De Sitter, Landscape and the Measure Problem

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including recent work with Gao / Junghans / Schreyer / Venken / Friedrich / Westphal

Outline

- The flux landscape – a brief reminder.
- The challenge of de Sitter in string theory
- Problems of KKLT / LVS and roads beyond.
- The measure problem: a re-evaluation in view of 'Rocky' and 'Swampy' landscapes
- End-of-the-Worlds branes at the beginning of time.

String Compactifications

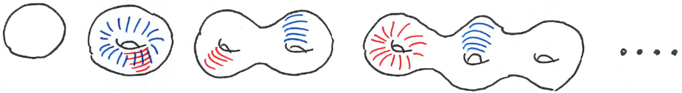
- String theory provides an (essentially unique) and UV-complete field theory in 10d:

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

[I focus on type IIB. Apologies to those pursuing other routes, such as heterotic – cf. A. Lukas et al. ....]

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

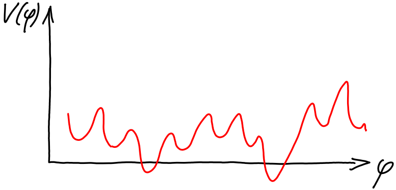
- The extra ingredient of fluxes induces an exponentially large landscape of discrete solutions.



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

String compactifications: flux landscape

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



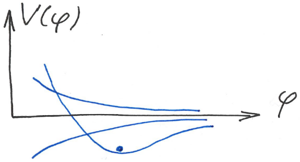
- But this picture jumps very far ahead.

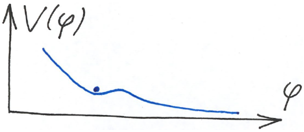
- So far we only stabilized the shape ('complex structure') moduli.

- 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.
- The simplest solutions are runaway.
  The next-simplest are SUSY-AdS.
- It takes a conspiracy between at least three 'runaway potentials' to get meta-stable de-Sitter vacua.





On the genericity of 'runaway potentials'

- Let us briefly pause and explain why 'runaway potentials' are hard to avoid.

- Consider a generic compactification with volume $\mathcal{V}$ and some energy source induced by (quantum) corrections:

$$\mathcal{L} \sim \mathcal{V}\left[\mathcal{R}_4 - \frac{(\partial\mathcal{V})^2}{\mathcal{V}^2} - E\right] .$$

- After Weyl-rescaling to the Einstein frame and introducing the canonical field $\varphi = \ln(\mathcal{V})$, one finds

$$\mathcal{L} \sim \left[\mathcal{R}_4 - (\partial\varphi)^2 - E\, e^{-\varphi}\right] .$$

- The exponent is usually $\mathcal{O}(1)$, so fast runaway is the rule.

- Nevertheless, three such effects can conspire to give dS!

The historical prime example: KKLT

Kachru/Kallosh/Linde/Trivedi

- Recall that Kahler moduli are still flat directions.
  Assume there is just one of those: the volume.

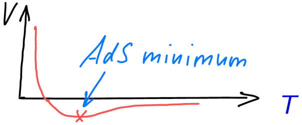
- To discover its potential, one needs to study the model with more precision:

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)

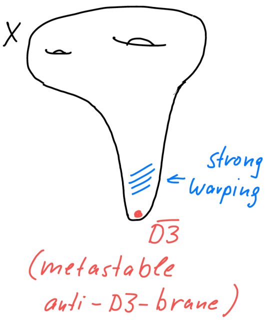
$\Rightarrow \quad V \sim e^{-2T} - |W_0| e^{-T}$

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



KKLT (continued)

- This construction of a fully stabilized AdS minimum is known as 'Step 1' of the KKLT construction.
- 'Step 2' involves 'uplifting' to dS by adding an anti-D3-brane.
- This requires a 'strongly warped region' or 'Klebanov-Strassler throat' to avoid destabilization.
- The latter is achieved by introducing a large amount of flux in an appropriate (conifold) region of the CY.

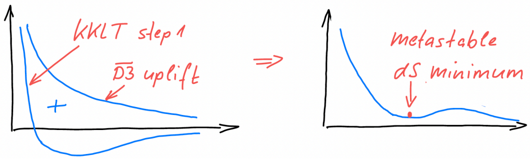


Warping:

$$ds^2 = dx^2 + dy_{CY}^2 \quad \Rightarrow \quad ds^2 = h^{-1/2}(y)dx^2 + h^{1/2}(y)dy_{CY}^2$$

KKLT (continued)

- If everything works, one obtains the desired deformation of the potential:



But full explicitness has remained elusive since:

- Finding fluxes which lead to $W_0 \ll 1$ is extremely hard.

