Swampland, Stringy de Sitter, and the Measure Problem

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with focus on recent work with Friedrich / Walcher / Westphal

Outline

- The flux landscape, the Swampland, and Stringy de Sitter
- Problems of KKLT/LVS. Can stringy quintessence help?
- The measure problem: a re-evaluation in view of 'Rocky' and 'Swampy' landscapes
- The (potentially) key role of the Cobordism Conjecture and End-of-the-Worlds branes
- Towards predictions....

String Compactifications

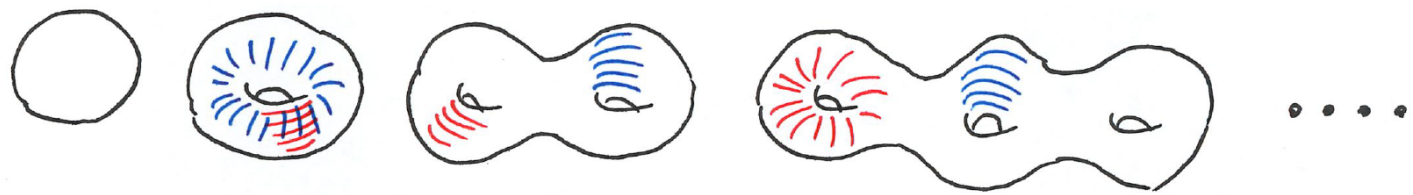
- String theory provides an (essentially unique) and UV-complete field theory in 10d:

$$S_{IIB} = \int_{10} \mathcal{R} - |F_{\mu\nu\rho}|^2 + \cdots$$

[Let's say type IIB, to be concrete.]

- Compactifying on Calabi-Yau-Orientifolds, one preserves $\mathcal{N} = 1$ SUSY and (classically) zero 4d cosmological constant.

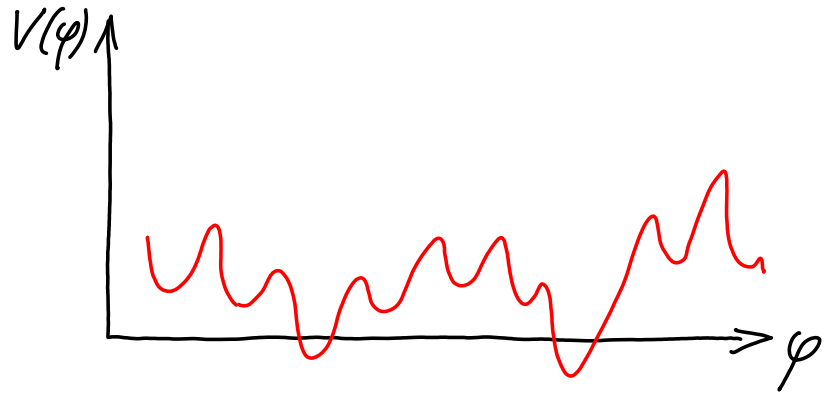
- The extra ingredient of fluxes induces an exponentially large landscape of discrete solutions.



Bousso/Polchinski, Giddings/Kachru/Polchinski, Denef/Douglas '04

String compactifications: flux landscape

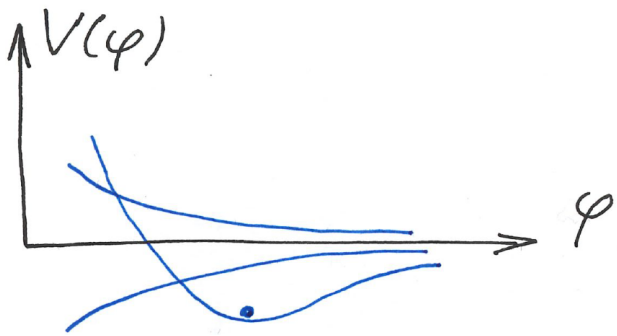
- One usually visualizes the emerging situation as follows: (just with $\varphi \rightarrow \{\varphi_1, \cdots, \varphi_N\}$)

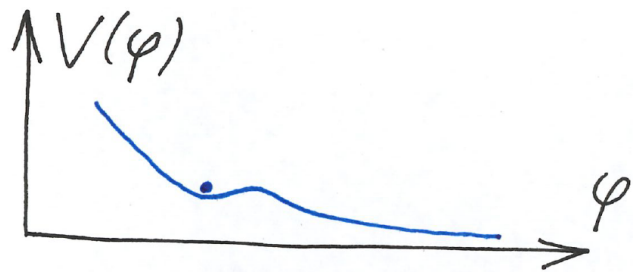


- But this picture jumps very far ahead.
- So far we only stabilized the shape ('complex structure') moduli.
- Classically, the size ('Kahler') moduli remain flat and the CC of all vacua is zero.

