a tree-level flux cont. that has to be same order as non-pert effects (LVS relaxes this and  $W_0$  can easily be  $\mathcal{O}(1)$  but AdS is SUSY so use of SUSY  $\langle \lambda\lambda \rangle$  result is more questionable)

\* Tuning  $W_0 \ll 1$  is equivalent to tuning small  $C_i$  in the BP model. Fluxes are discrete so not obviously possible

hep-th/0503124: Denef, Douglas, Florea, Grassi, Kachru show it is explicitly in F-TW

# WTC II

$$V = V_{\text{SUSY ADS}} + V_{\text{DB}}$$

(4)

Before going to step 3, I'll summarize the recent work which constitutes a debate regarding the possibility of a 10D description of the non-perturbative effects.

many other papers I won't discuss keep a 4D EFT pt of view

chronologically

1707.08678 : Moritz, Retolaza, Westphal

- the backreaction of DB's in the uplift on the SUSY ADS potential makes achieving dS impossible

(Also Sethi: 1709.03554)

Camp 1

1812.06097, 1902.01410 Hamada, Hebecker, Shiu, Soler

1902.01412 Carta, Moritz, Westphal

Camp 2

1810.08518, 1902.0415 Gautason, Van Hemelryck, Van Riet, (Venken)

These 2 camps correct some technical errors in the 1707... and use technical advancements from 1812... to study GKP +  $\langle \lambda \lambda \rangle$

consider:  $\mathcal{L} = \int_M \frac{e^{2A}}{2\pi} |G_3^-|^2 + e^{-6A} |2(e^{4A} - \alpha)|^2 + \frac{e^{2A}}{2\pi} \left( \frac{1}{4} (T_{mn}^m - T_{\mu\nu}^\mu) - 2\pi\rho_3 \right)$

Camp 1 Both agree w/ 4D EFT for SUSY ADS

$$T_{MN}^{\langle \lambda \lambda \rangle} = \frac{\delta S(G_{MN}, \lambda \lambda(T))}{\delta G_{MN}}$$

Agree w/ 4D EFT; Find exact "on-shell" agreement however  $\downarrow V$  does not match "off-shell"; there isn't a local 10d description. If Camp 2 included off-shell potential relating  $\langle \lambda \lambda \rangle$  and T They would agree

how does  $\langle \lambda \lambda \rangle$  contribute

Camp 2

$$T_{MN}^{\langle \lambda \lambda \rangle} = \frac{\delta S(G_{MN}, \lambda \lambda)}{\delta G_{MN}} \Big|_{\lambda \lambda(T)}$$

Doesn't agree w/ 4D EFT; once the backreaction of DB is taken into account there is a no-go for dS

Camp 3: 1908.04788 Kachru, Kim, McAllister, Zimet

Compute full off-shell potential for Kahler modulus only taking IR  $\langle \lambda \lambda \rangle$  into account at the level of EOM but including coupling of  $\langle \lambda \lambda \rangle$  to flux at 10D.   
 condensation breaks CY geometry so generalized geometry changes the 10D action

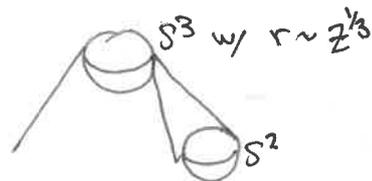
\* Notably absent: connection to Dasgupta, Emelin, Mehedi Faruk, Tatar : where is the tower of unsuppressed operators/states that destroys EFT for time-ind dS

Step 3: the uplift



Warped throats: generally CY's can have conifold singularities  
conifold is a <sup>complex</sup> cone w/ base (topologically)  $S^3 \times S^2$ :  $\sum_{i=1}^4 \omega_i^2 = 0$

deformed conifold is instead  $\sum \omega_i^2 = z$



•  $z$  is a complex structure moduli

• Adding flux  $\int_{A=S^3} F_3 = M$  and  $\int_{B=S^2} H_3 = K$  GKP show that

$W = \int G \wedge \Omega$  fixes  $z \propto e^{-\frac{2\pi K}{g_s M}}$  ( $z = \int_A \Omega$ )

