Challenges of Stringy de Sitter and Asymptotic Acceleration

Arthur Hebecker (Heidelberg)

based on work with **Simon Schreyer and Gerben Venken**

(cf. also earlier work with **Xin Gao/Junghans and Xin Gao/Schreyer/Venken**)

Outline

- **Reminder:** Need for de Sitter / Singular-Bulk Problem of KKLT / LVS Parametric Tadpole Constraint.
- Curvature Corrections for Anti-D3 in Warped Throat: Fundamental Problem or Blessing in Disguise?
- The real thing: Curvature Corrections for NS5.
- Asymptotic Acceleration without de Sitter?

The construction of controlled dS in String Theory remains a key challenge

.....as emphasised e.g. in

... Danielsson/Van Riet; Obied/Ooguri/Spodyneiko/Vafa '18 ...

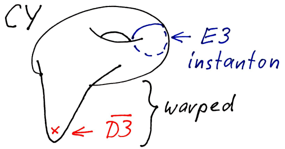
- Quintessence is certainly an alternative, but technically it runs into similar (or worse) problems....

  cf. Cicoli/Pedro/Tasinato '12 .... AH/Skrzypek/Wittner '19 .....

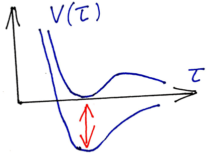
- Thus, the paradigmatic approach of 'AdS-minimum' plus 'Uplift' appears to remain the main road towards controlled dS models.

The former flagship model KKLT appears to be in trouble....

- Reminder:



$\Rightarrow$



- The dS vacuum relies on the competition of two small quantities:

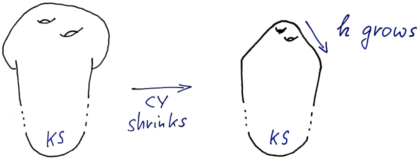
$$V_{AdS} \sim \exp(-\tau) \qquad \text{and} \qquad V_{up} \sim \exp(-N/g_s M^2)$$

This matching implies that
the throat can not be parametrically smaller than the bulk....

Carta/Moritz/Westphal '19

Control problem of KKLT:

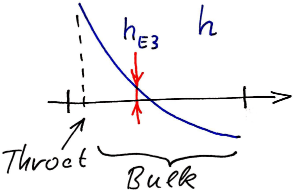
- As a result, strong warping sets in already in the bulk:



- This implies the (potentially deadly) 'singular bulk problem':

Gao/AH/Junghans '20

$$ds_{10}^2 = h(y)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu$$
$$+h(y)^{1/2}\tilde{g}_{mn}dy^m dy^n$$

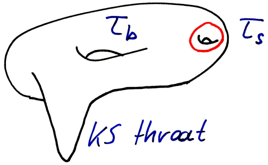


(see however Carta/Moritz, Demirtas et al. '21)

Control problem also for LVS?

- The LVS is naively safe since the volume $\mathcal{V} \sim \tau_b^{3/2}$ is exponentially large:

$$\boxed{\tau_s \sim \xi^{2/3}/g_s \quad , \quad \mathcal{V} \sim \exp \tau_s}$$



- However, the combination of several constraints may nevertheless lead to control problems ....

Junghans '22

- The key constraint of bulk curvature corrections may be overcome using a large D3-tadpole:

$\rightarrow$ LVS Parametric Tadpole Constraint

Gao/AH/Schreyer/Venken '22

The LVS Parametric Tadpole Constraint:

- .....explicitly, the bound on the required neg. D3-tadpole reads:

$$|Q_3| > N = N_* \left(\frac{1}{3} \ln N_* + \frac{5}{3} \ln c_N + 8.2 + \cdots \right) ,$$

$$\text{with} \qquad N_* \equiv \frac{9 g_s M^2}{16\pi} \sim \frac{g_s M^2}{5} .$$

and with $c_N \gg 1$ controlling bulk curvature corrections.

