Swampland, Cobordism, and the Beginning of the Universe

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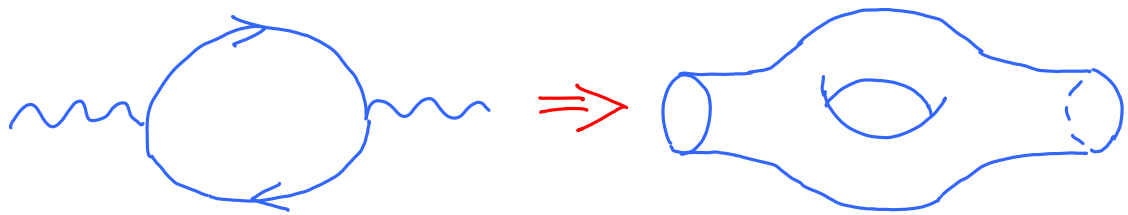
based on work with **Bjoern Friedrich, Johannes Walcher and Alexander Westphal**

Outline

- Setting the stage: Landscape, Swampland, de Sitter, ...
- An Aside: Swampland beyond String Theory?
- The Cobordism Conjecture
- Cobordism and end-of-the-world (ETW) branes:
  4d EFT view and bubbles of nothing/something.
- Implications for cosmology / measure-problem.

String theory: 'to know is to love'

- String theory defines a perturbatively finite QG theory in 10d:



- The divergences at $\vec{k} \to \infty$ are now removed (roughly because the 'singular' interaction point is gone).

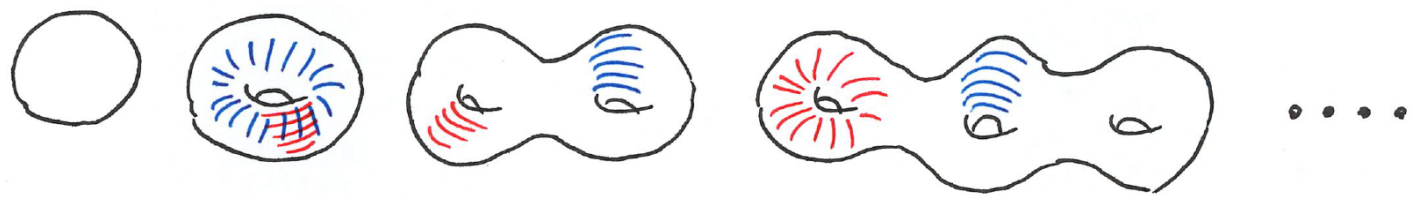
- Thus, in 10 dimensions but at low energy ($E \ll 1/l_{string}$), we get an (essentially) unique 10d QFT:

$$\mathcal{L} = R[g_{\mu\nu}] - F_{\mu\nu\rho}F^{\mu\nu\rho} - H_{\mu\nu\rho}H^{\mu\nu\rho} + \cdots$$

The 'classical' string theory landscape

- 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.

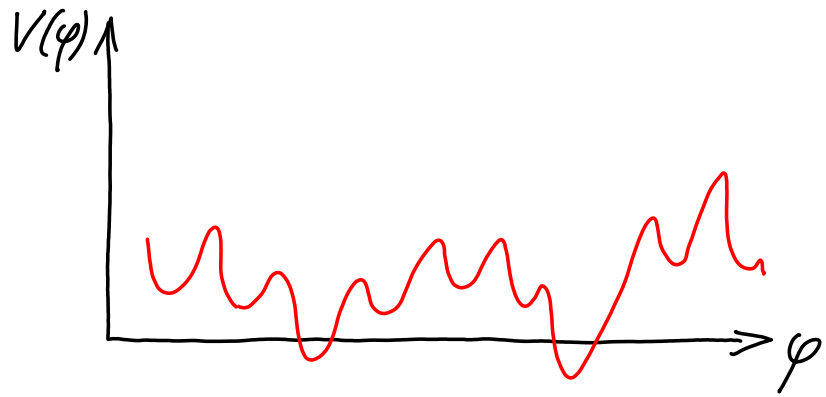


Bousso/Polchinski, Giddings/Kachru/Polchinski, Denef/Douglas '04

- This has lead to an overly optimstic **'anything goes'** attitude (in the sense that more or less any EFT can be realized).

String compactifications: flux landscape

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



- But this picture jumps very far ahead (and may in fact be entirely misleading).

- Indeed, 'at leading' order only part of the moduli get stabilized. Crucially, the volume remains a flat direction.

- Quantum corrections can stabilize the volume, but getting de Sitter vacua remains a hard technical problem.

A new perspective: The Swampland paradigm

- More recently, an alternative approach came to the fore:
  Ask which EFTs **can not** be found in the landscape!

  Vafa '05, Ooguri/Vafa '07

- This turned out to be very fruitful and inspiring
  (though much has remained at the level of conjectures ....)

  See e.g. reviews by Brennan/Carta/Vafa, Palti, van Beest/Calderon-Infante
  Mirfendereski/Valenzuela, Grana/Herraez, Agmon/Bedroya/Kang/Vafa

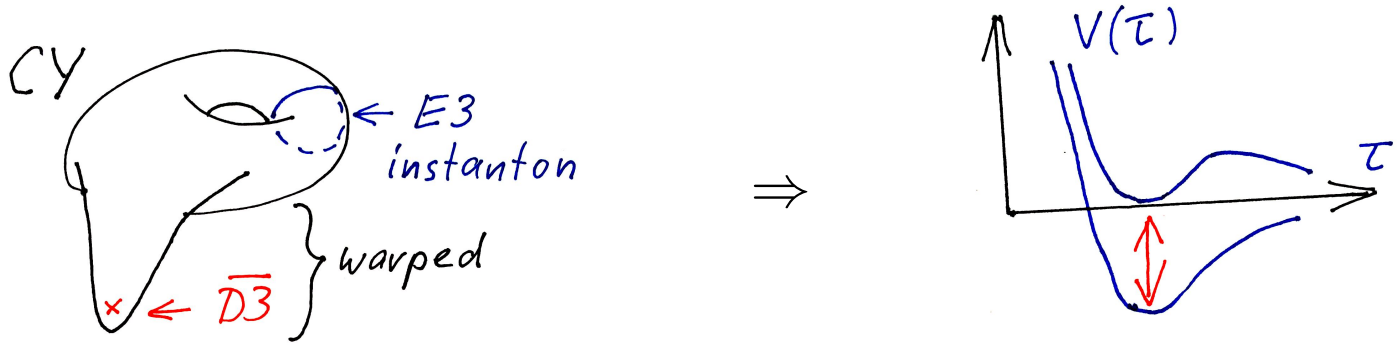
- One controversial but potentially impactful conjecture claims:
  The absence of (quasi-) de Sitter vacua in the landscape.

