Challenges and phenomenological opportunities for the LVS

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based on work with **Xin Gao/Schreyer/Venken,** **with Cicoli/Jaeckel/Wittner,** **with Jaeckel/Kuespert** **and with Friedrich/Strauss/Salmhofer/Walcher**

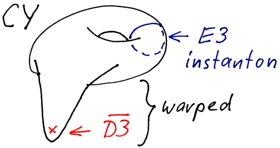
(includes comments on earlier work with **Xin Gao/Junghans**)

Outline

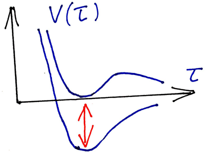
- Reminder of the singular-bulk problem of KKLT.
- The 'parametric tadpole constraint' of the LVS.
- Light fields in the LVS:
  QCD-Axion, Dark Radiation, Mixing with hidden $U(1)$s.
- A novel ('local WDW') proposal for the measure problem.

KKLT

- Reminder:



$\Rightarrow$



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

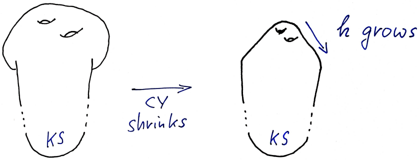
$$V_{AdS} \sim \exp(-\tau) \qquad \text{and} \qquad V_{up} \sim \exp(-N/g_s M^2)$$

A simple parametric analysis shows that this implies a 'throat-gluing problem' ....

Carta/Moritz/Westphal '19
see also Blumenhagen/Gligovic/Kaddachi '22

Control problem of KKLT ....

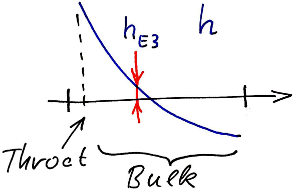
- This is not necessarily deadly ....



- But, what is worse, this situation entails a (potentially deadly) ‘singular bulk problem’:

Gao/AH/Junghans ’20

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



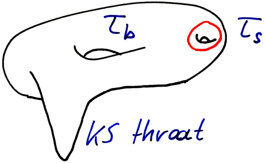
(see however Carta/Moritz, Demirtas et al. ’21)

Control problem also for LVS?

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

$$V_{LVS} \;\sim\; \frac{g_s\sqrt{\tau_s}\, e^{-2\tau_s}}{\mathcal{V}} + \frac{g_s\tau_s W_0\, e^{-\tau_s}}{\mathcal{V}^2} + \frac{\xi W_0^2}{\sqrt{g_s}\,\mathcal{V}^3}$$

$$\Rightarrow \quad \boxed{\tau_s \sim \xi^{2/3}/g_s \quad , \quad \mathcal{V} \sim W_0\, e^{\tau_s}}$$



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

Junghans '22

Our analysis shows:

Gao/AH/Schreyer/Venken '22 + talk by Venken

- There is indeed a constraint on $\mathcal{V}$ (related to the total D3 charge) which limits the achievable quality of control.
- We quantify this as the 'LVS parametric tadpole constraint'.
- The starting point is, as before, the competition between ...

$$V_{AdS} \sim \frac{g_s \sqrt{\tau_s} W_0^2}{\mathcal{V}^3} \qquad \text{and} \qquad V_{up} \sim \frac{1}{g_s M^2 \, \mathcal{V}^{4/3}} \exp(-N/g_s M^2)$$

(Recall that M is the flux on the A-cycle of the KS throat and $g_s M^2$ may be viewed as controlling the $\overline{D}3$-brane metastability.)

$$V_{AdS} \sim W_0^2/\mathcal{V}^3 \qquad \text{vs.} \qquad V_{up} \sim \exp(-N/\cdots)/\mathcal{V}^{4/3}$$

- Small V_{up} needs large N, limited by $N < |Q_3|$.
- Large W_0 helps, but is limited by $2\pi g_s W_0^2 \leq |Q_3|$.

Denef/Douglas '04, ... thanks to Plauschinn.

- Smallness of warping corrections controlled by

$$1 \gg \frac{1}{c_N} \equiv \# \frac{N}{g_s \mathcal{V}^{2/3}} \sim \frac{N}{\exp(N/\cdots)}\,.$$

[Precise def. of c_N uses corrections from $\int d^4x\, d^6y\, R_{10}^4\, e^{-2A(y)}$ to V_{LVS}.]

Junghans '22

- Combining this set of constraints, one straightforwardly derives a bound on the required negative tadpole of the model:

$$|Q_3| > N = N_* \left(\frac{1}{3} \ln N_* + \frac{1}{3} \ln \frac{c_N^5 a_s^3}{\kappa_s^2} + 8.2 + \mathcal{O}(\ln(\ln)) \right) \,,$$

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

- For the crucial control parameter $g_s M^2$ of $\overline{D3}$-brane metastability, bounds of $12 \cdots 46$ have been discussed.

