ETW Branes and the Beginning of the Universe

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based on work with **Bjoern Friedrich, Alexander Westphal**

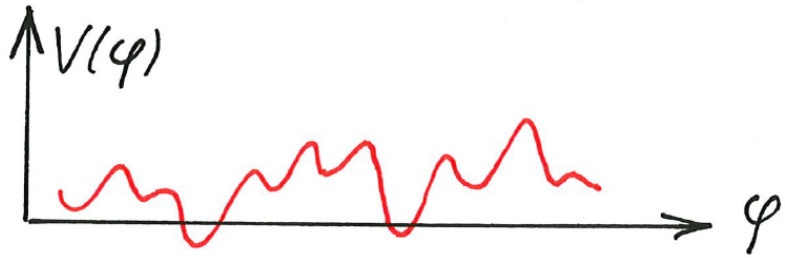
(cf. also earlier work with **Friedrich/Walcher/Salmhofer/Strauss**)

Outline

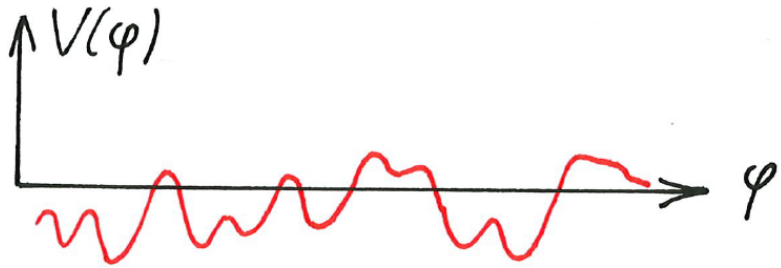
- The Measure Problem (or better: Initial Condition Problem) remains important!
- Progress and problems in defining an explicit, usable approach: ('Local Wheeler-DeWitt Measure')
- Unambiguous implication: Initial conditions are decisive!
- Two options: Hartle-Hawking or Linde-Vilenkin sign choice.
- While HH is phenomenologically problematic, LV implies that ETW branes are crucial for inflationary predictions.

Introduction/Motivation

- Old (even then misleading) view of the landscape:



- More up-to-date view of the landscape:
  (This is an optimistic version because it still includes rare dS vacus and/or inflationary plateaus)



Introduction (continued)

- This change of perspective arose from some bold conjectures...

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

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

  ...followed (& preceded) by detailed scrutiny of KKLT/LVS etc.

  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 would argue that serious, unresolved issues exist.

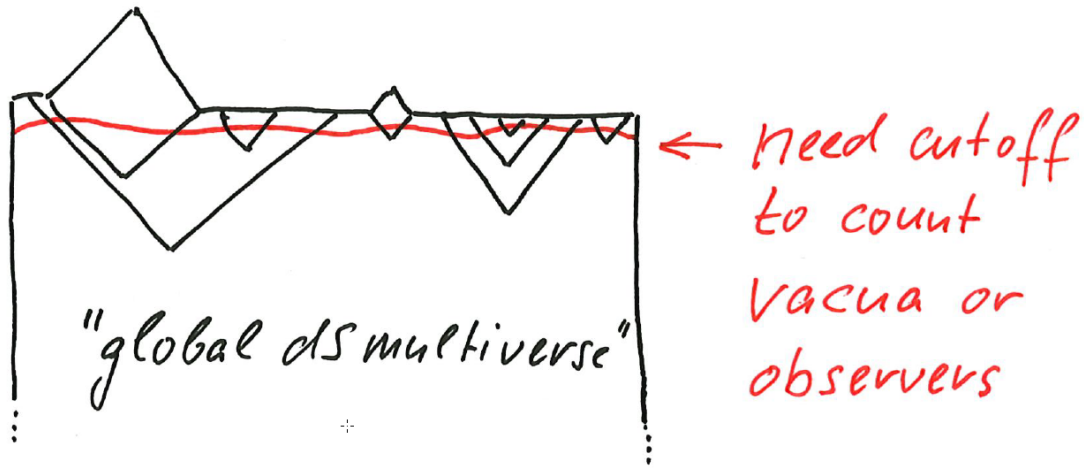
  Cf. Carta/Moritz/Westphal, Gao/AH/Junghans, Junghans, Gao/AH/Schreyer/Venken, AH/Schreyer/Venken, ...