Klebanov - Strassler: hep-th/0108101: Herzog, Klebanov, Ouyang

• so far  $F_5$  has been a spectator. It must solve a Bianchi identity that is referred to generally as a tadpole condition:

$\int_M [dF_5 = H_3 \wedge F_3 + Q S^6(\gamma - \gamma_{D3})] \Rightarrow 0 = KM + N_{D3}^{(total)}$

$KM + N_{D3} = \frac{\chi}{24}$  ← Euler # of F-th 4-fold: accounts for D3-charge carried by D7's in F-th compactification

• so "far away" the WDC can be matched to the metric of a stack of D3

$dS_{KSTP}^2 = \underbrace{\sqrt{\frac{T K}{g_s M}} e^{-\frac{4\pi K}{3g_s M}}}_{\propto z^{2/3}} g_4 dx^\mu dx^\nu + g_s M (d\Omega_3^2 + \frac{1}{T} (d\rho^2 + \rho^2 d\Omega_2^2))$

• I'm dropping lots of factors (mostly numerical) that are really going to be important

•  $e^{4A_{tip}} = \sqrt{\frac{T K}{g_s M}} e^{-\frac{8\pi K}{3g_s M}}$

Why? why have I gone through this?  $\overline{D3}$ 's are going to fall to the tip! drives branes to smallest warping

Gauge potential  $C_4 = \alpha dx^1 \dots dx^3$

$\vec{F}_1 = -dV$

$\vec{F}_{D3} = -2\mu_3 d\gamma = 2\mu_3 d\gamma e^{4A(r)} \rightarrow \text{tip}$

So now we can evaluate the  $\overline{D3}$ :  $S_{DBI} + S_{CS} = 2S_{DBI}$  at the tip

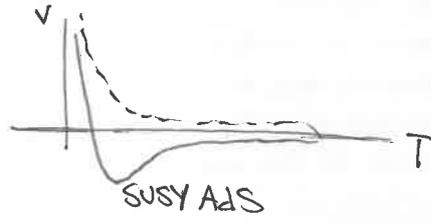
$$\int d^4x \sqrt{-g} V_{\overline{D3}} = -2S_{\overline{D3}} = 2\mu_3 p \int d^4y \sqrt{g(\text{ind})} \Rightarrow V_{\overline{D3}} = 2\mu_3 p e^{-12\sigma} e^{4A+4\phi} = \frac{2\mu_3 p k}{g_s M} e^{-\frac{8\pi k}{3g_s M}} \text{tip}$$

$$T = \int_{\Sigma_4} \sqrt{g_{\text{ind}}(\Sigma_4)} e^{-4\phi} e^{4\sigma} = e^{4\sigma}$$

Assume  
 most of the CY is not highly warped  
 - (trivially) normalize its volume to  $1 e^{6\sigma}$

"schematic"  $\frac{T^2}{g_s M}$   
 probe correct  $\frac{T^2}{g_s M}$   
 KKLT has  $T^{-2}$  wrong

This is the uplift term: it is important that it can be exponentially suppressed



roughly:  $\frac{D}{T^2}$  w/  $D \sim |W_0|^2 \ll 1$

Does this uplift interfere w/  $\langle \lambda \lambda \rangle$ ?

Camp 3: yes but computation is still valid

$$\phi = \phi_{BK} + \delta\phi_{\langle \lambda \lambda \rangle} + \delta\phi_{\overline{D3}}$$

10D fields w/o  $\langle \lambda \lambda \rangle$  or  $\overline{D3}$   $\rightarrow T_{uv} = T_{uv} |_{\phi_{BK} + \delta\phi_{\langle \lambda \lambda \rangle}} + T_{uv} |_{\phi_{\overline{D3}}} + \text{subleading}$

Carra, Moritz, Westphal: computation is still valid but numerology kills you for a single Kähler modulus and "generic" CY