String compactifications: beyond leading order

- The size moduli (let's say just the volume) get a (much smaller) potential from quantum corrections.
- All known effects are of exponential runaway type.
- Two such effects can give SUSY-AdS.
- It takes a conspiracy between at least three 'runaway potentials' to get meta-stable de-Sitter vacua.

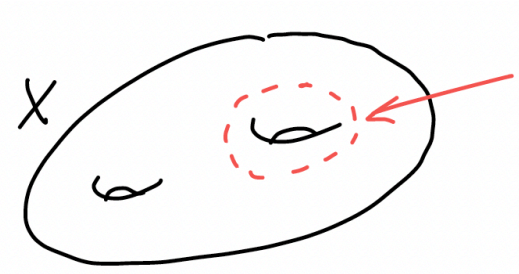




The historical prime example: KKLT

Kachru/Kallosh/Linde/Trivedi

- Assume there is just one of flat direction: the volume.
- Its potential comes from a non-perturbative effect:



euclidean D3 brane wrapped on 4-cycle $\Rightarrow$ Instanton Correction

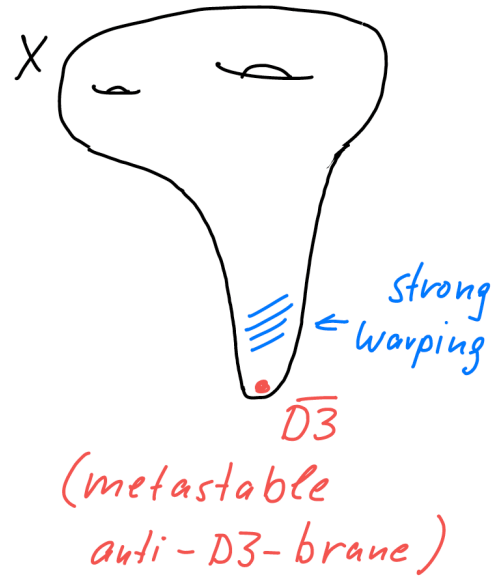
$\Rightarrow \quad W = W_0 + e^{-T}$, (where W_0 is the previous flux effect)

$\Rightarrow \quad V \sim e^{-2T} - |W_0| e^{-T}$

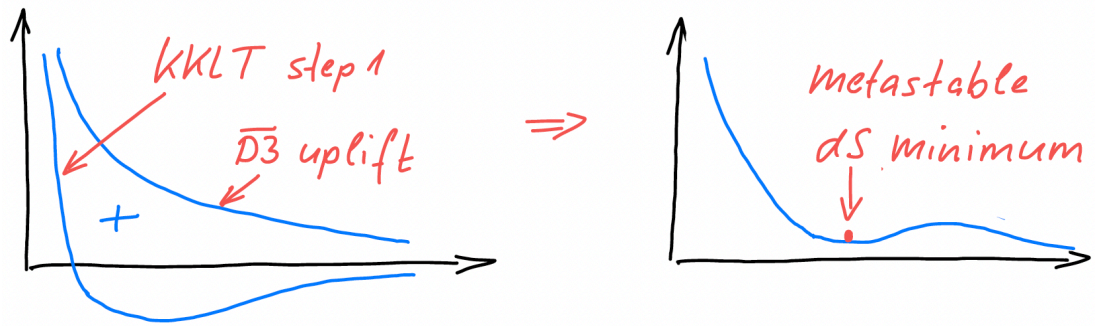
$\Rightarrow$ Kahler modulus stabilized (controlled for $W_0 \ll 1$).

- This AdS model is 'Step 1' of KKLT.