(For $g_s M^2$, metastability bounds of $12 \cdots 46$ have been discussed. See e.g. KPV, Bena et al., Blumenhagen et al. Scalisi et al., Lüst/Randall '22)

- Optimistically, rather modest bounds of $N \sim 40$ follow. However, things are really more complicated....

Curvature Corrections affecting the $\overline{\mathrm{D3}}$

- As correctly emphasised by Junghans, $\overline{\mathrm{D3}}$ curvature corrections tend to strengthen the PTC:

$$V_{\overline{\mathrm{D3}}} = \frac{\mu_3}{g_s}\left[1 - R_{10}(\overline{\mathrm{D3}})^2\right] = \frac{\mu_3}{g_s}\left[1 - \frac{c}{(g_s M)^2}\right]$$

with $c = 5.92$.

Junghans '22 (2nd paper), cf. also AH/Schreyer/Venken '22

- To control this corrections, one needs sizeable $g_s M$.

Together with the KPV-bound $1/M < 0.08$, this drives the key parameter $g_s M^2$ to larger values.

$\overline{\mathrm{D3}}$ Curvature Corrections – a Blessing in Disguise?

AH/Schreyer/Venken '22

- However, the uplift potential

$$V_{\overline{\mathrm{D3}}}\, h_{\mathrm{tip}}^{-1} \;\sim\; \frac{\mu_3}{g_s}\left[1 - \frac{c}{(g_s M)^2}\right] e^{-N/g_s M^2}$$

  does not suffer phenomenologically if $[1 - c/(g_s M)^2] \to 0$.
  On the contrary!

- One must only avoid $(g_s M)^2 < c$, since then the uplift is lost.

- Thus, allowing even for all higher-order corrections, i.e.

$$[1 - c/(g_s M)^2] \quad \to \quad [1 - \Delta_{\mathrm{curv}}(g_s M)]\,,$$

  there are two logical possibilities:

Possibility A:

- $[1 - \Delta_{\rm curv}(g_s M)]$ remains positive even for not so large $g_s M$.
- Then curvature corrections only renormalise the uplift.
- The overall consistency of the LVS (in particular the PTC) is not affected significantly.

Possibility B:

- For some $g_s M$, the factor $[1 - \Delta_{\rm curv}(g_s M)]$ changes sign.
- Then, by continuitiy, one can find an appropriate (integer) M and some highly tuned value of g_s such that

  $\boxed{[1 - \Delta_{\rm curv}(g_s M)] \text{ becomes extremely small.}}$

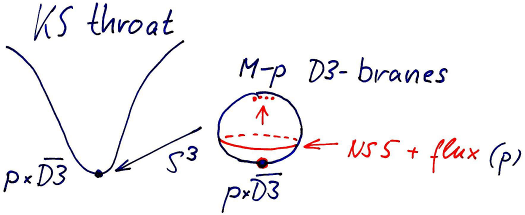
- Thus, trusting the power of landscape tuning of g_s, we can have exponentially small $\overline{D3}$ uplift without deep throats!

....however, the full truth is much more complicated:

NS5-brane curvature corrections

AH/Schreyer/Venken '22; Schreyer/Venken '22

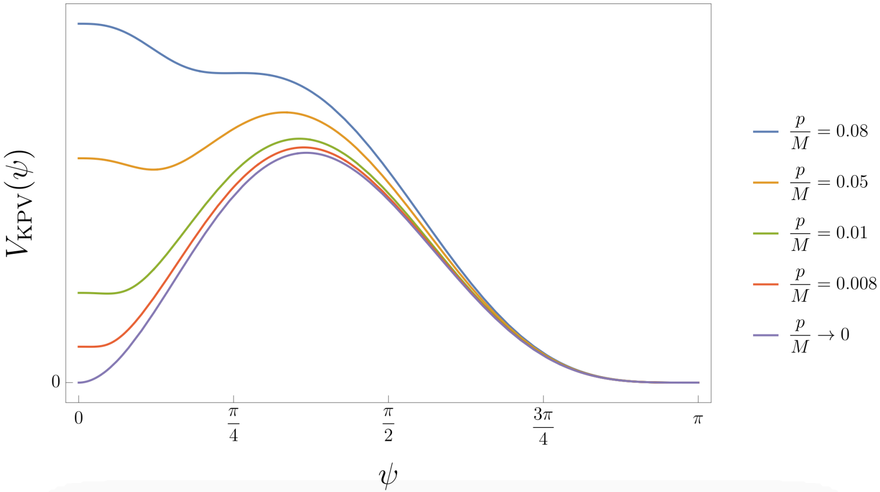
- The $\overline{\mathrm{D3}}$ has well-known 'KPV' NS5-brane decay channel:



- The curvature at the tip is controlled by $g_s M$, in particular $R_{S^3} \sim \sqrt{g_s M}$.

- At small $g_s M$, a key concern are NS5-brane curvature corrections and the stability of the KPV-potential!

Reminder of KPV potential (with ψ the NS5-brane altitude)



- Dp curvature corrections known.
  Symbolically:

  Bachas/Bain/Green '99; Junghans/Shiu '14

$$-\frac{1}{g_s}\int_{Dp}\sqrt{g+\mathcal{F}}\,(1-\alpha'^2 R^2)$$

(Here 'R^2' stands for various contractions of 10d Riemann tensor and 2nd fundamental form of Dp-hypersurface.)

- For $D3$, which is $SL(2,\mathbb{Z})$ invariant,
  the all-orders g_s dependence is 'known':

$$\frac{1}{g_s}\alpha'^2 R^2 \quad\rightarrow\quad E_1(S,\overline{S})\alpha'^2 R^2 \qquad (\; S = C_0 + \frac{i}{g_s}\;)$$

- Based on the fact that a fluxed D5 with geometry $\mathbb{R}^{1,3}\times S^2$ gives a $D3$ in the shrinking S^2-limit, we conjecture:

The $E_1(S,\overline{S})$ prefactor also appears for $D5$s.

- Thus, we write for the D5

$$-\frac{1}{g_s}\int_{D5}\sqrt{g+\mathcal{F}}\,\left(1-E_1(S,\overline{S})\,\alpha'^2 R^2\right)\,,$$

and S-dualize $(g_s \to 1/g_s)$,

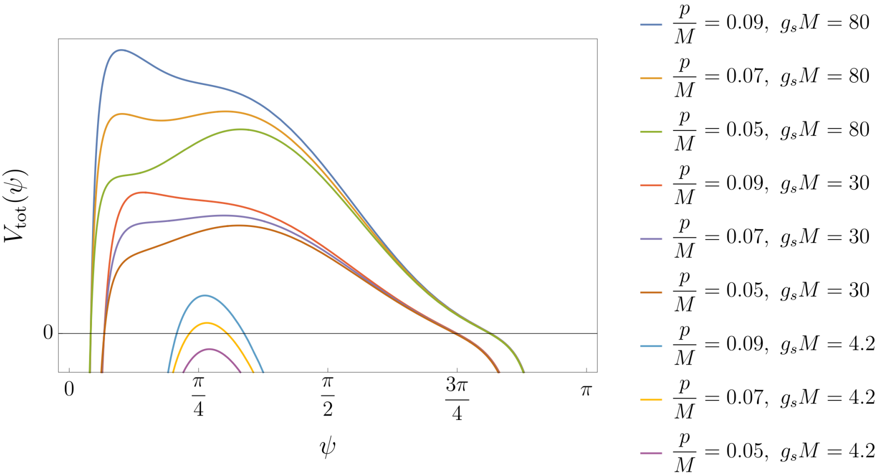
using also $E_1(S,\overline{S}) \sim g_s$ at large g_s, to find:

$$\boxed{S_{NS5} \sim -\frac{1}{g_s^2}\int_{D5}\sqrt{g+\mathcal{F}}\,\left(1-\alpha'^2 R^2\right)}$$

- This result (or conjecture) is consistent with the expectation that, also for a fluxed NS5 on $\mathbb{R}^{1,3}\times S^2$, one expects to get a $D3$ in the shrinking S^2-limit.