  (See however Carta/Moritz, McAllister et al., Antoniadis, Cicoli, Quevedo and many other....)

- **But:** A derivation for the 'dS Conjecture' has also remained elusive. For our recent 'Horizon Criterion' attempts – see parallel talk by Björn Friedrich.

- Be this as it may, there is certainly enough reason to doubt the 'old' eternal-inflation-view on string landscape predictions.

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



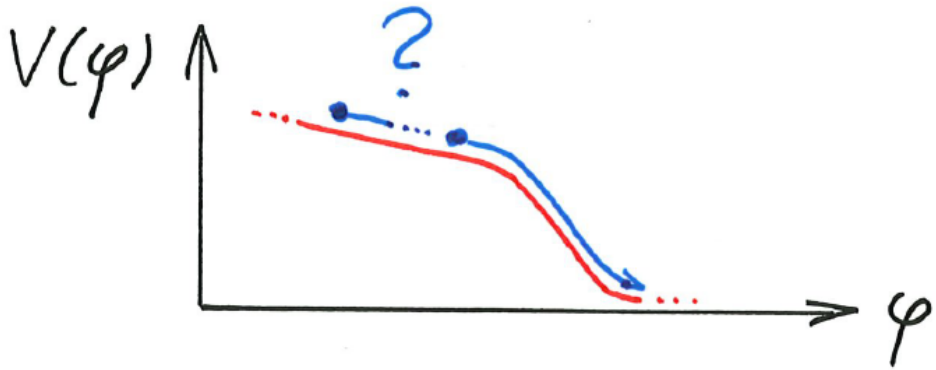
Reasons for doubt:

- No / only short-lived dS vacua.
- Issues with the transitions (see parallel talk by T. Coudarchet).
- Global perspective may be fundamentally flawed.

Important comment:

- Even if no dS vacua exist, we must ask which inflationary plateau we came from and which (quintessence-type) vacuum we live in.

- Even if the landscape has just a single such plateau and adjacent late-time vacuum, we must ask where on the plataeu our universe was born.



$\Rightarrow$ Measure / Initial condition problem unavoidable.

Towards a 'Quantum-Measure'

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

- Cosmological Central Dogma (Banks, Susskind) :

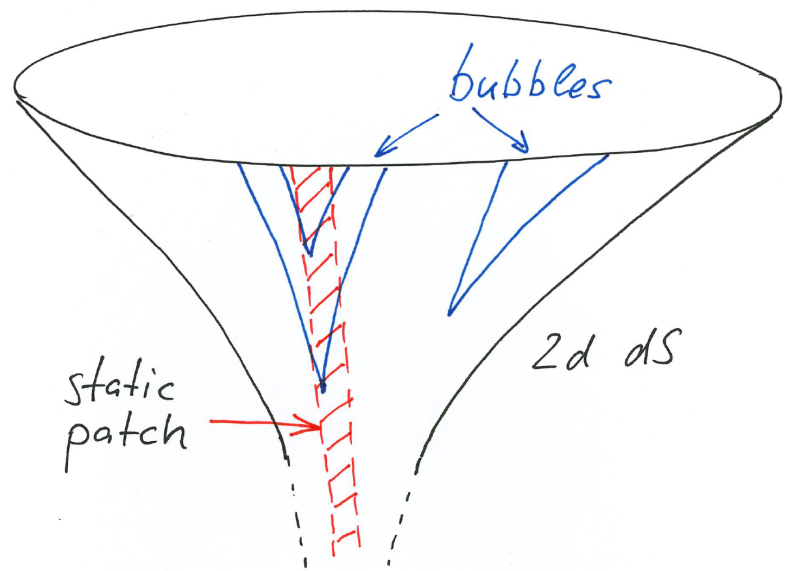
  dS space is a finite system with $\dim(\mathcal{H}) = e^S$.