KKLT (continued)



- 'Step 2' involves 'uplifting' to dS by adding an anti-D3-brane.
- This requires a 'strongly warped region' or 'Klebanov-Strassler throat' (realized by introducing a large amount of flux in an appropriate (conifold) region of the CY).
- Eventually, one may hope for the desired potential:



But:

Full explicitness has remained elusive for technical reasons.

The swampland (counter?) revolution and the dS conjecture

- This, and some important variants (like 'LVS') has remained the main evidence for 'stringy dS'.
- No analogues in type-I, IIA, heterotic, 11d SUGRA were found.
- Based on this, it has been proposed that stringy dS is impossible as a matter of principle ('is in the Swampland').

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

(see also Bena, Grana, Sethi, Dvali, ...)

- Subsequently, constructions like KKLT and LVS have been subjected to intense scrutiny (with varying success).

Bena/Grana/Van Riet, Van Riet, Moritz/Retolaza/Westphal, Gautason/Van Hemelryck/Van Riet, Hamada/AH/Shiu/Soler, Bena/Dudas/Grana/Lüst, Lüst/Randall, ...

Eventually, serious problems were identified:

- To get a small uplift, throat must be very large (including 'thick')

  Carta/Moritz/Westphal '19

- This leads to strong warping in bulk and 'Singular Bulk Problem'

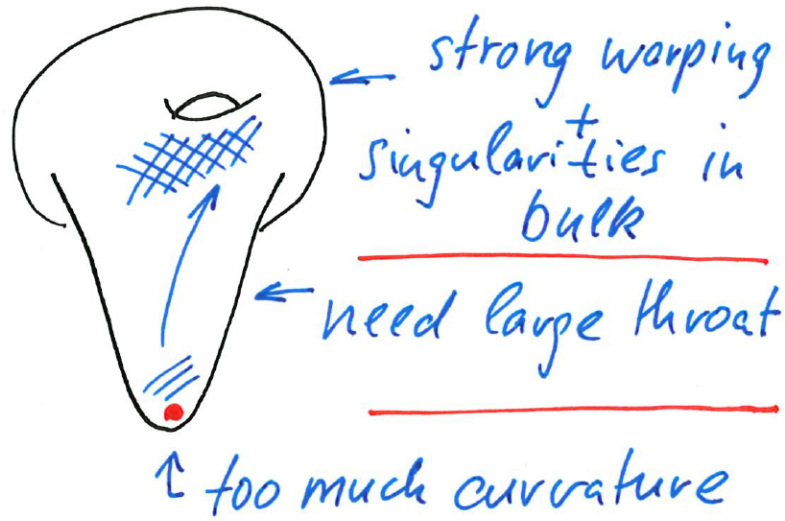
  Gao/AH/Junghans '20

- Simplest KKLT-models become uncontrolled; Very large tadpole needed for LVS

  Junghans; Gao/AH/Schreyer/Venken '22

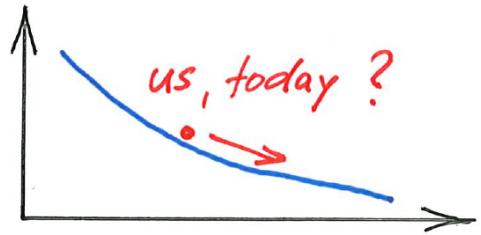
- Including effects of curvature at the bottom of the throat makes this much worse

  Junghans '22
  AH/Schreyer/Venken '22
  Venken/Schreyer, Venken ...'24



Crucial aside:

(Stringy) Quintessence:



- In a nutshell: It does not help!
  (in spite of many attempts...)

  Selection of older and recent work: Cicoli/Pedro/Tasinato/Burgess; Cicoli/DeAlwis/Maharana/Muia/Quevedo; Acharya/Maharana/Muia; Emelin/Tatar; Hardy/Parameswaran; Cicoli/Cunillera/Padilla/Pedro; ....

- One (in my opinion key) argument goes as follows:

  (cf. 'F-Term Problem' in AH/Skrzypek/Wittner '19)

  Our world has SUSY broken at TeV, i.e.

$$|F|^2 \quad \sim \quad e^K |DW|^2 \quad \sim \quad \text{TeV}^4$$

  (This part of the superpotential can not be rolling to zero – we would see that!)

What's the status of the 'dS landscape'?:

- Maybe it's there as expected, just in a more complex and less controlled form.... McAllister/Moritz/Nally/Schachner ....