  Danielsson/Van Riet, Obied/Ooguri/Spodyneiko/Vafa

- Let me pause for a personal comment its status ....

Comment on the construction of controlled dS in String Theory

- The most explicit models (KKLT and LVS) rely on the inerplay of several higher-order effects:



- This requires a lot of 'tuning' within the famous '10^{500}' flux choices. But parametric control looked possible.

- This last point has recently been called into question.

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

- At present, it appears that the fundamental issue of 'Stringy dS' hinges on (perceived) technicalities....

Aside: Swampland beyond String Theory

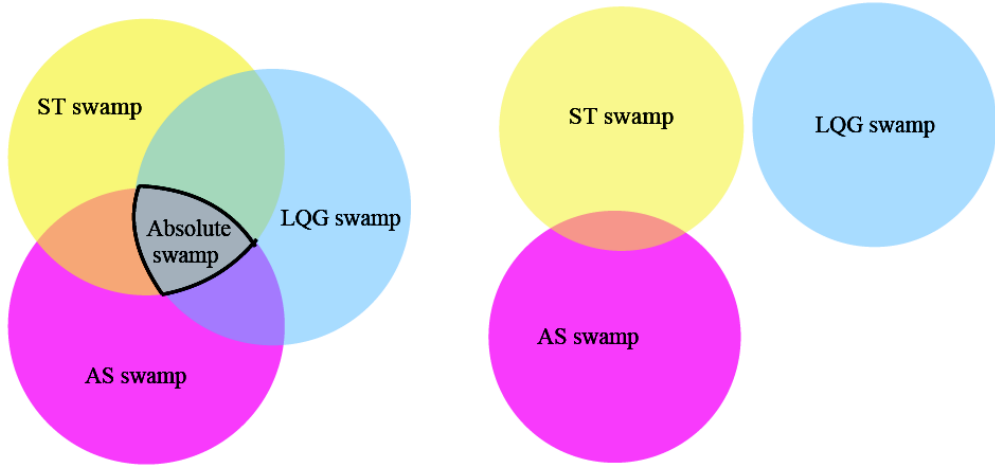
- The main 'swampland story' assumes string theory in the UV. But one may also consider 'UV completion in any quantum gravity model' (e.g. Asymptotic Safety, Loop QG, ...)

  de Alwis/Eichhorn/Held/Pawlowski/Schiffer/Versteegen, Basile/Platania, Knorr/Platania, Montero/Tatraglia, Borrisova/Eichhorn/Ray

  for recent reviews see e.g. Eichhorn/AH/Pawlowski/Walcher, Basile/Buoninfante/Di Filippo/Knorr/Platania

- Generically, the swamplands of different models are distinct (e.g. AS does not appear to have trouble with de Sitter....)

- But is there still a common denominator in the sense of an 'absolute swamp'?



- For much of this talk,
  I will be agnostic about the underlying QG model.

- I will also be agnostic about de Sitter.

  (but focus on QG models somehow related to our real-world accelerating solutions)

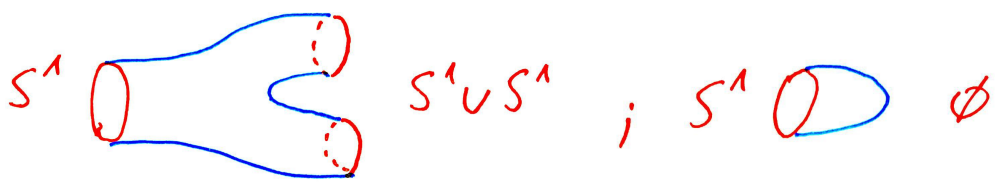
- I will, however, use the string-based motivation for the so-called ...

Cobordism Conjecture

McNamara/Vafa '19

- Definition: Two manifolds of dimension d are cobordant if they form the boundary of a manifold of dimension $d+1$.

- Examples:



Cobordism (continued)

Cobordims Conjecture:

In quantum gravity, all cobordims groups are trivial.