  Recent progress: e.g. Krippendorf/Schachner/... & McAllister et al.

- The anti-D3 in the strongly warped region is only controlled in 10d supergravity (no stringy or SUSY-QFT analysis).

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, IIB, 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

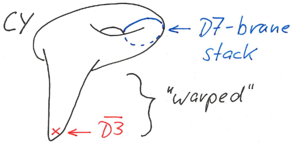
  (see also Bena, Grana, Sethi, Dvali, ...)
- Subsequently, constructions like KKLT and LVS have been subjected to intense scrutiny (with varying success).

  Bena/Grana/Van Riet, Van Riet, Moritz/Retolaza/Westphal, Gautason/Van Hemelryck/Van Riet, Hamada/AH/Shiu/Soler, Bena/Dudas/Grana/Lüst, Lüst/Randall, ...
- I will focus on what I feel is most critical.....

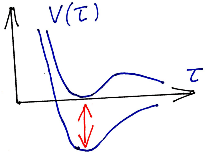
Singular Bulk Problem of KKLT

Carta/Moritz/Westphal '19; Gao/AH/Junghans '20

- Reminder:



$\Rightarrow$

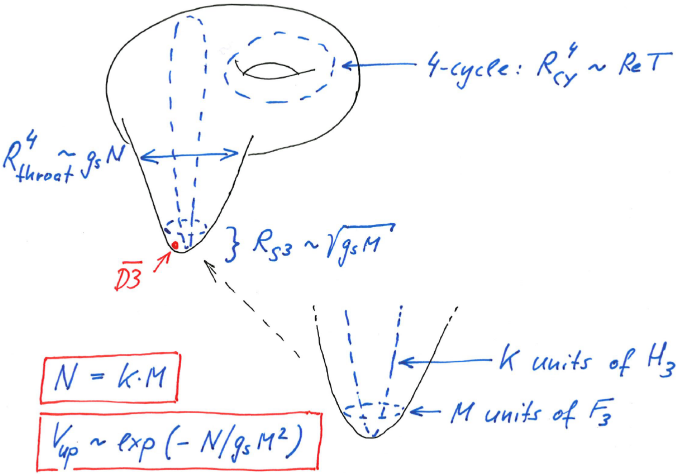


- The dS vacuum relies on the competition of two small quantities: (with the definitions $(Volume)^{2/3} \sim \text{Re}\, T \sim \tau$)

$$V_{AdS} \sim \exp(-T) \qquad \text{and} \qquad V_{up} \sim \exp(-\text{'Throat-Flux'})$$

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

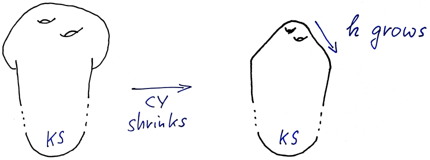
Some geometric details:



$\Rightarrow$ 'Throat gluing problem'

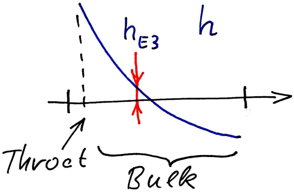
Singular Bulk Problem of KKLT (continued)

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



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

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



[McAllister et al. discuss overcoming this issue with geometries where a large volume arises from ~ 100 2/4-cycles, some of them string-sized...]

Related problems in the 'Large Volume Scenario' (LVS):

Balasubramanian/Berglund/Conlon/Quevedo

- The LVS is a close cousin of KKLT
  (with two relevant 4-cycles, on of them exponenetially large)

- However, due to higher curvature corrections of the type
  $R + R^2 + R^3 + \cdots$ control is nevertheless at risk.

  Junghans '22

- Control can be maintained if a sufficiently large 'D3-tadpole' is available:

  Gao/AH/Schreyer/Venken '22

  ['D3-tadpole' $\equiv$ 'geometry-based upper bound on flux']

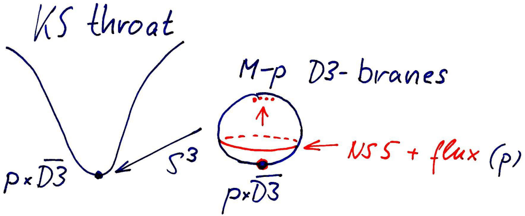
- <u>But:</u> For known CY-orientifolds the D3-tadpole
  is only marginally sufficcient.