  ...maybe we need an 'F-term-uplift' to replace the anti-D3....

  ...AH/Leonhardt; Krippendorf/Schachner; Lanza/Westphal....

- Maybe string pheno must be completely rethought.

- Very likely: Stringy dS (or even just slow-roll) vacua are more fine-tuned and rare than expected.

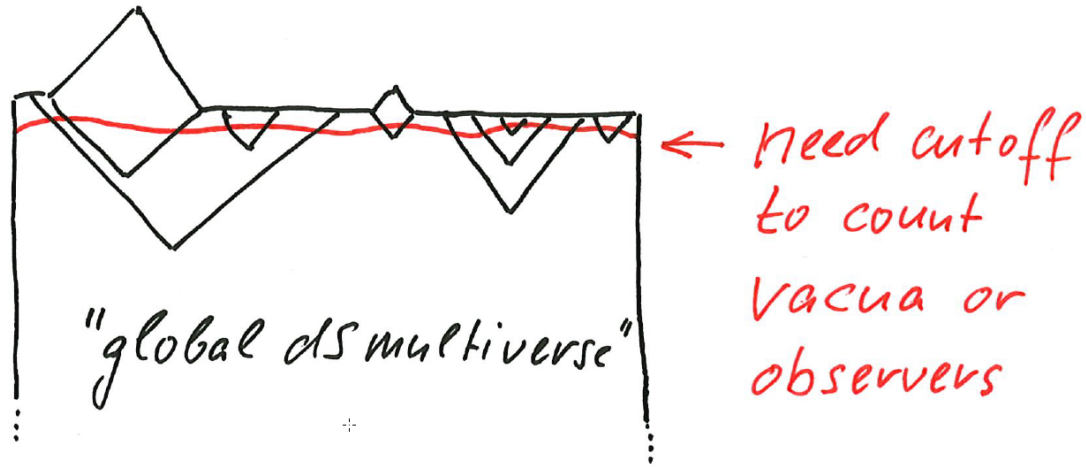
The measure problem

- In any case, the landscape is not likely to become a single vacuum.

  $\Rightarrow$ 'Measure problem' (or 'initial condition problem') is still there. Let's revisit it!

Measure problem and potentially decisive role of creation processes

- Standard view: Different vacua $\rightarrow$ different patches in 'global dS multiverse'. Measure problem $\equiv$ problem of cutoff choice.



- Based on the 'Cosmological Central Dogma', Banks '01, Susskind '21

  we want to argue for a more fundamental, quantum-mechanical measure.

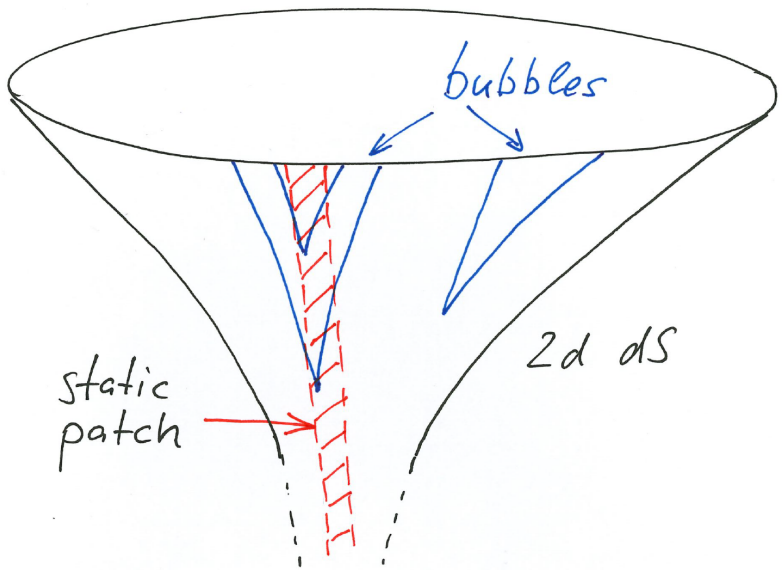
  Friedrich/AH/Salmhofer/Strauss/Walcher '22, Friedrich/AH/Westphal '24

Towards a 'Quantum-Measure'

- Cosmological Central Dogma:

  dS space is a finite system with $\dim(\mathcal{H}) = e^S$.