- no bkrxn on CY:  $T \gg N_{DB}^{(\text{throat})} |z|^{-4/3} = \frac{1}{4} \langle \lambda \lambda \rangle$ : no throat, cont time uplift
- Warped region:  $N_{DB}^{(\text{th})} |z|^{-4/3} \gg T \gg N_{DB}^{(\text{th})}$ : significant warping that doesn't break overall CY geometry

$\rightarrow$  requirement  $T \gg N_{DB}$  needed to not break overall geometry (needed for assumption eg.  $T \approx e^{4\sigma}$ ) is at odds with needing the uplift to be small enough

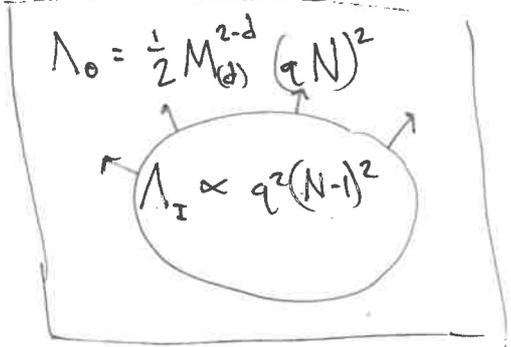
Continue under the assumption that some explicit version of a KKLT-like soln exists, generating a flux landscape and providing an anthropic soln to the CC-problem together with the BT instantons.

Inflation: Unwinding Inflation w/ D'Amico, Gobbetti + Kleban

- Plan
- 1) @ level of 1<sup>st</sup> lecture: Mechanism in BP landscape
  - 2) @ level of 2<sup>nd</sup> lecture: detailed construction in KS throat
- (could also mention D-brane inflation or axion-monodromy)  
sm field range or Fibre int. use more ingredients than KKLT

Recall BT bubbles

$$F_d = qN \epsilon_{m_1 \dots m_d}$$



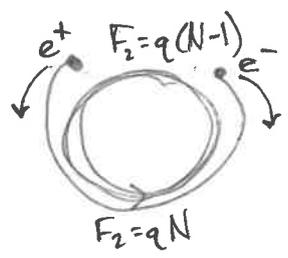
What if the bubble is localized in a compact direction?

Flux cascade: repeated self-collisions can discharge many units of flux

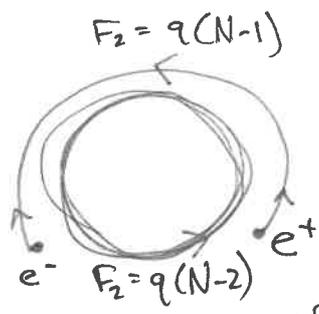
E.g. 1+1 dimension



BT

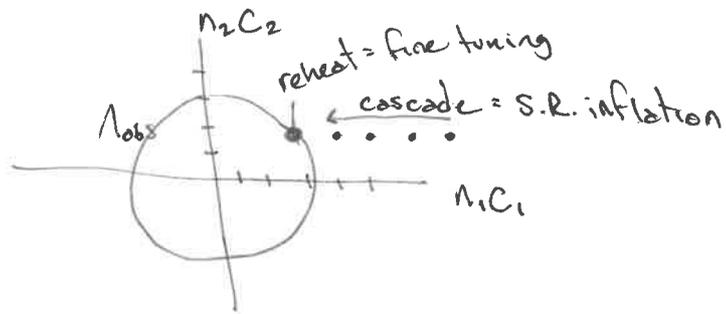


electric force



no annihilation if charges are moving relativistically

in the landscape



Prototype:  $dS_4 \times S^1$    
 ↑ sourced by  $F_5$  flux   
 ← fixed by other sources