Things get even worse:

NS5-brane curvature corrections

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

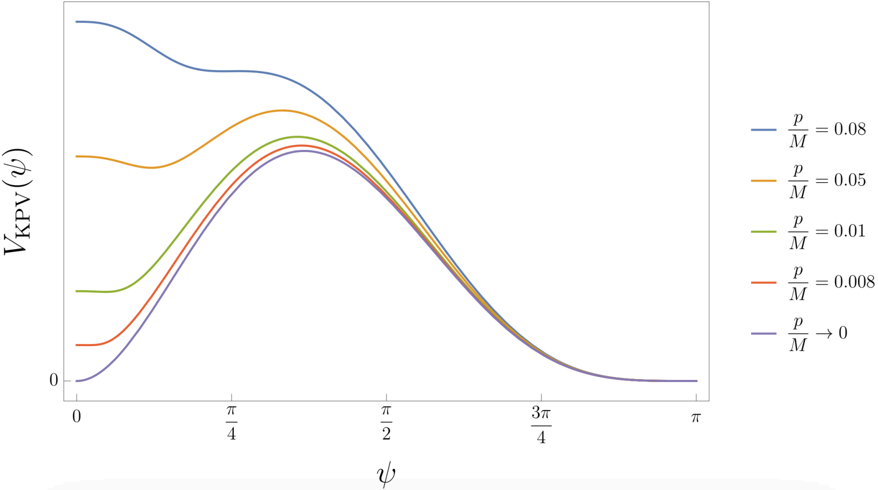
- The $\overline{\text{D3}}$ has a well-known 'KPV' NS5-brane decay channel:



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

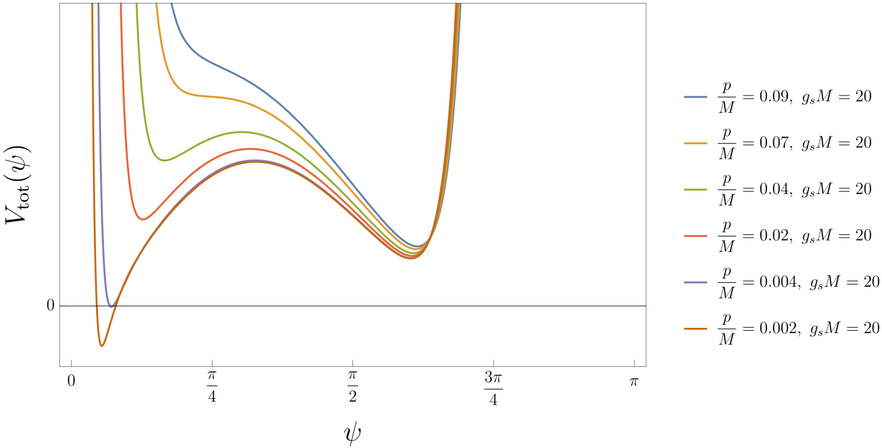
- At small $g_s M$, the NS5-brane curvature corrections endanger the stability of the KPV-potential

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



Curvature and higher-order-flux-corrected KPV potential

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



Key implication: Need $g_s M \gg 1$ to maintain KPV result
$\Rightarrow$ KKLT/LVS are even more fragile.

Intermediate summary

- KKLT/LVS appear to be on much more shaky footing than we thought. More work needed!

- Personally, I would bet less on 'saving' KKLT/LVS and more on the F-term uplift, i.e. on 'accidental' non-SUSY minima of

$$V \sim e^K(|DW_0|^2 - 3|W_0|^2 \ .$$

- If all fails, we need to rethink strings and string pheno from scratch. [I personally do not believe quintessence is a way out.]

- But even in case of sucess (i.e. existence of stringy dS), these vacua may be much more rare and fragile than thought.

..... and now for something completely different ....

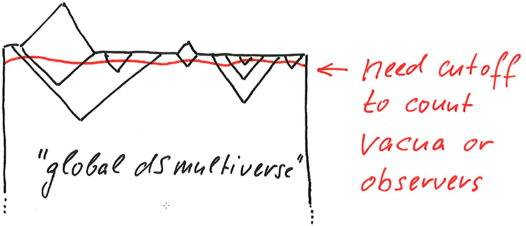
(but not completely unrelated)

The measure problem

- Even if the landcape is maybe not as large and ‘dS-friendly’ as we thought, it’s not likely to boil down to a single vacuum.
- So the infamous ‘measure problem’ is still there and it may be worthwhile revisiting — for its own sake and in view the swampland/landscape discussion.