- Eternal Inflation $\equiv$ Series of transitions between different subspaces (with $\dim(\mathcal{H}_i) = e^{S_i}$).



The 'Local Wheeler-DeWitt Measure'

Friedrich/AH/Salmhofer/Strauss/Walcher '22,
Friedrich/AH/Westphal '24

- To formalize this 'CCD' perspective, the right approach should be the Wheeler-DeWitt equation.

- Upon gauging time-diffeomorphisms, one has

$$H\psi = i\dot{\psi} \qquad \rightarrow \qquad H\psi = 0$$

- In our context, the WDW equation needs a source:

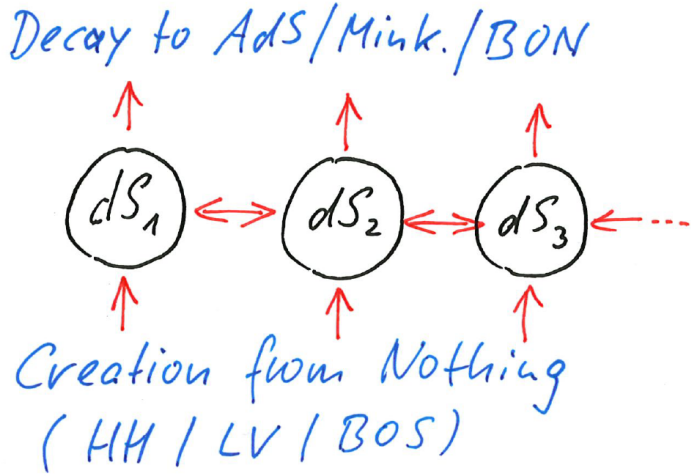
$$H\psi = \chi$$

- Such a source term for the creation from nothing is unavoidable since there is also decay to AdS.

The 'Local Wheeler-DeWitt Measure'

- Formally, we have to solve $H\psi = \chi$ for ψ
  and calculate the probability for vacuum dS_i as $p_i = \left\| \psi|_i \right\|^2$.

- In practice, this reduces to rate equations for a
  'flow through the landscape':



(Here any of the 'dS_i' could
also be just a slow-roll plateau)

The outcome is similar to certain 'local measures': Bousso/Freivogel/Yang '06, Garriga/Vilenkin.. '05...'11, Nomura '11, Bousso/Susskind '11, Hartle/Hertog '16

'Local Wheeler-DeWitt Measure' (continued)

- Denote the sources by J_i and the decay rates by $\Gamma_{i\to j}$.
- Then the relevant rate equations read

$$J_i = \sum_{j\in dS} \left(p_i \Gamma_{i\to j} - p_j \Gamma_{j\to i} \right) + p_i \sum_{y\in Terminal} \Gamma_{i\to y} \ .$$

- The solution can be given as a series:

$$p_i = \frac{1}{\Gamma_i} \left\{ J_i + \sum_j J_j \frac{\Gamma_{j\to i}}{\Gamma_j} + \sum_{j,k} J_j \frac{\Gamma_{j\to k}}{\Gamma_j} \frac{\Gamma_{k\to i}}{\Gamma_k} + \cdots \right\}$$

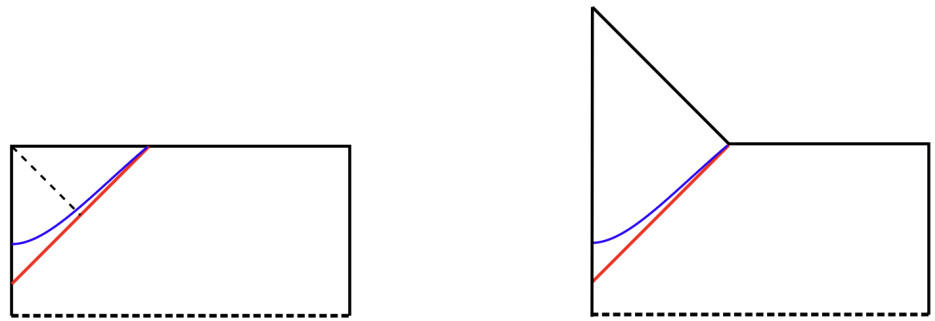
(Here Γ_i is the total decay rate of vaccum i.)

