ETW Branes and Inflationary Predictions
for Rocky and Swampy Landscapes

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based on work with **Bjoern Friedrich, Alexander Westphal and Sebastian Zell**

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

Outline

- The Measure Problem ist still there!
  How is it affected by the 'Swampland Revolution'?
- Our attempt to define an explicit, usable measure:
  'Local Wheeler-DeWitt Measure'
- Input from 'Rocky Landscapes': KKLT, LVS etc.
- Input from 'Swampy Landscapes': maybe no (long-lived) dS,
  Cobordism.
- Towards a prediction for the scale of inflation.

Introduction/Motivation

- Generically: Many vacua / Multiverse $\Rightarrow$ Measure Problem.
  Linde/Mezhlumian '93

- Concretely: Flux Landscape; "10^{500} vacua"
  $\Rightarrow$ Measure Problem goes center stage.
  Bousso/Polchinski '00, Denef/Douglas '04, ...

- With KKLT/LVS under pressure,
  the (flux) landscape does not go away.

- Even if only slow-roll (or short-lived dS) exist...
  ....need a method to 'predict' our 'vacuum'

Introduction/Motivation (continued)

Key new 'swampland' input:

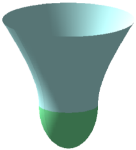
- Maybe no (multitude of) long-lived dS;
  Maybe instead mostly/only slow-roll.

- Cobordism Conjecture $\Rightarrow$ End-of-the-World Branes abundant

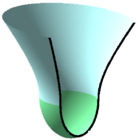
  These ETW branes can be key players
  in 'Creation from Nothing'.

  (to be quantified below ....)

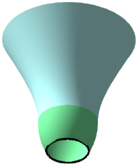
  Preliminary illustration:



'No-Boundary'



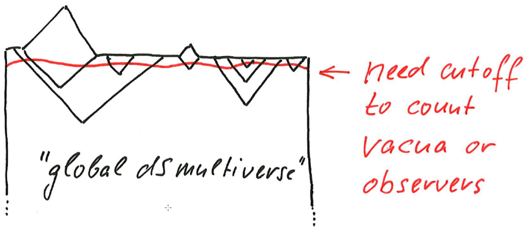
'Bubble-of-Something'



'Boundary proposal'

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/Zell - to appear

Towards a 'Quantum-Measure'

- Cosmological Central Dogma:

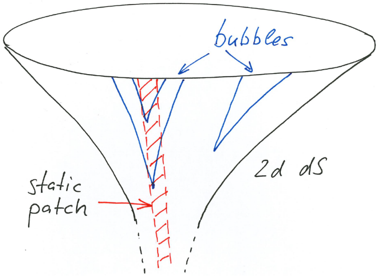
  dS space is a finite system with $\dim(\mathcal{H}) = e^S$.

- 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:

  $H\psi = \chi$

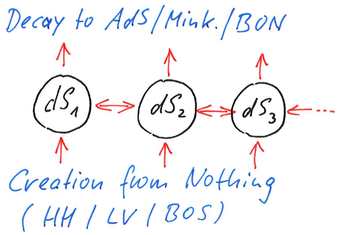
- Crucially, a source term for the creation from nothing is unavoidable.



The 'Local Wheeler-DeWitt Measure'

Friedrich/AH/Salmhofer/Strauss/Walcher '22,
Friedrich/AH/Westphal/Zell - to appear

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

'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.)

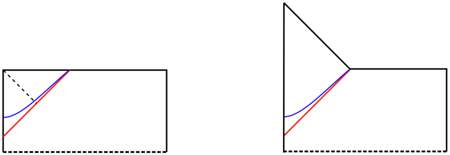
A conceptual problem: Reheating to Minkowski

- 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.

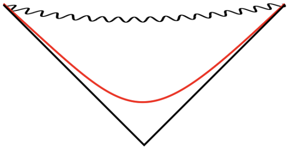
- However, this changes once we include Minkowski-bubbles:



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:

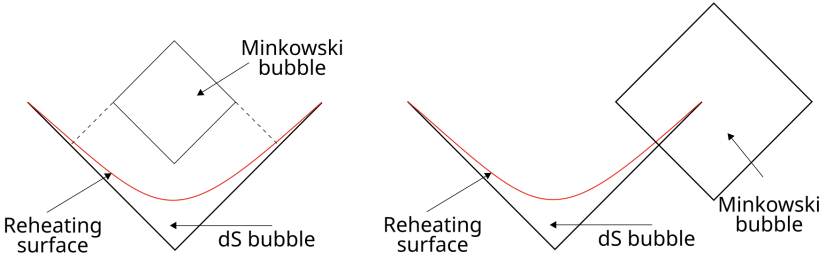
- One might think that this problem problem also arises for reheating in an AdS bubble. After all, $\dim(\mathcal{H}_{AdS}) = \infty$ and the reheating surface is infinitely large:



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

Second Aside:

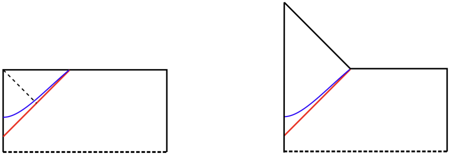
- Maybe the problem is absent because there can be no observers on a Minkowski-space reheating surface (e.g. due to $\mathcal{N} = 2$ SUSY). cf. Douglas '12
- However, even though Minkowski bubbles as such are in this case harmless, bubble collisions are not!



- 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:

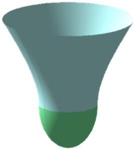
If no Minkowski-space reheating surfaces with observers exist in the landscape/multiverse, then collision rates with Minkowski bubbles determine the most likely vacuum.

... unsatisfactory....?

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

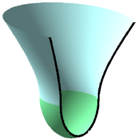
Towards explicit predictions

- 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:



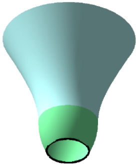
'No-Boundary'

Hartle/Hawking
Linde/Vilenkin



'Bubble-of-Something'

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

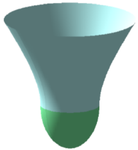


['Boundary proposal']

[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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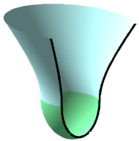

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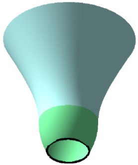
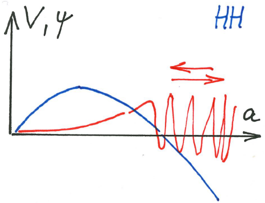
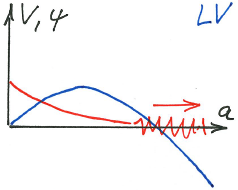


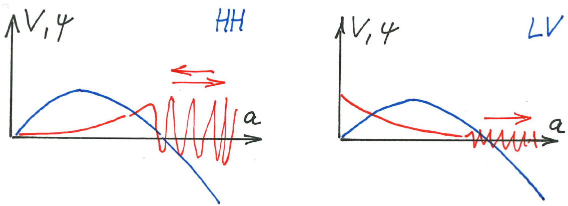
'Boundary proposal'

- 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:







- 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.

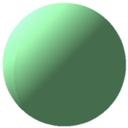
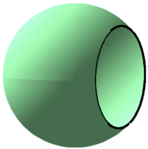
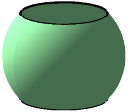
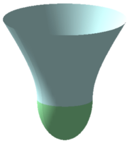
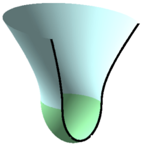
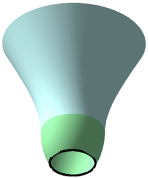
as recently quantified in Maldacena ’24

- By contrast, the LV sign choice suffers from a ‘matter-instability’. This may remove the exponential suppression.

Rubakov ’84

- For the time being, we will remain open to both sign choices.

- Thus we have: $J \sim exp(\pm\mathcal{S})$ 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, the 'bos'/'b' creation processes always dominate over 'nb' when the pos./neg.-tension ETW branes exist.

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:

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

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:

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

(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.

$\Rightarrow$ 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.

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

- 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':

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

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

Summary / Conclusions

- Predictions in any landscape (swampy or rocky) need a measure. I argued that, in a proper quantum approach, this is sensitive to 'Creation from Nothing'.

- Given the Cobordism Conjecture, a key ingredient in these creation events are ETW branes,
  allowing for 'BOS's or 'boundary processes'

- A key complication of the advertised 'local WDW measure' are Minkowski-space reheating surfaces.
  (We suggested how to proceed, but this may not be final.)

- We derived simple equations giving explicit predictions, e.g. for the scale of inflation. But input is missing, including crucially :

  ETW branes – tensions and availability?
  Creation of small tori?