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

- Even better: Write down corresponding Wheeler-DeWitt equation:

  $H\psi = \chi$

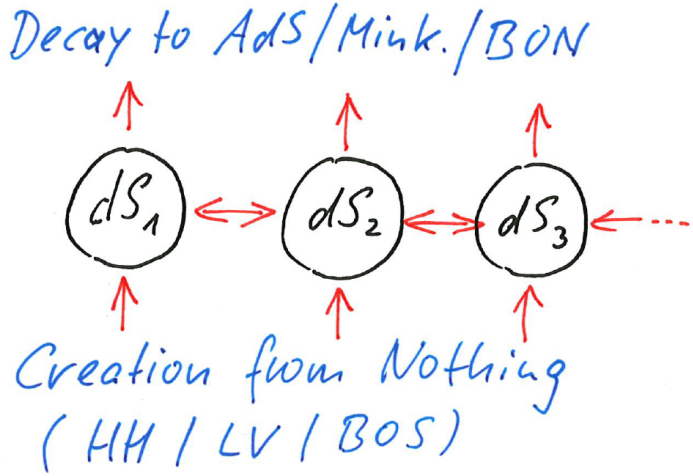
- Crucially, a source term for the creation from nothing is unavoidable.



$\Rightarrow$ The 'Local Wheeler-DeWitt Measure'

- Formally, we have $H\psi = \chi$,
  with the probability for vacuum dS_i given by $p_i = \left\| \psi|_i \right\|^2$.

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



The outcome is similar to certain 'local measures': Bousso '06, Garriga/Vilenkin.. '05...'11, Nomura '11, Bousso/Susskind '11, Hartle/Hertog '16
(some recent related work: Pedro/Westphal, Halverson/Long, Khoury/Wong)

'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

$$0 = J_i + \sum_{j\in dS} \left(p_j \Gamma_{j\to i} - p_i \Gamma_{i\to j} \right) - p_i \sum_{y\in Terminal} \Gamma_{i\to y} \ .$$

- The solution can be given as a series:

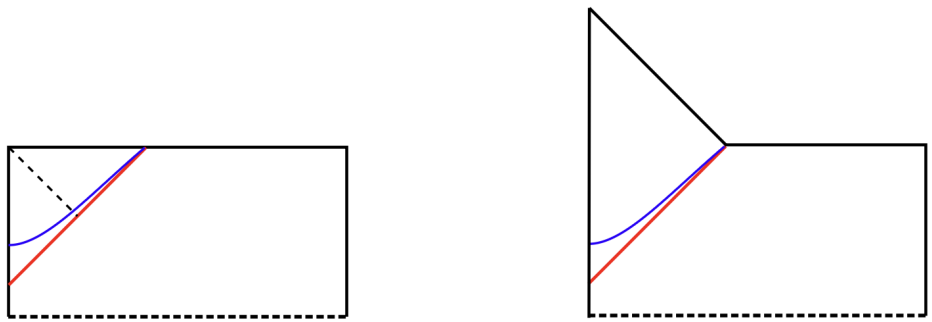
$$p_i = \frac{1}{\Gamma_i} \left\{ J_i + \sum_j J_j \frac{\Gamma_{j\to i}}{\Gamma_j} + \sum_{j,k} J_j \frac{\Gamma_{j\to k}}{\Gamma_j} \frac{\Gamma_{k\to i}}{\Gamma_k} + \cdots \right\}$$

(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.