A conceptual problem: Reheating to Minkowski

- As long as there are only dS and AdS vacua (and a non-zero rate for creation from nothing), finiteness is obvious.
- There is a sensitivity to the number of observers on the horizon-sized patch of the reheating surface.

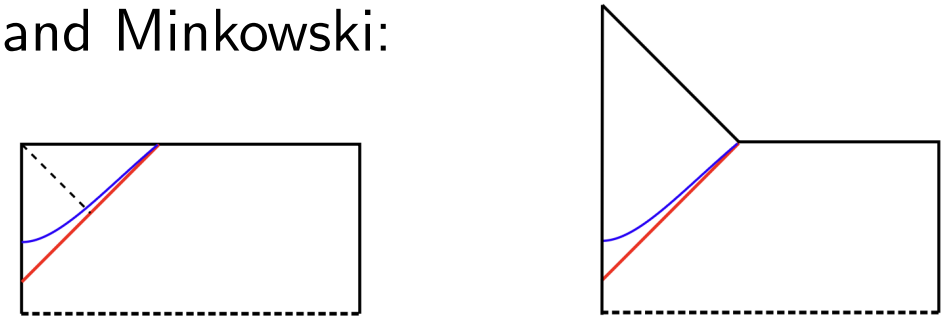
  But we ignore this (non-exponential) effect.
- However, this changes once we include Minkowski-bubbles:

  Now we get an infinite reheating surface and
  no 'natural' cutoff at the horizon:



Our proposal:

- Appeal to an **'Effective CCD'**, based on the similarity of the reheating surfaces in dS and Minkowski:



- **Claim:** Even in Minkowski only a finite portion of the surface ($\sim 1/H_{\rm reh}^3$) is independent – the rest is gauge redundant.

$\Rightarrow$ Finiteness is regained

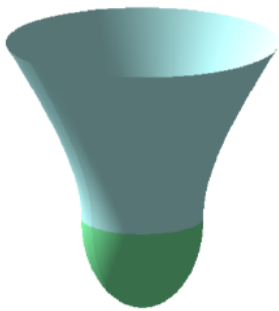
Alternative possibility:

- Take infinite Minkowski-space reheating surfaces seriously.

$\Rightarrow$ Key prediction: The dark energy in our universe will decay – our future is Minkowski space.

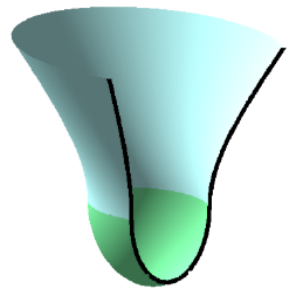
Towards explicit predictions

- To solve the rate equations, we obviously need transition rates.
- But, in addition, our local measure crucially depends on creation rates. These depend on End-of-the-World branes:



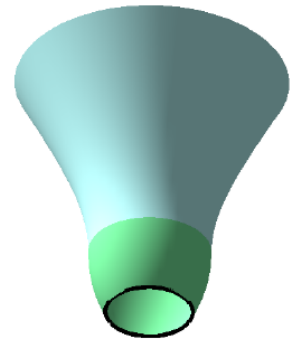
'No-Boundary'

Hartle/Hawking
Linde/Vilenkin



'Bubble-of-Something'

Hawking/Turok
Bousso/Chamblin
Garriga, Blanco-Pillado, ...



['Boundary proposal']

[Friedrich/AH]

[Cf. recent discussion of 'Bubble of Something' for String Landscape in Friedrich/AH/Walcher '23. Also, much recent work on inverse 'Bubble of Nothing' process: Garcia-Etxebarria/Montero/Sousa/Valenzuela, Draper et al., Angius/Calderon-Infante/Delgado/Huertas/Uranga, ...]

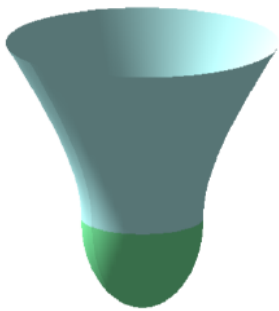
ETW Branes

- Traditionally, Hartle-Hawking/Linde-Vilenkin are the leading proposals; alternatives with ETW branes are at best exotic.