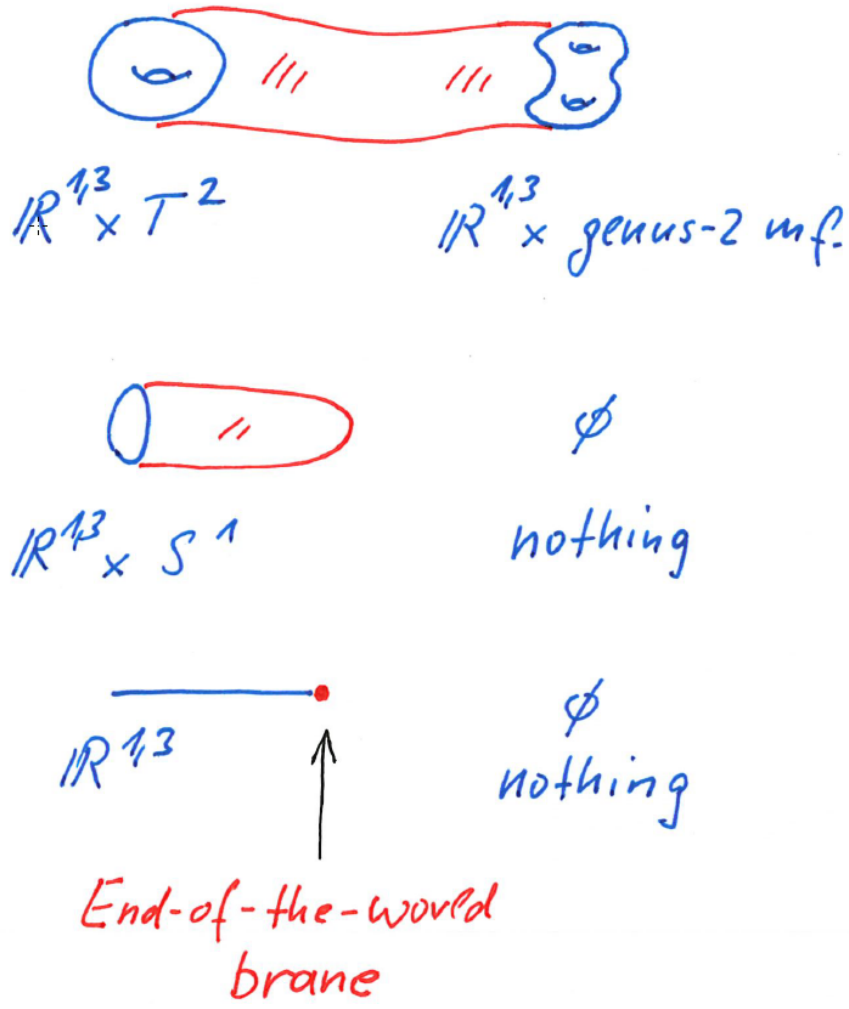
McNamara/Vafa '19

(Much subsequent work,
e.g. by Heckman, Ooguri, Montero, Valenzuela, Blumenhagen, ...)

- Fact: Not all manifolds are cobordant.
- The conjecture nevertheless makes sense because it is to be applied to manifolds with additional structure.
- It is about deforming one compact space into another, using all allowed singularities, branes etc.
- In spirit, the conjecture says that, in string theory, 'all vacua are connected' (e.g. by domain walls).

Cobordism (continued)

- For obvious reasons, the string-theorist's view of the cobordism-conjecture is through compactifications ....



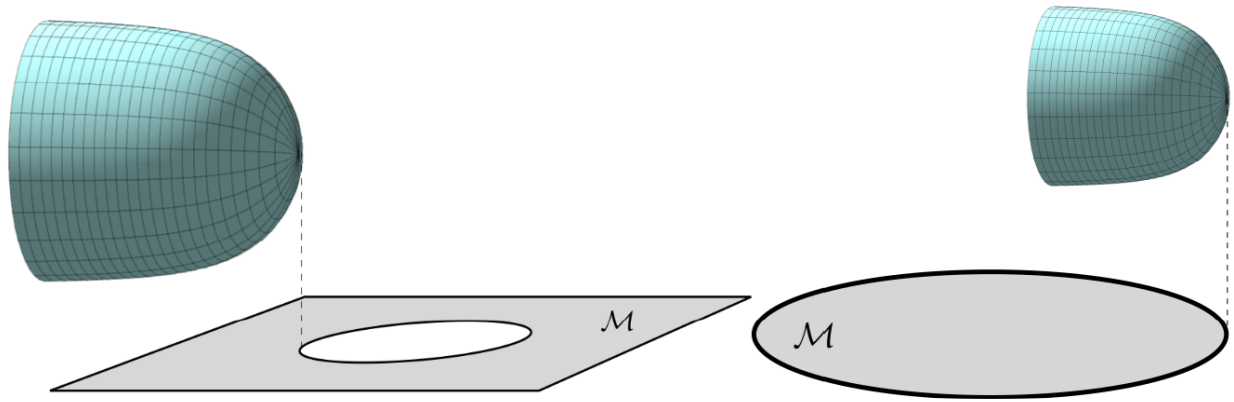
Cobordism (continued)

- Thus, the cobordism conjecture says that all compactifications (in particular all landscape vacua) are connected, incuding to 'nothing'.
- The dynamical question of how these landscape vacua are created/decay remains important.
- Due to the cobordism conjecture, end-of-the-world branes are ubiquitous
- Studying their role in 'landscape dynamics' is important!

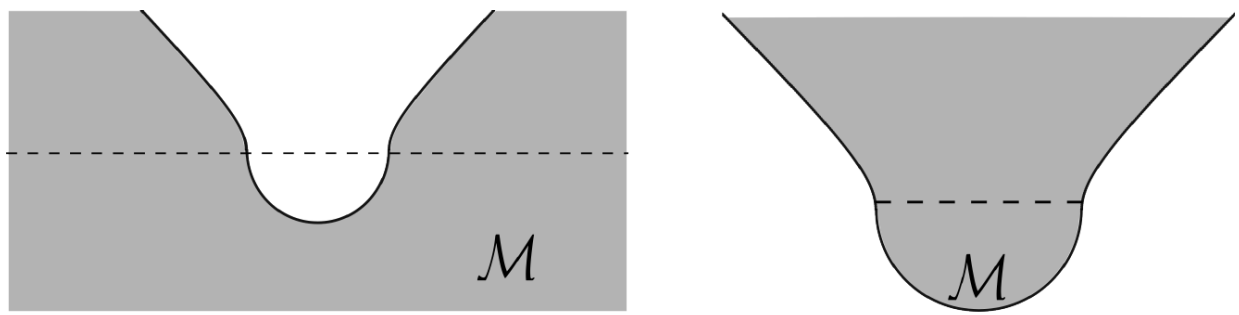
(Witten's) Bubble of Nothing/Something

- Let us start by with ETW branes as they appear in 'Witten's bubbles' for S^1 compactifications.

- Euclidean:



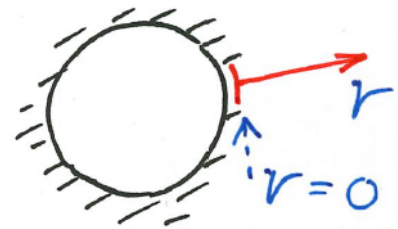
- Lorentzian:



Bubble of nothing / ETW-brane – basic formulae

Lots of older and recent work: Horowitz/Orgera/Polchinski '07... Blanco-Pillado et al. '10 ... Dibitetto/Petri/Schillo '20 ... Garcia-Extebarria/Montero/Sousa/Valenzuela ... Buratti/Calderon-Infante/Delgado/Uranga ... Draper/Garcia/Lillard ... Dierigl/Heckman/Montero/Torres ....