Measure problem and potentially decisive role of creation processes

- Standard view: Different vacua → different patches in 'global dS multiverse'. Measure problem ≡ 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.

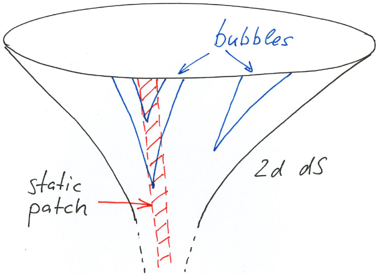
Friedrich/AH/Salmhofer/Strauss/Walcher '22, Friedrich/AH/Westphal '24

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

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

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

$$H\psi = \chi$$

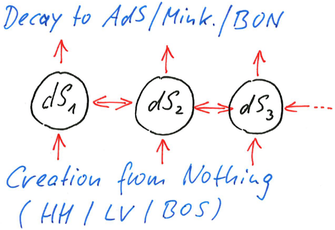
- Such a source term for the creation from nothing is unavoidable since there is also decay to AdS.

cfn.png

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':



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:

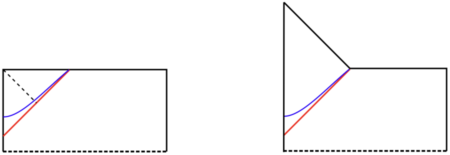
$$p_i = \frac{1}{\Gamma_i} \left\{ J_i + \sum_j J_j \frac{\Gamma_{j\to i}}{\Gamma_j} + \sum_{j,k} J_j \frac{\Gamma_{j\to k}}{\Gamma_j} \frac{\Gamma_{k\to i}}{\Gamma_k} + \cdots \right\}$$

(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.

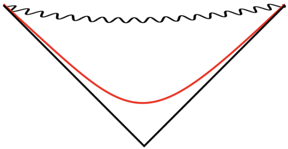
  But we ignore this (non-exponential!) effect.
- However, this changes once we include Minkowski-bubbles:



Now we have no reason to cut off the reheating surface at horizon size. Technically, the projection $\left\|\psi|_i\right\|^2$ can be infinite.

First Aside:

- One might think that this problem problem also arises for reheating in an AdS bubble. After all, $\dim(\mathcal{H}_{AdS}) = \infty$ and the reheating surface is infinitely large:

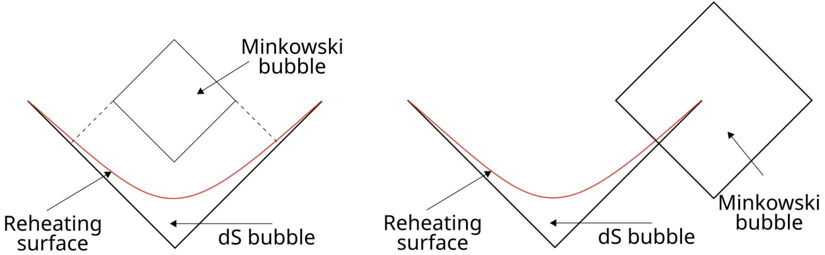


- However, we believe this can be dismissed because the future singularity ensures that there is no infinity in any causally connected region.

Second Aside:

- Maybe the problem is absent because there can be no observers on a Minkowski-space reheating surface (e.g. due to $\mathcal{N} = 2$ SUSY). cf. Douglas '12

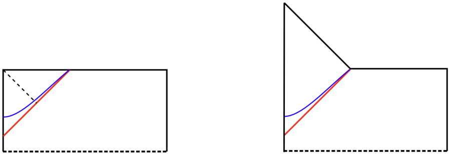
- However, even though Minkowski bubbles as such are in this case harmless, bubble collisions are not!



- What is worse: The observer-infinity in Minkowski depends on fine details of bubble-dynamics. Kleban '11, Freivogel '11

Our proposal:

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



- In essence, we claim that even in Minkowski only a finite portion of the surface $(\sim 1/H_{\rm reh}^3)$ is independent.

- Finiteness is then regained even in in the presence of bubbles with Minkowski-space reheating.