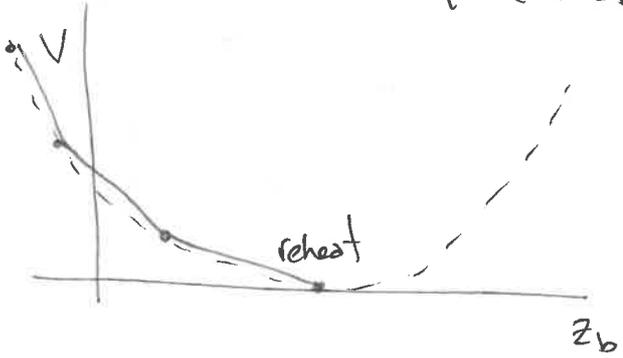
$$S_5 = \int_{S^1} dz \int d^4x \sqrt{g_4} (-2T \delta(z-z_b) \sqrt{1-(\partial_t z_b)^2} - |F_5|^2)$$

integrate over  $S^1$  for  $z_b = z_b(t)$    
 → no fluctuations

$$q^2 N^2 = q^2 \left( N_0 - \left[ \frac{2z_b}{l_{S^1}} \right] \right)^2$$

$$S_4 = \int \sqrt{-g_4} d^4x (-2T \sqrt{1-(\partial_t z_b)^2} - V(z_b))$$

$$V'(z_b) = q^2 (N(z_b)^2 - (N(z_b) - 1)^2) = -2q^2 \left( N_0 - \left[ \frac{2z_b}{l_{S^1}} \right] - \frac{1}{2} \right)$$



piecewise linear approx to quadratic

- approximately an  $m^2 \phi^2$  model (DBI kin. term decreases tensor to scalar ratio)
- oscillations in power spectrum related to size of  $S^1$

2) What about in a "realistic" compactification: i.e. KKLT

Pg 4 I

The uplift potential for an  $\overline{D3}$  is strictly speaking only valid

for a single  $\overline{D3}_1$  at the tip:  $S_{\overline{D3}} = 2m_3 (p=1) \int d^4y \sqrt{g^{(ind)}} = \frac{2m_3 p k}{g_s M} \frac{e^{-\frac{2\pi k}{3g_s M}}}{T^2}$

The induced metric  $g^{(ind)}_{ab} = G_{\mu\nu} \frac{dx^\mu}{d\beta^a} \frac{dx^\nu}{d\beta^b}$

For a stack of  $N$  branes we get a  $U(N)$  gauge theory where the position of the stack in the transverse coord. are adjoint scalars  $x^i = \alpha' \Phi^i$ ,  $\Phi^i$  is an  $N \times N$  matrix and the pullback is

$$g^{(ind)}_{ab} = G_{ab} + 2\pi\alpha' G_{i(a} D_{b)} \Phi^i + \alpha'^2 G_{ij} D_a \Phi^i D_b \Phi^j$$

$$D_a \Phi^i = d_a \Phi^i + i[A_a, \Phi^i] \quad A_a = U(N) \text{ gauge field}$$

In the presence of a  $(p+4)$ -RR-flux  $F_{p+4} = f \epsilon_{\mu_1 \dots \mu_{p+4}}$  this generates a non-trivial potential

D3's w/  $F_3 = *F_7$

$$g_s V_{\text{eff}} \approx \sqrt{G_{11}} \left( \varphi - \frac{i 4\pi^2}{3} F_{ijk} \text{Tr}([\Phi^i, \Phi^j] \Phi^k) - \frac{\pi^2}{g_s^2} \text{Tr}([\Phi^i, \Phi^j]^2) \right)$$

with EOM  $[[\Phi^i, \Phi^j], \Phi^k] - i g_s^2 f \epsilon_{ijk} [\Phi^j, \Phi^k] = 0$

$\rightarrow$  SU(2) soln  $[\Phi^i, \Phi^j] = -i g_s^2 f \epsilon_{ijk} \Phi^k$

$\bar{D}3$  branes polarize into a NS5 wrapping an  $S^2$  w/ radius decided by the flux:  $f = g_s M$  in KS

NS5 in WDC



$$d\Omega_3^2 = d\psi^2 + \sin^2 \psi d\Omega_2^2$$

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$$S_{\text{NS5}} = \frac{\mu_5}{g_s^2} \int d^4 x \sqrt{-\det G_{11}} \det [G_{11} + g_s (2\pi\alpha' F_2 - C_2)] - \mu_5 \int B_6$$