- 5d (or higher-dimensional) metric:



$$ds^2 = e^{2\alpha\varphi(r)}\left(dr^2 + f(r)^2 d\Omega_3^2\right) + e^{2\beta\varphi(r)}\, ds_n^2$$

- Coefficients α and β chosen such that 4d Einstein-frame metric is

$$ds_4^2 = dr^2 + f(r)^2 d\Omega_3^2 \qquad \text{with internal radius} \qquad 2\pi R = e^{\beta\varphi}$$

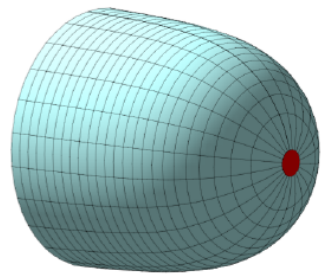
- Crucial: at $r \to 0$ we have $\varphi \to -\infty$, $f(r) \to 0$.

- $\Rightarrow$ The 4d description of the ETW brane at $r = 0$ is problematic since $2\pi R(r) = e^{\beta\varphi(r)} \to 0$ implies that the 4d Planck mass goes to zero in 5d Planck (or string) units.

- $\Rightarrow$ Length scales transverse to the ETW brane (in particular the bubble radius) vanish in the 4d EFT.

- $\Rightarrow$ 4d decay rate calculation in terms of ETW brane tension is impossible.

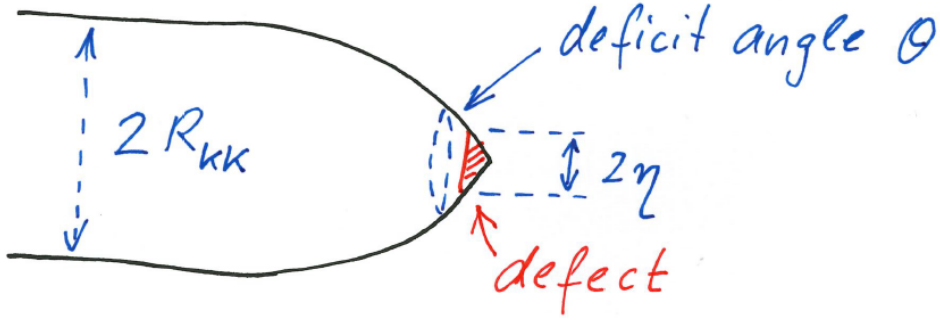
Our goal: Resolve this issue in a universally applicable way.



Idea:

In many cases (e.g. shrinking CY rather than S^1) the tip of 'Witten's cigar' will anyway be singular or carry a defect.

Hence, we may as well assign a defect to $r = 0$ from the start.



- The defect is characterized by its size η and its tension or, equivalently, its deficit angle:

$$T_{def} = \theta \qquad \text{with} \qquad 1 - \frac{\theta}{2\pi} = \left.\frac{dR}{dx}\right|_{x=0} .$$

(where x is the proper radial distance).

- Given η, θ and R_{KK}, the full solution is determined.

- In the limit $\eta \to 0$ and $\theta \to 0$, Witten's geometry is recovered.

- Crucially, due to the cutoff at $R = \eta$, we have a non-singular 4d description.

- What is more, our solution follows from the 4d action

$$S = \int_{\mathcal{M}} \sqrt{g} \left(-\frac{1}{2}\mathcal{R}_4 + \frac{1}{2}(\partial\varphi)^2 + V(\varphi) \right) - \int_{\partial\mathcal{M}} \sqrt{h}(\mathcal{K}_4 - T_{4,\eta}) \,.$$

  Here $\mathcal{K}_4$ is the extrinsic curvature at $R = \eta$ and

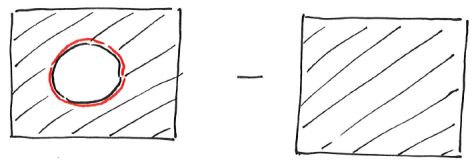
$$T_{4,\eta} = -\left(1 - \frac{\theta}{2\pi}\right) \frac{1}{\sqrt{2\pi\eta^3}} \,.$$

- The (regulated) divergence $\sim 1/\sqrt{\eta^3}$ is an artifact of using the 4d Einstein frame.

- The, '1' comes from the shrinking geometry, the 'θ' from the defect.

- Our action formulation allows for a universally usable equation for bubble-of-nothing decay rates:

$$\Gamma \sim exp(-B)\ , \qquad B = S_{instanton} - S_{vacuum}$$



$$\Rightarrow \quad B = \frac{\pi^2 M_P^2 R_{KK}^2}{(1-\theta/2\pi)^2}$$

- For $\theta = 0$, this reproduces Witten's result.

- It can be phrased purely in 4d terms:

$$B = 8\pi^2 \frac{M_4^6}{T_4^2} \qquad \Rightarrow \qquad T_4 = 8(1-\theta/2\pi) M_P^2 \Big/ R_{KK}$$

(However, specifically in this case the wall is as thick as the bubble radius and the 'thin wall' picture is only qualitative.)