Note: Could also use S-dual setting and D5 rather than NS5 (cf. Gautason/Schillo/Van Riet '16), but conclusions not better.

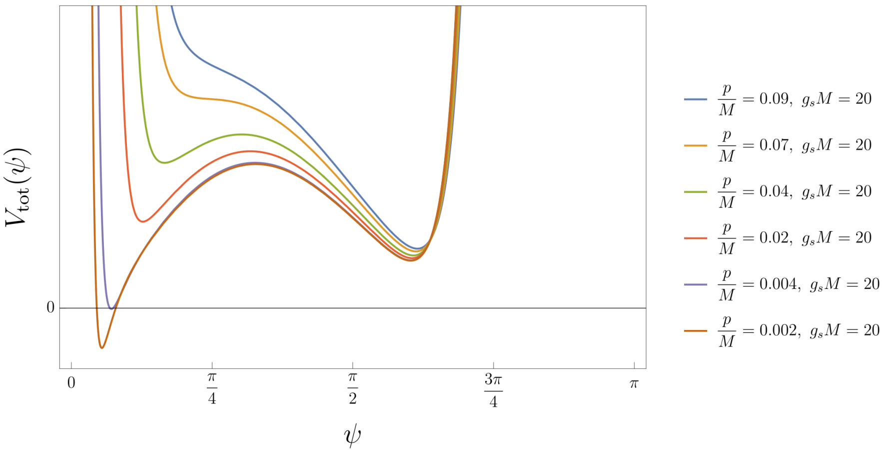
Curvature-corrected KPV potential



Note the very large $g_s M$-value needed for a metastable minimum and the still large value needed for a positive barrier!

Curvature and higher-order-flux-corrected KPV potential

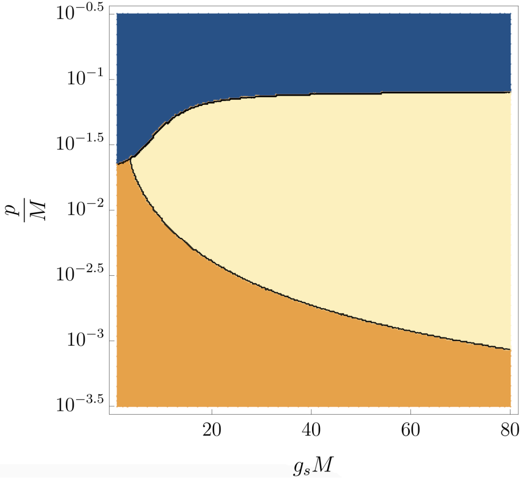
Schreyer/Venken '22 (using results of Robbins/Wang, Garousi, Babaei/Jalali)



Note: One can now actually see, also using the NS5-brane, that the SUSY-breaking minimum falls below zero ($\rightarrow$ weak-warping uplift).

Curvature and higher-order-flux-corrected KPV potential

Schreyer/Venken '22 (using results of Robbins/Wang, Garousi, Babaei/Jalali)



Optimal (borderline):

$g_s M \simeq 3.6$
$p/M = 1/40$

Yellow: Metastable minimum exists; Blue: No metastable minimum; Orange: Metastable minimum at negative energy.