Labels:   
 -  $\int d^4 x$ : spacetime filling   
 -  $G_{11}$ :  $S^2$  on  $S^3$    
 -  $F_2 = 2\pi\alpha' p$ : conservation of D3 charge   
 -  $\int_{S^3} dC_2 = \int_{S^3} F_3 = M \cdot 4\pi\alpha'$

DS:  $F_3 = dC_2 + H \wedge C_1$    
 NS5:  $H_3 = dB_6 + F_3 \wedge C_1$    
 or  $F_2 \wedge C_1$  w/ gauge choice

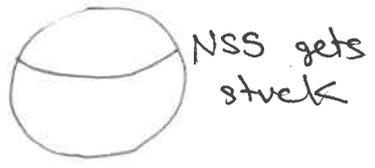
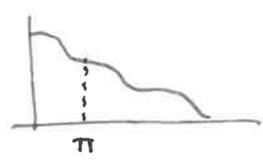
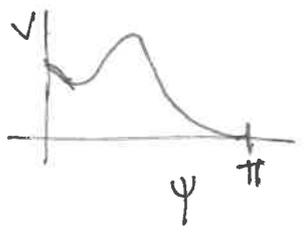
Plug in (in scratch) integrates  $S^2$

$$\propto \int d^4 x a^3(t) \left[ \sin^4 \psi + \left( \frac{\pi p}{M} - \psi + \frac{1}{2} \sin 2\psi \right)^2 \right] \sqrt{1 - \frac{g_s M h_0^{1/2}}{r^{1/2}} \psi^2} + \frac{\pi p}{M} - \psi + \frac{1}{2} \sin 2\psi$$

$$V_{\text{eff}} \propto \sqrt{\sin^4 \psi + \left( \frac{\pi p}{M} - \psi + \frac{1}{2} \sin 2\psi \right)^2} + \frac{\pi p}{M} - \psi + \frac{1}{2} \sin 2\psi$$

$\frac{p}{M} \lesssim .08$

$\frac{p}{M} \gg 1$



Flux cascade

I. In the WDC we have  $F_5, F_3, H_3$  and we saw in KKLT that positive energy comes from  $\overline{D3}$  - naturally discharges  $F_3$

• Obstacle to unwinding: Bianchi Identity

$$\int dF_5 = H_3 \wedge F_3 + Q^{\text{tot}} \delta^6(D3) : KM + N_{D3} = 0$$

- BT nucleation changes flux #'s ( $\Delta F_3 \neq 0$ ) but preserves D3 charge

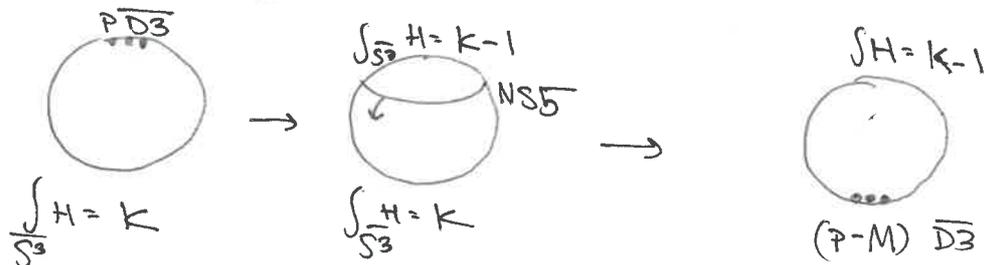
- need to specialize to Brane-Flux-annihilation

Kachru-Pearson-Verlinde: hep-th/0112197

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II

$$\int_{S^0} F_3 = M (4\pi\alpha') \quad \int_{S^3} H_3 = K (4\pi^2\alpha')$$



NS5 electrically charged under  $H_3 = *F_3$

$$P = MK$$

$$P - M = M(K-1)$$

if  $M > P$  left w/  $D3$ : done

$M < P$  left w/  $\overline{D3}$  → repeat

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END

up: Mechanism of Unwinding realized using well-understood components

down: Numerology, Kill you in same way as in Carte, Moritz, Westphal  
seems to

find  $MK \sim 10^7 > 10^6$  lgst known Euler #