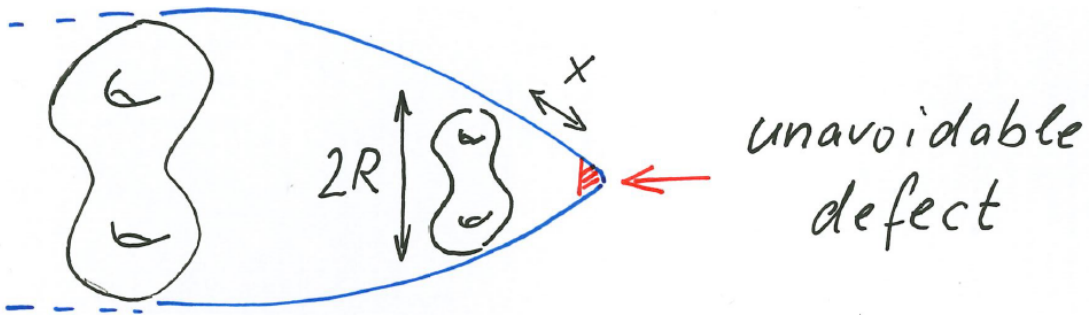
Bubble of nothing / ETW-brane – General case

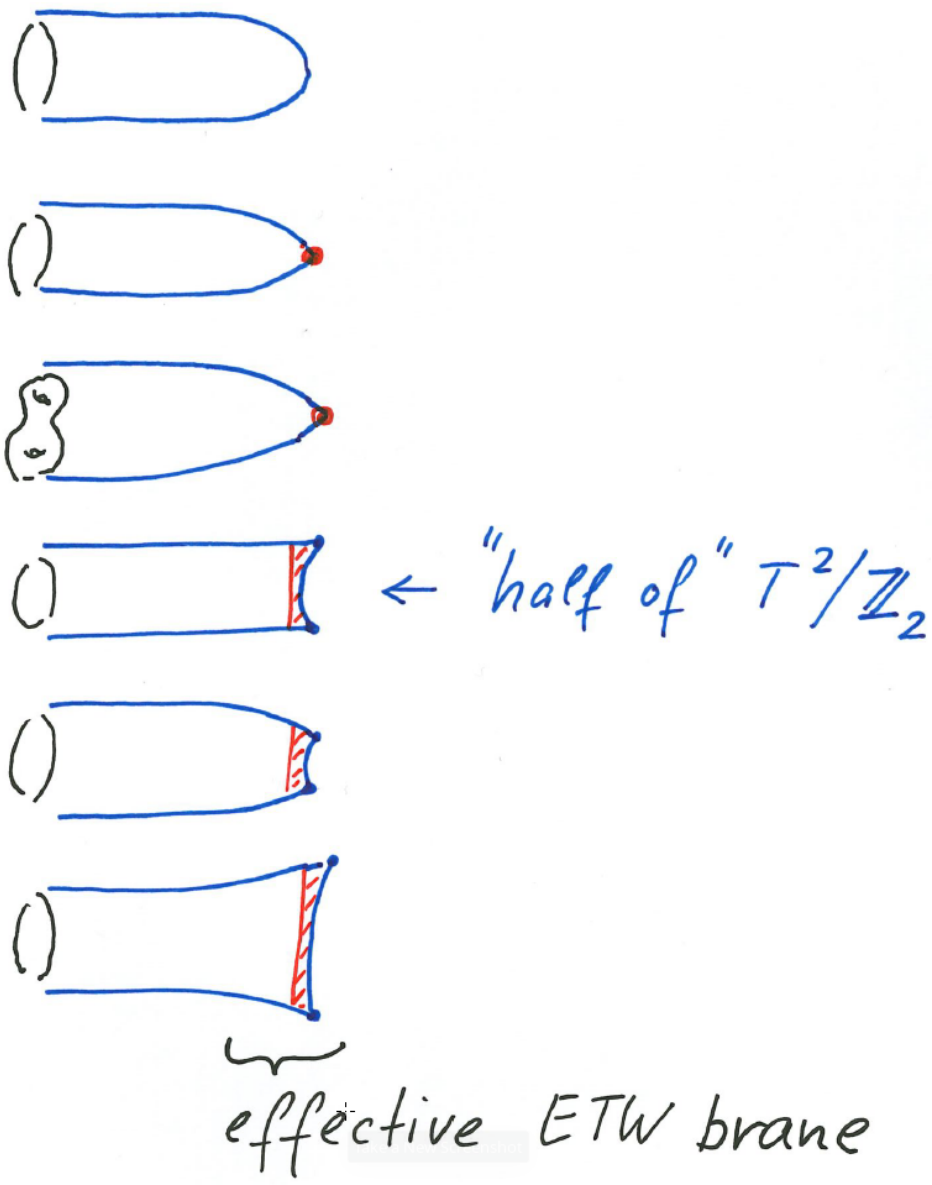
- Our 4d EFT approach can be easily generalized:

  – Only $\mathcal{O}(1)$ numerical coefficients change if we vary the shrinking-space dimensions and the non-compact dimensions.

  – While θ loses the literal meaning of a deficit angle, its definition and relation to the defect tension remain:

$$1 - \frac{\theta}{2\pi} = \left.\frac{dR}{dx}\right|_{x=0} .$$





... many different options for the an ETW-brane geometry can be described in our 4d EFT approach ...

cf. Garcia Etxebarria/Montero/ Sousa/Valenzuela '20

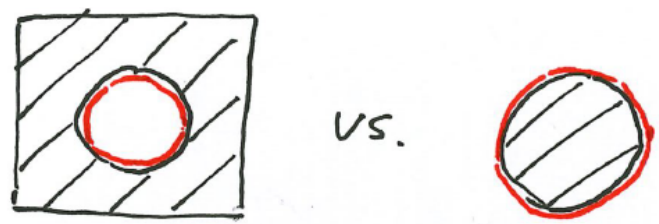
- The exponent for the corresponding bubble-of-nothing decay can be given explicitly in all these case.

- For example, specifically for the $10d \to 4d$ situation and assuming Ricci-flatness:

$$B = 8\pi^2 \frac{M_4^6}{T_4^2} = \frac{\pi^2 M_P^2 R_{KK}^2}{16(1-\theta/2\pi)^2} \left(\frac{R_{KK}}{\eta}\right)^2$$

  (Recall that η is the defect size.)

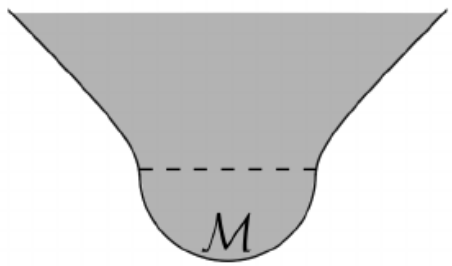
- Crucially, for sufficiently high defect tension the ETW brane tension T_4 turns positive and bubbles of something become possible.