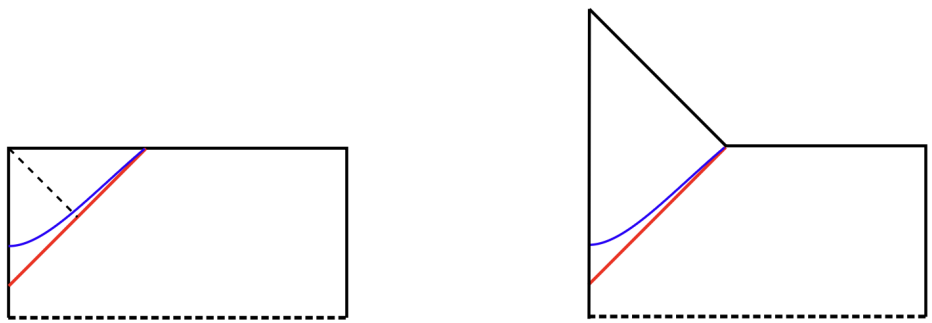
  But we ignore this (non-exponential!) effect.
- However, this changes once we include Minkowski-bubbles:



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.

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:

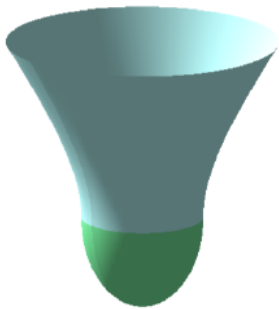
- We could try to take the infinity of Minkowski-space reheating surfaces seriously (no redundancy).

- This would imply a key prediction: The dark energy in our universe will decay – our future is Minkowski space.

  (Unclear how that would work in a proper string model.
  Interesting challenge! Extra motivation to realize
  'Dark Dimension' and related ideas explicitly.)

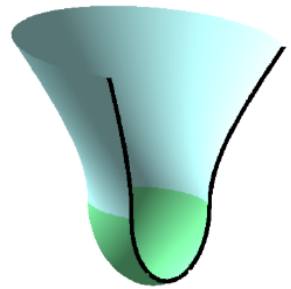
Towards explicit predictions

- 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:



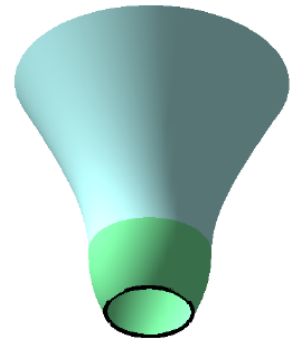
'No-Boundary'

Hartle/Hawking
Linde/Vilenkin



'Bubble-of-Something'

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

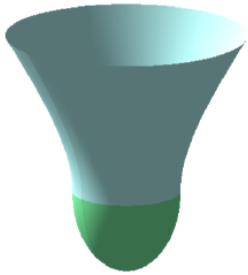


['Boundary proposal']

[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, ...]

Creation Rates



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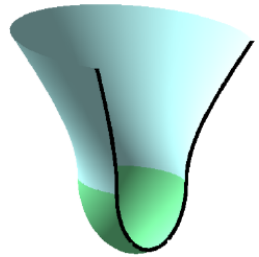
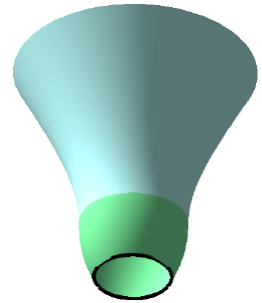
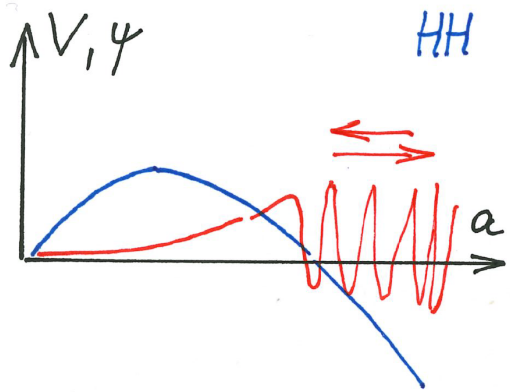