Alternative possibility:

- We could try to take the infinity of Minkowski-space reheating surfaces seriously (no redundancy).
- This would imply a key prediction: The dark energy in our universe will decay – our future is Minkowski space.

A Footnote:

If no Minkowski-space reheating surfaces with observers exist in the landscape/multiverse, then collision rates with Minkowski bubbles determine the most likely vacuum.

... unsatisfactory....?

For now, we will use the **'Effective CCD'** logic....

Towards explicit predictions

- We need creation/decay rates.
- In contrast to volume-weighted measures, our local measure crucially depends on creation rates. So let's start from those:

nobo.png	bos.png	bo.png
'No-Boundary'	'Bubble-of-Something'	['Boundary proposal']
Hartle/Hawking Linde/Vilenkin	Hawking/Turok Bousso/Chamblin Garriga, Blanco-Pillado, ...	[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, ...]

Creation Rates

nobo.png

bos.png

bo.png

'No-Boundary' 'Bubble-of-Something' 'Boundary proposal'

- A key question for all three processes is the sign in the exponent of the rate: $J \sim exp(\pm\mathcal{S})$ ('LV vs. HH')
- Illustration of our (subjective, inconclusive) view:

hhlv.png

hhlv.png

- The (by definition real) HH version describes a 'ground state of the universe'. Maybe not suitable for 'creation rates'?

- Also, in strong tension with observation.

as recently quantified in Maldacena '24

- Thus we have: $J \sim exp(\pm \mathcal{S})$ with:

all.png

Another key concern:

- Small torus dS universes can expand from zero size without any potential barrier.

  $\Rightarrow$ no exponential suppression.

  Zeldovich/Starobinsky '84, Coule/Martin '99, Linde '04

- All dS vacua equally likely to be created (?)

- This 'creation with non-trivial topology' deserves much more attention!

Next step toward predictions:

$$\text{Transition rates} \qquad (\Gamma \sim \exp(-B))$$

Here only brief summary (see paper for more). We are building on KKLT/LVS-type flux vacua, but the conclusions look generic....

(1) Decay of the uplift / Decay by SUSY restoration:

$$B \sim T^4/(\Delta V)^2 \qquad \text{(field theory regime, very fast)}$$

(2) Decay to decompactification:

$$B \sim S_f - \mathcal{O}(1)S_f \qquad \text{(much slower)}$$

(3) Flux transitions:

$$B \sim S_f - M_P^6/T^2 \qquad \text{(almost maximally suppressed)}$$

Key conclusion: $$\frac{\sum_{k\in \mathrm{dS}} \Gamma_{j\to k}}{\Gamma_j} \ll 1$$

(Transiting to any other dS is much less likely then terminal decay.)

$\Rightarrow$ Our solution-series converges fast.

$\Rightarrow$ We may restrict attention to direct creation from nothing or creation from nothing plus one tunnelling event.
(i.e. only one or two step processes are relevant.)

Towards explicit predictions:

- Focus on observers on post-inflationary reheating surfaces (like us).
- Include inflationary plateaus as (short-lived) dS vacua 'inf(i)', decaying to vacuum i.

$\Rightarrow$ Key formula: $$p_{\mathrm{obs}(i)} \simeq J_{\mathrm{inf}(i)} + \sum_{o \neq \mathrm{inf}(i)} J_o \frac{\Gamma_{o\to\mathrm{inf}(i)}}{\Gamma_o}$$

- Question 1: Does direct production (first term) or one-step tunnelling (second term) dominate?
- Question 2: What does this imply for the probability of 'observing' (in our past) a high- or low-scale inflationary plateau? (for earlier analyses of this, cf. Pedro/Westphal '13)
- Our paper gives a detailed discussion of the answer, depending on various assumptions (see above....).
- Here, only one 'example answer':

  Let's accept the LV sign, assume slow-roll vacua with high-tension ETW-branes exist $\Rightarrow$ Bubbles of something win!

  (Energy scale of inflation determined by available ETW branes!)

Summary / Conclusions

- The problem of realizing (metastable) de Sitter vacua in string theory remains unsolved.
- One appears to need a lot of technical detail. This is unsatisfcatory. But it's one possibility for making progress ....
- Either way (with or without a large dS landscape), predictions need a measure.
- I argued that, in a proper quantum approach, this is sensitive to 'Creation from Nothing'.
- A key ingredient in these creation events are ETW branes, allowing for 'BOS's or 'boundary processes'.