Bubble of something – a short preview

(a.k.a. 'bubbles from nothing')

- They have been studied since quite some time....
  Hawking/Turok '98, Garriga '98, Bousso/Chamblin '98,
  Blanco-Pillado/Ramadhan/Shlaer '11, Cespedes/de Alwis/Muia/Quevedo '23, ...
- A key difference compared to the 'no-boundary' creation à la Hartle-Hawking/Linde-Vilenkin is the applicability to Minkowski/AdS.
- As we will see later, they can play a decisive role in quantum cosmology.
- But before going there, let's briefly discuss ETW brane in the 'actual' stringy landscape



Towards bubbles of anything in the actual string landscape

- So far, we have convinced ourselves that:

  – Generic compactifications lead to ETW-branes allowing for 4d EFT treatment.

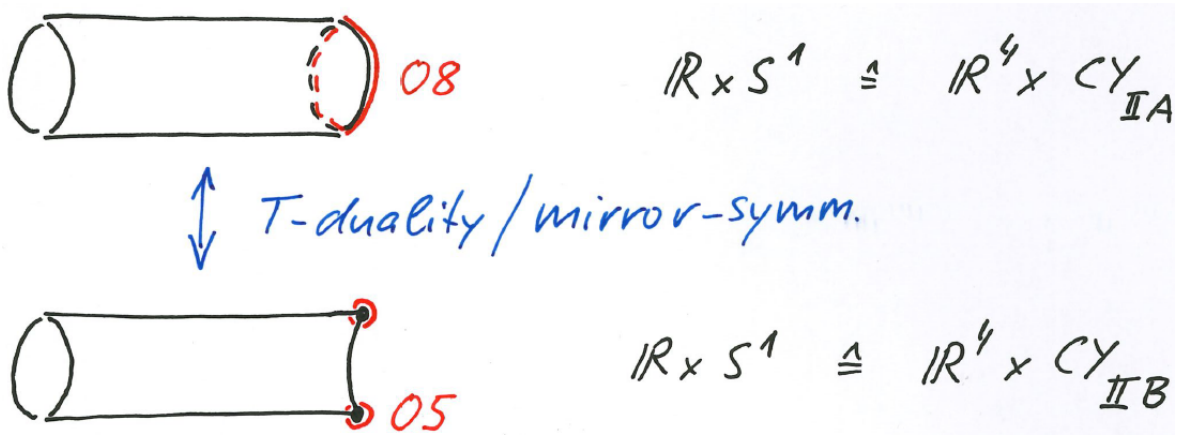
  – This allows for a straightforward calculation of 'tunneling exponents' for bubbles of something/nothing.

  (We will see later how this may affect landscape predictions.)

- Next, let us (as an example) construct a 'universal' ETW-brane for the type IIB flux landscape ....

- For type-IIA on CY_3, we can end space by simply including an O8-plane (with local tadpole cancellation by D8s).

- This can be taken to type-IIB by mirror symmetry/T-duality:

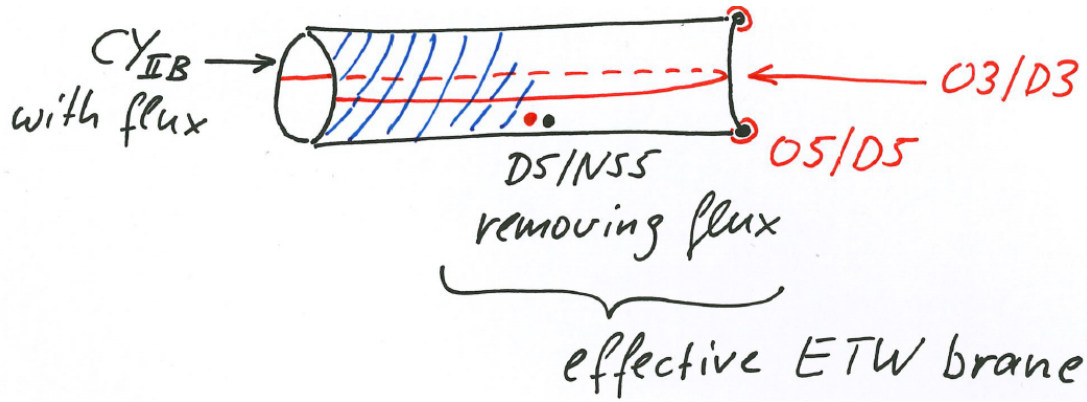


- Alternatively, one may get this by directly orientifolding $\mathrm{CY}_{\mathrm{IIB}}$:

  Combine an anti-holomorphic involution of the CY with $X^3 \to -X^3$ (where X^3 is a non-compact coordinate).

The real thing: ETW-brane with fluxes in 4d....

- Now, in parallel to our O5/D5 ETW brane, we must add a D5/NS5 domain wall to remove the flux.



- The effective tension can be positive or negative.
  Its determination is a key outstanding task!

- At the moment, we can only parameterize the result:

$$|T_4| \sim \epsilon \frac{M_4^3}{(R_{KK} M_{10})^4} \qquad \text{with} \qquad \epsilon \equiv \frac{R_{KK}}{\ell_{AdS}} \ .$$

Towards cosmological applications

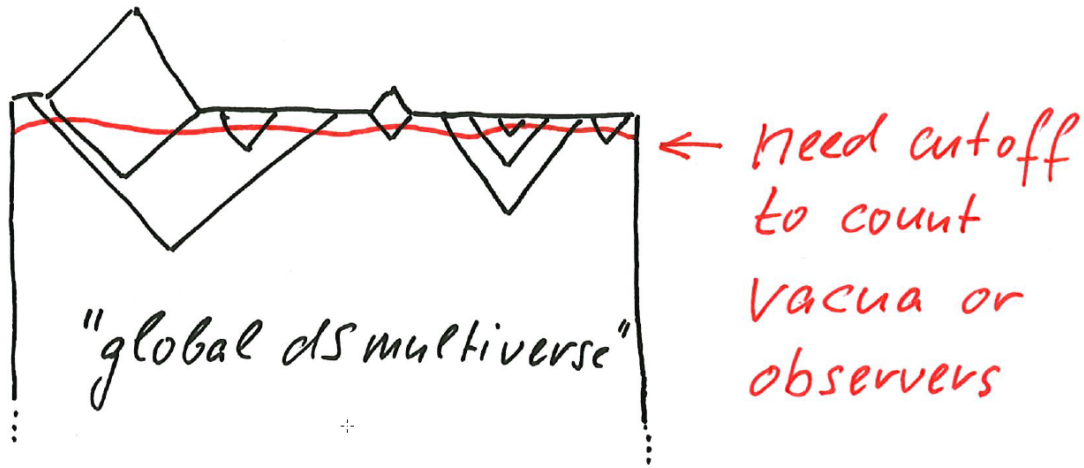
- If our fundamental quantum gravity theory has many 4d solutions, we need to predict (at least statistically) where we find ourselves.