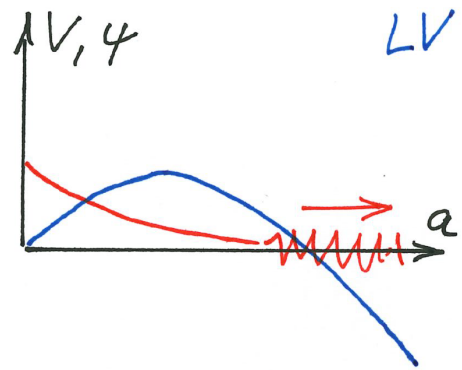
'Bubble-of-Something'

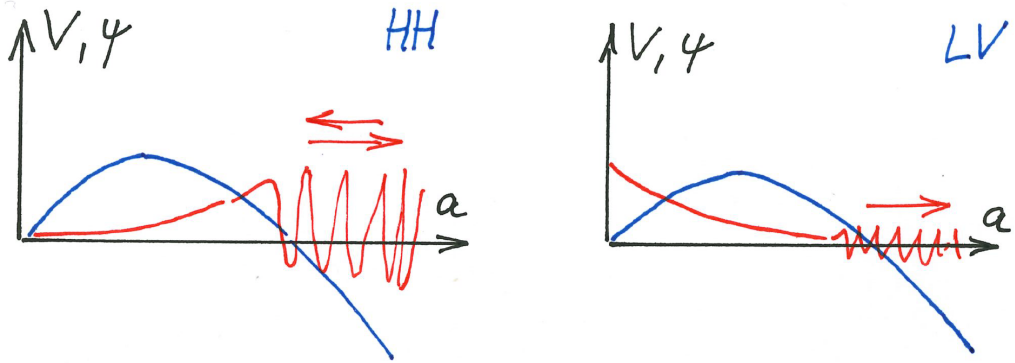


'Boundary proposal'

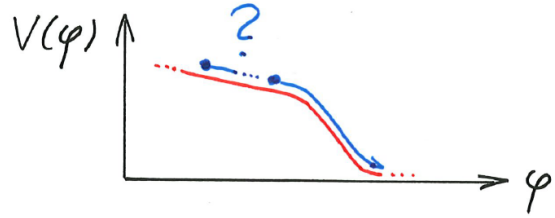
- The pictures above 'calculate' instanton actions $\mathcal{S}$.
- A key question for all three processes is the sign with which they enter the rate: $J \sim exp(\pm|\mathcal{S}|)$ ('HH vs. LV')
- Illustration of our (subjective, inconclusive) view:







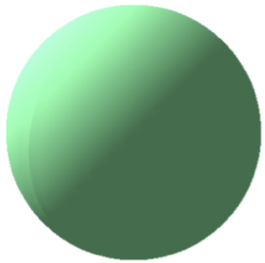
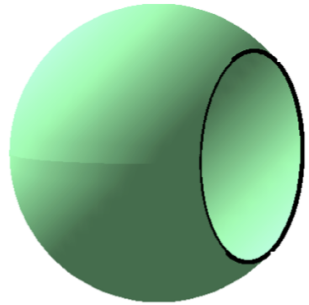
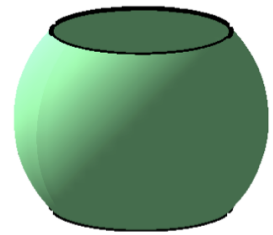
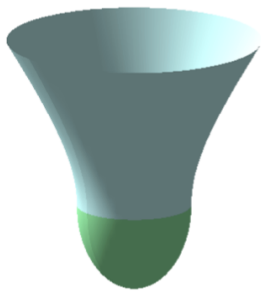
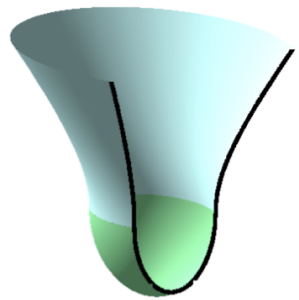
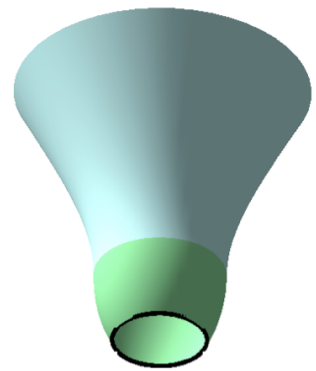
- The (by definition real) HH version describes a 'ground state of the universe'. $\Rightarrow$ Arguably not suitable for 'creation rates'.
- Also, HH is in tension with observation.
  as recently quantified in Maldacena '24