Impact on: LVS parametric tadpole constraint:

- It is now more useful to take $g_s M$ rather than $g_s M^2$ as the basic control parameter of the throat:

$$|Q_3| > N = \frac{2^{8/3}\kappa_s^{2/3}(g_s M)^2}{2\pi^2\xi^{2/3}}\left(\frac{1}{4}\ln g_s M + \frac{5}{8}\ln c_N + 3.04 + \cdots\right)^2 .$$

- Choosing $g_s M = 3.8$, $c_N = 5$, $\kappa_s = 0.1$ (this is optimistic!), one finds $N \simeq 560$.

- Recent best value: $Q_3 = -252$. $\Rightarrow$ potential problem!
  Crino/Quevedo/Schachner/Valandro '22

  (Larger $|Q_3|$ values in models with 'Whitney branes' or generic F-theory geometries have their own control problems.....)

  For more see parallel talk by S. Schreyer.

Cosmological Acceleration at the Asymptotics of Field Space

(possibly without de Sitter):

Ooguri/Palti/Shiu/Vafa; AH/Wrase '18; Grimm/Li/Valenzuela '19; Bedroya/Vafa; Rudelius '21; .... Shiu/Tonioni/Tran '23; van de Heisteeg/Vafa/Wiesner/Wu '23

- A key motivation: Possibly, getting metastable de Sitter is so hard because cosmological horizons are fundamentally sick.

- So let's focus on getting cosmological horizons in the simplest way, maybe based on

$$V \sim e^{-\gamma\varphi} \qquad \text{at} \qquad \varphi \to \infty \qquad \text{with} \qquad \gamma < \gamma_{acc} \equiv \frac{2}{\sqrt{d-2}}\,.$$

- If we succeed, we will earn the right to be more optimistic about (poorly controlled) metastable dS models.

Asymptotic Acceleration (continued)

AH/Schreyer/Venken, to appear today!

Conjecture ('Asymptotic Acc. Implies dS' or 'AA⇒dS'):

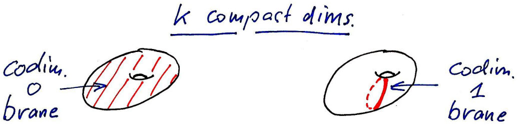
Accelerated expansion at the asymptotics of field space in d dimensions is only possible on the basis of a compactification of a metastable $(d+k)$-dimensional dS vacuum.

Argument:

- All (relevant) asymptotics are decompactification limits.
  Based on 'Emergent String', Lee/Lerche/Weigand '18
- Analyse energy sources in k-dimensional compact space.
- Leaders: Branes with codim. 0 (i.e. C.C.) and codim. 1.
- Observe:

$$\gamma_{\mathrm{codim.}\,0} < \gamma_{\mathrm{acc}} < \gamma_{\mathrm{codim.}\,1} \,.$$

Asymptotic Acceleration – explicitly....



$$\gamma_{\mathrm{codim.\,0}} < \gamma_{\mathrm{acc}} < \gamma_{\mathrm{codim.\,1}}$$

$$\frac{\gamma_{\mathrm{codim.\,0}}}{\gamma_{\mathrm{acc}}} < 1 < \frac{\gamma_{\mathrm{codim.\,1}}}{\gamma_{\mathrm{acc}}}$$

$$\sqrt{\frac{k}{k+d-2}} < 1 < \frac{k+d/2-1}{\sqrt{k(k+d-2)}}$$

For more see parallel talk by G. Venken.

Summary / Conclusions

- KKLT has fundamental problems ('Singular Bulk'); LVS faces quantitative issues ('Parametric Tadp. Constraint').
- Things could be much better if strong curvature drives uplift-energy to zero! (cf. our new, finely tuned uplift.)
- In any case, analysing KPV with NS5-brane curvature corrections appears to be *the* way forward.

- One may hope to establish asymptotic acceleration rather than dS, to prove that nothing is wrong with cosmic horizons.
- However, we argue (conjecture) that: 'AA⇒dS.

For exciting new results concerning Kinetic Mixing and Cobordism in the Landscape cf. parallel talks by R. Küspert and B. Friedrich.