  KPV, Bena et al., Blumenhagen et al. Scalisi et al., Lüst/Randall '22

- Agnostically/conservatively, let us look at one example:

$$g_s M^2 = 90; c_N = 5; a_s = 2\pi; \xi = \kappa_s = 1 \quad \Rightarrow \quad N \gtrsim 220 \,.$$

- In view of explicit models with $-Q_3 \simeq 150 \cdots 250$ (or even $-Q_3 \simeq 3300$ for Whitney branes),

  see e.g. Crino/Quevedo/Schachner/Valandro '22

  the parametric tadpole constraint looks relevant but not deadly.

- Recently, a further 'PTC-related' analysis by Junghans appeared claiming much larger $|Q_3|_{min}$.

- A key difference is that, in addition to $g_s M^2 \gg 1$, also the constraint $g_s M \gg 1$ is envoked (for a large S^3 in KS).

  Our constraint implies the latter only asymptotically.

- How large a number for $g_s M$ one has to demand remains unclear since no corresponding decay channel is known...

- Further work needed to fix numbers....

Loop corrections

- .... relevant for the LVS in many cases (though not threatening the existence).

- First discussed many years ago in field-theory context, but already for generic CY.

  Gersdorff/AH '05

  Method: Dimensional/Scaling arguments.

$$\Rightarrow \qquad \delta K \sim \frac{1}{\tau^2}\,, \qquad \delta V \sim \frac{g_s W_0^2}{\mathcal{V}^2} \cdot \frac{1}{\tau^2}\,.$$

- Subsequently: Explicit string loop calculation, but restricted to torus orientifolds:

  Berg/Haack/Koers '05

$$\Rightarrow \qquad \delta K \sim \frac{g_s}{\tau} + \frac{1}{\tau^2}\,, \qquad \delta V \sim \frac{g_s W_0^2}{\mathcal{V}^2} \cdot \left(\frac{g_s^2}{\tau^2} + \frac{1}{\tau^2} \right)\,.$$

see also Berg/Haack/Pajer, Cicoli/Conlon/Quevedo '07

Loop corrections - our recent paper

Gao/AH/Schreyer/Venken

- Goal: Understand discrepancy concerning the g_s/τ term between the BHK/BHP string loop analysis and field-theory expectations (Gersdorff/AH).

- Goal: Derive statement of BHP-conjecture studying directly loops effects on CY (using 10d field theory).

  cf. talk by Schreyer for detailed results

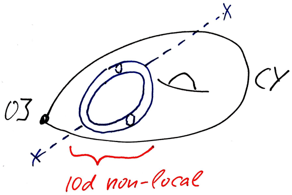
- One key result:
  'String Loops' correspond, in field-theory language, to three types of effects:

  Genuine Loops ; Local α' Corrections ; Warping

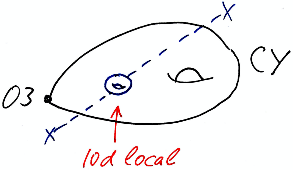
  The BHK/BHP g_s/τ correction is a local α' correction.
  (It is a 'UV-scale' higher-dimension operator effect.)

Illustration of ‘genuine loop’ and ‘local α' effects

- Genuine loop correction
  (needs only $\mathcal{N} < 2$ SUSY).



- Local α' correction
  as part of a string loop effect.



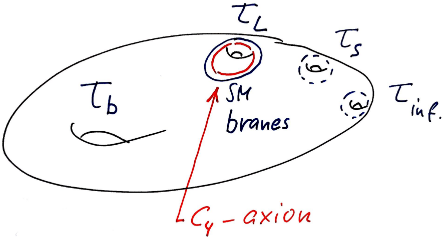
.... in fact, the most relevant case is not for the closed but for the open string, corresponding to R^4 on D7 (log enhanced!)

... let us take the optimistic view that, one way or another, the LVS will survive and to turn to ...

Phenomenology: QCD Axions and Dark Radiation

- Specifically, we wanted to take the promise of a 'natural' stringy QCD axion seriously and see what it implies.

Cicoli/AH/Jaeckel/Wittner



- The basic setting requires a D7-brane Standard Model on a loop-stabilized cycle τ_L.

see in particular Conlon '06, Cicoli/Goodsell/Ringwald '12

QCD Axion and the 'Dark Radiation Hydra' (continued)

- Cosmological bounds on f_a enforce large $\mathcal{V}$ and hence LVS.
- Since SM must be on D7, we have $m_{3/2} \gg \text{TeV}$.
- The fine-tuned Higgs mass operator induces strong coupling $\tau_b\, hh$ and solves 'conventional' DR problem.
  (as originally discovered by Cicoli/Conlon/Quevedo & Higaki/Takahashi)
- But now the inflaton (of blowup-inflation) becomes the longest-lived particle and again creates (too much?) DR.
- But, fortunately, the mixing $\tau_{inf} - \tau_L$ is large enough to produce so many SM gauge bosons that we land spot-on at a non-excluded but discoverable amount of DR!