- I would argue that the 'Cobordism Conjecture' is one of the most convincing Swampland conjectures; McNamara/Vafa '19
  It implies that ETW branes are ubiquitous.

  [The conjecture roughly says that the space of geometries is connected. This includes the connection to 'nothing' by a boundary.]

- Rates depend on brane-tensions. Getting those is a challenge...



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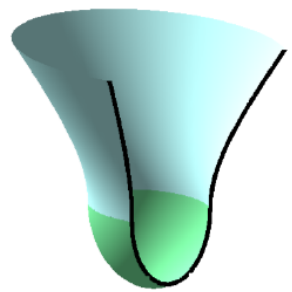
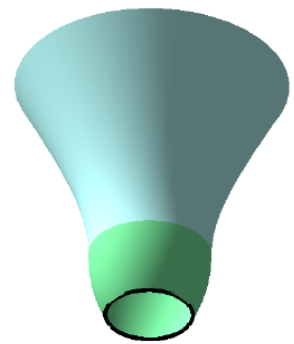
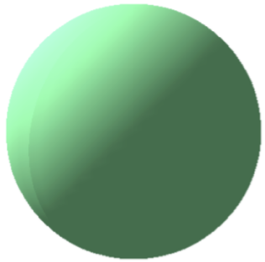
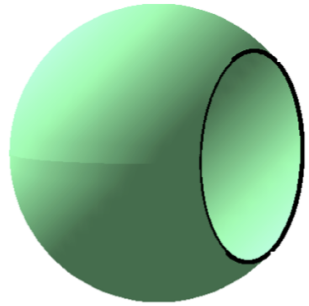
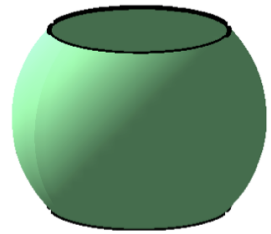
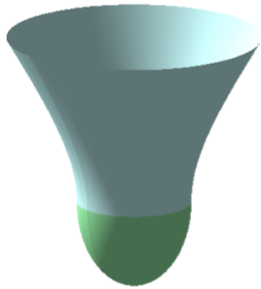
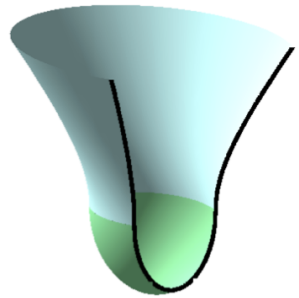
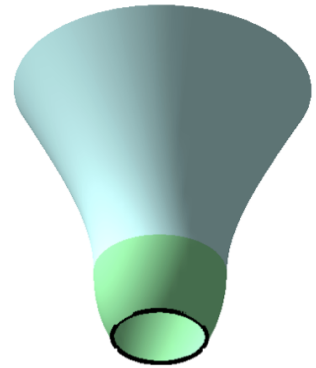


'Bubble-of-Something'



'Boundary proposal'

- Explicitly, creation rates are: $J \sim exp(\pm \mathcal{S})$ with:

	No-Boundary (nb)	Bubble of Something (bos)	Boundary (b)
			
			
$\mathcal{S} =$	$-8\pi^2 M_P^2 \ell_{dS}^2$	$-4\pi^2 M_P^2 \ell_{dS}^2 \left(1 - \frac{T\ell_{dS}}{\sqrt{T^2\ell_{dS}^2+4M_P^4}}\right)$	$-8\pi^2 M_P^2 \ell_{dS}^2 \sqrt{\frac{T^2\ell_{dS}^2}{T^2\ell_{dS}^2+4M_P^4}}$

$\Rightarrow$ For LV sign choice, the 'bos'/'b' creation processes always dominate over 'nb' when the required ETW branes exist.

Summary / Conclusions

- The problem of realizing (metastable) de Sitter vacua in string theory remains unsolved.
- One is forced to dive into technical details. This is unsatisfcatory. But it's one possibility for making progress ....
- Either way (with or without long-lived dS), predictions need a measure.
- I argued that, in a proper quantum approach, this is sensitive to 'Creation from Nothing'.
- A key 'new' ingredient in this are ETW branes, allowing for 'Bubbles of something' or 'boundary processes'.
- The tensions of those ETW branes are a key research target!