- Even if there is only one 4d vacuum and one inflationary plateau, it is a controversial question where on it inflation starts (and how 'natural' this is in the first place).

- Thus, the 'Measure Problem' or 'Initial Conditions Problem' remains important in one form or another....

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.

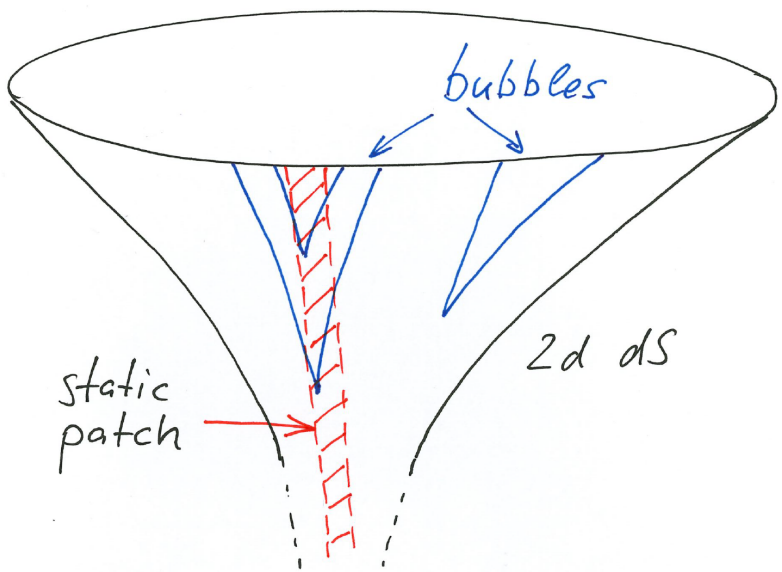
  Friedrich/AH/Salmhofer/Strauss/Walcher '22, Friedrich/AH/Westphal '24

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.

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

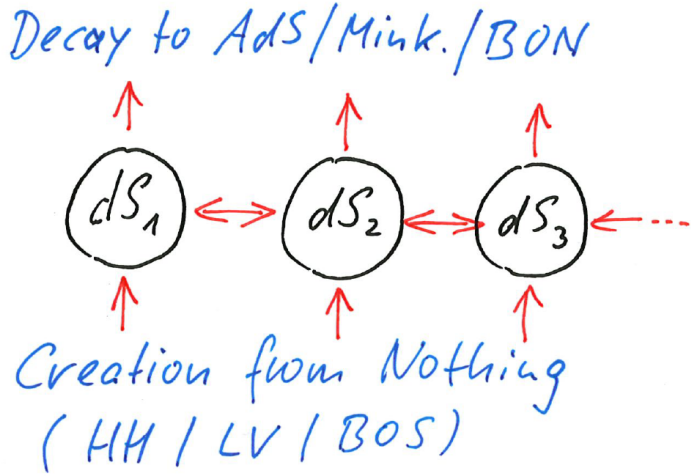
$$H\psi = 0 \qquad \rightarrow \qquad H\psi = \chi$$

- 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':



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

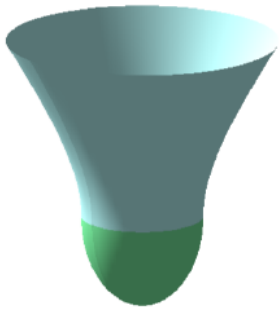
$$J_i = \sum_{j\in dS} \left(p_i \Gamma_{i\to j} - p_j \Gamma_{j\to i} \right) + p_i \sum_{y\in Terminal} \Gamma_{i\to y} \ .$$

- The solution can be given as a series:

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

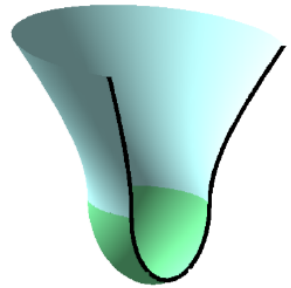
(Here Γ_i is the total decay rate of vaccum i.)

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



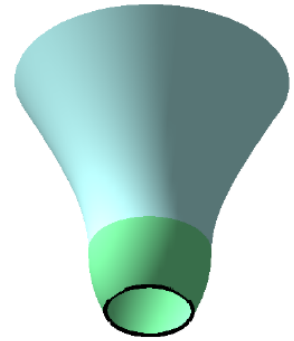
'No-Boundary'

Hartle/Hawking
Linde/Vilenkin



'Bubble-of-Something'

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

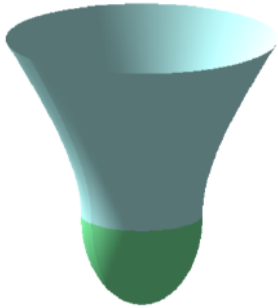


['Boundary proposal']

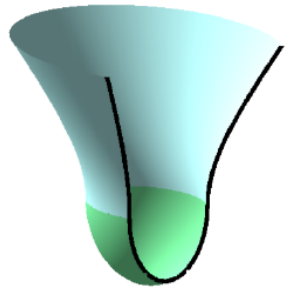
[Friedrich/AH]

[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, ...]