Thanks to Michele Cicoli!

.... for details see v3 of our paper.

Phenomenology: Hidden $U(1)$s and kinetic mixing

AH/Jaeckel/Kuespert, in preparation

- It's a very old story ....

  Holdom 86', Dienes '97, Abel/Goodsell/Jaeckel/Khoze/Ringwald '08, ...

$$\mathcal{L}_{4d} \supset F_1^2 + F_2^2 + \chi_{12} F_1 F_2 \, .$$

  ... with recently revived activity
  (related to Swampland/WGC and dark matter pheno).

  .... Benakli/Branchina/Laforgue-Marmet, Obied/Parikh,
  Ban et al., Guidetti/Righi/Venken/Westphal '22

- Historically, the challenge was to convince oneself that, if a hidden $U(1)$ exists, then kinetic mixing is expected:

$\chi_{12} \sim g_1 g_2$ from

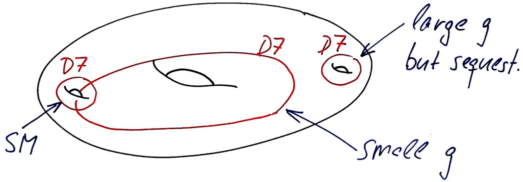
Our new perspective:

Study mechanisms by which mixing can be kept small

for details see talk by Kuespert

- Indeed, WGC and completeness appear to enforce $\chi_{12} \sim g_1 g_2$.
- Making one of the g's small is limited by the WGC.

Benakli et al., Obied/Parikh



- But, obviously, small mixing $(\chi \ll g_1 g_2)$ nevertheless arises from stringy and symmetry-based sequestering....

What are the achievable limits?

And now for something completely different:

The Measure Problem (for landscape-based predictions)

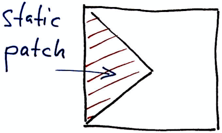
- In spite of the problem remaining fundamental and unsolved, activity has recently been low.
- This may be natural if one is questioning the very existence of dS and eternal inflation.
- But it is wrong since, even if just two short-lived inhabitable vacua exist, the fundamental challenge of predicting (statistically) which one is ours remains.
- In what follows, I will start from eternal inflation in the landscape, but the result will turn out to remain meaningful if no such thing exists.

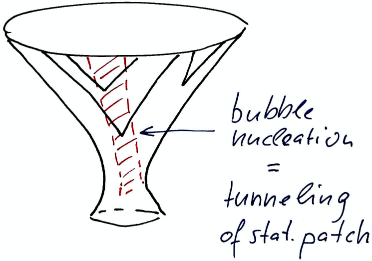
A local Wheeler-DeWitt Measure

Friedrich/AH/Salmhofer/Strauss/Walcher '22

- Input 1: Cosmological central dogma: dS space is a finite QM-system with Hilbert space dimension $\exp(M_P R^2)$.

  Banks, Susskind





- Input 2: Wheeler-DeWitt equation: We must search for a stationary wave function on...

$$\mathcal{H} = \sum_i \mathcal{H}_{dS,\,i} + \sum_\alpha \mathcal{H}_{AdS,\,\alpha}$$

related 'local' approaches:
e.g. Nomura, Garriga/Vilenkin

A local Wheeler-DeWitt Measure (continued)

- Approx. block-diagonal Hamiltonian, with off-diagonal terms $H_{ij}, H_{i\alpha} \sim$ semiclass. tunneling rates.
- Find consistency with ergodictiy / Shirelman theorem (largest Hilbert-subspaces are most probable)
- But: since probabilty flow goes off to infinity in AdS subspaces, stationarity demands presence of sources.

  $\Rightarrow$ Must allow for universe creation a la Linde/Vilenkin or Hartle/Hawking.
- Eventually: Arrive at stationary solution for rate equation with sources and 'sinks'. Either dS-dS tunneling or LV/HH-type sources may dominate.

  cf. similar rate eqs. in Linde/Mezhlumian, Garriga/Vilenkin

More details: Talk by Friedrich.

Summary / Conclusions

- Unambiguously establishing/excluding stringy dS remains a key challenge. Danielsson/Van Riet, Obied/.../Vafa '18
- Given the issues of KKLT (Singular-Bulk Problem), the focus is maybe shifting to the LVS.
- As it turns out, the LVS is also not free of problems.
  But a sufficiently large tadpole provides parametric control, in principle..... (Parametric Tadpole Constraint).
- In parallel to these efforts, the optimist may continue thinking about pheno implications (axions, dark radiation, $U(1)$-mixing) and the measure problem (Local WDW Measure).