- By contrast, the LV sign choice suffers from a 'matter-instability', which may remove exponential suppression. Rubakov '84
- Finally, LV may be dominated by torus rather than sphere creation. Zeldovich/Starobinsky '84, Coule/Martin '99, Linde '04

- Taking the (exponentially strong!) pheno-problem of HH seriously, let me from now on admit a bias for **LV**.

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

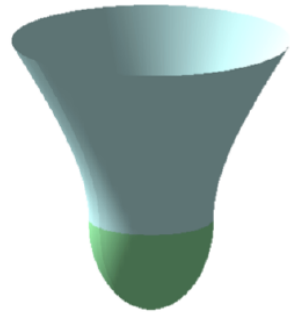
	No-Boundary (nb)	Bubble of Something (bos)	Boundary (b)
			
			
$\mathcal{S} =$	$-8\pi^2 M_P^2 \ell_{dS}^2$	$-4\pi^2 M_P^2 \ell_{dS}^2 \left(1 - \frac{T\ell_{dS}}{\sqrt{T^2\ell_{dS}^2+4M_P^4}}\right)$	$-8\pi^2 M_P^2 \ell_{dS}^2 \sqrt{\frac{T^2\ell_{dS}^2}{T^2\ell_{dS}^2+4M_P^4}}$

$\Rightarrow$ Boundary creation processes (bos/b) always dominate when the appropriate (pos./neg.) tension ETW branes exist.

Comparison of creation rates $J \sim exp(-|\mathcal{S}|)$

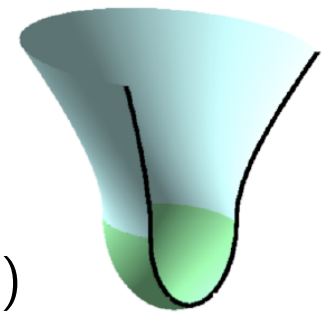
- Classical No-Boundary tunneling-exponent:

$$|\mathcal{S}| = -8\pi^2 M_P^2 \ell_{dS}^2$$



- Bubble-of-Something tunneling-exponent:

$$|\mathcal{S}| = -4\pi^2 M_P^2 \ell_{dS}^2 \left(1 - \frac{T\ell_{dS}}{T^2\ell_{dS}^2 + 4M_P^4}\right)$$

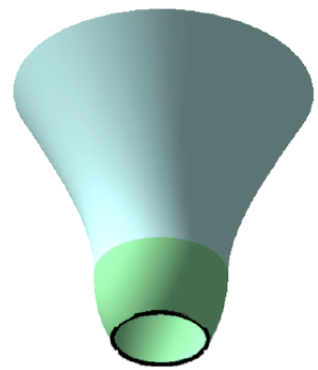


(wins against No-Boundary-Process if ETW-brane exists)

- Boundary-Process tunneling-exponent:

[follows from standard saddle-point analysis!]