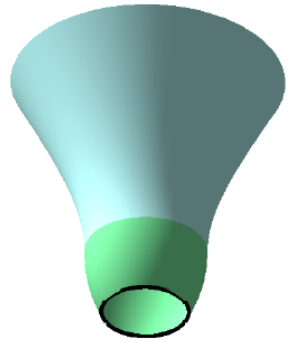
Creation Rates



'No-Boundary'

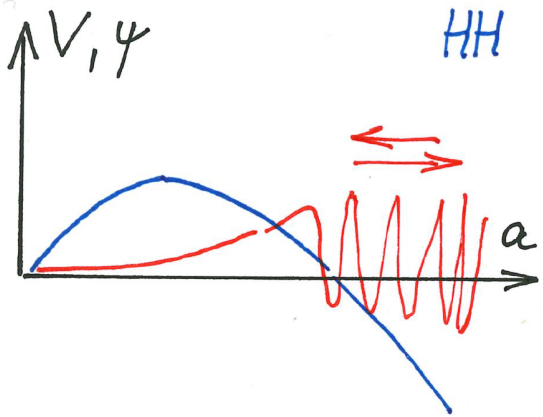


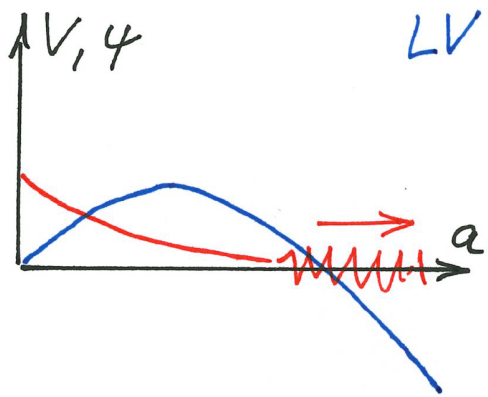
'Bubble-of-Something'

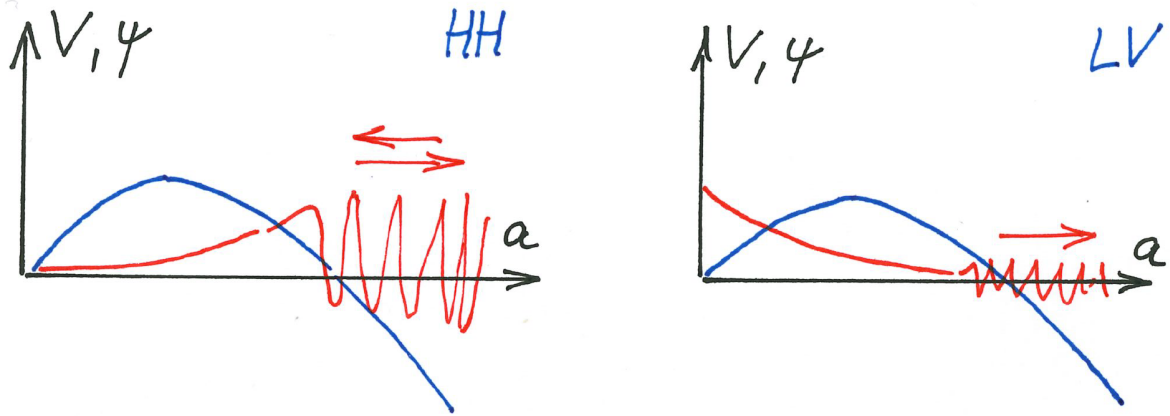


'Boundary proposal'

- 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:







- 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.

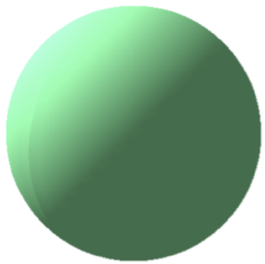
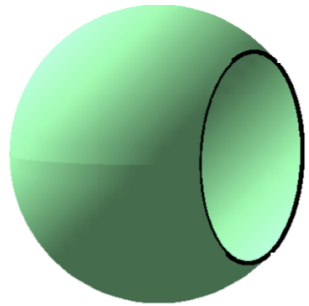
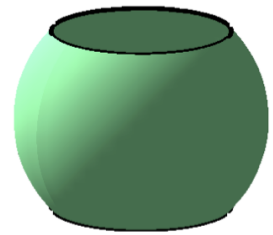
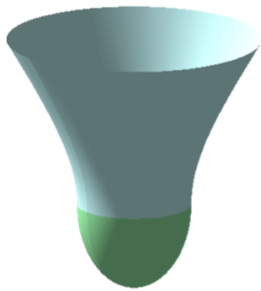
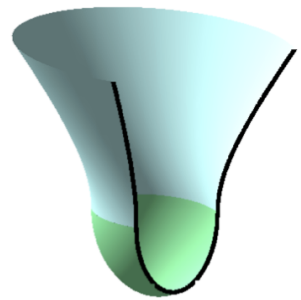
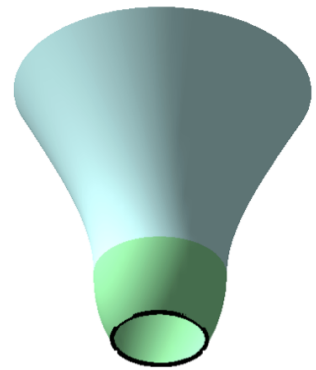
  as recently quantified in Maldacena '24

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

  Rubakov '84

- For the time being, we 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 appropriate ETW branes exist.

Towards explicit results

I want to highlight only one of the various (preliminary) findings from our recent paper:

- Let's accept the LV sign choice.
- Assume that slow-roll inflationary vacua with high-tension ETW-branes exist.

  $\Rightarrow$ Bubbles of something win!

  $\Rightarrow$ Energy scale of inflation
  determined by availability of ETW branes!

Summary / Conclusions

- I perceive the Cobordism Conjecture as a particularly compelling and relevant swampland conjectures.
- A key implications is the ubiquity of End-of-the-World branes.
- At the technical level, we showed how to obtain an EFT-description of 'Witten-type' ETW branes.
- We also characterized an explicit and generic ETW brane for the landscape.
- We showed that ETW branes can be decisive in some of the best-motivated approaches to the 'measure' or 'initial condition' problem.
- ETW branes are worth studying, also outside string theory.