$$|\mathcal{S}| = -8\pi^2 M_P^2 \ell_{dS}^2 \sqrt{\frac{T^2\ell_{dS}^2}{T^2\ell_{dS}^2 + 4M_P^4}}$$

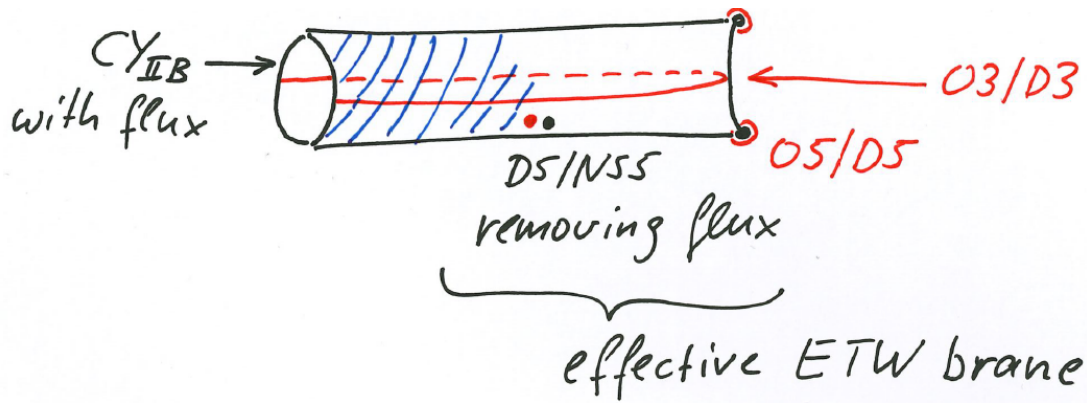


(wins in total if negative-tension ETW-brane exists)

Comments:

- The use of a spacelike ETW-brane in the off-shell region is similar to Witten's bubble of nothing but more extreme. More studies required!

- Explicit construction of an ETW-brane for the 'realistic' type-IIB flux landscape exists, but the tension has not been calculated. (only 3d $\mathcal{N} = 1$ SUSY - non-trivial problem!)



[Cf. Friedrich/AH/Walcher '23, building on earlier work by e.g. Garcia-Etxebarria/Montero/Sousa/Valenzuela, Draper et al., Angius/Calderon-Infante/Delgado/Huertas/Uranga, ...]

Next step toward predictions:

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

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:

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

(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: $\dfrac{\sum_{k\in \mathrm{dS}} \Gamma_{j\to k}}{\Gamma_j} \ll 1$

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

$\Rightarrow$ Our solution-series converges fast.

$\Rightarrow$ 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 '$\mathrm{inf}(i)$', decaying to vacuum i.

$\Rightarrow$ Key formula: $$p_{\mathrm{inf}(i)} \simeq \frac{1}{\Gamma_{\mathrm{inf}(i)}} \left(J_{\mathrm{inf}(i)} + \sum_{o \neq \mathrm{inf}(i)} J_o \frac{\Gamma_{o \to \mathrm{inf}(i)}}{\Gamma_o} \right)$$

- 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':

  Accept LV sign, assume slow-roll vacua with ETW-branes exist

  $\Rightarrow$ Bubbles of something or Boundary process win.

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

Summary / Conclusions

- Arguably, in a proper quantum approach, what used to be the 'measure' crucially depends on 'Creation from Nothing'.
  $\rightarrow$ 'Initial condition problem'

- By the Cobordism Conjecture, ETW branes always exist.
  'Bubble-of-Something'/'Boundary processes' always compete!

- HH has serious phenomenological problem. If, on this basis, LV is taken seriously ETW-branes determine the predictions.

- We derived simple formulae for explicit predictions (e.g. for scale of inflation). But there is missing input data / open problems:

  Technical: ETW-brane tensions for realistic vacua.
  Conceptual: Minkowski-space infinity problem.
  Competition from torus universes.

Finally, for our recent 'proper' string pheno work, see talk by J. Steiner