Cobordism, Bubbles of Anything and the Boundary Proposal

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based on work with **Bjoern Friedrich and Johannes Walcher**

Outline

- Cobordism and end-of-the world (ETW) branes:
  4d EFT view and applications
  to bubbles of nothing/something.
- An explicit ETW brane for the type IIB landscape.
- Bubbles of Anything and the Measure Problem.
- The Boundary Proposal.

Cobordism and the Landscape

- In spite of all the well-known issues with KKLT/LVS, let's be optimistic that some form of realistic string landscape (not necessarily dS) exists.

- If so, the question of how these landscape vacua are created/decay remains important.

- By the cobordism conjecture, end-of-the-world branes are expected to be ubiquitous.

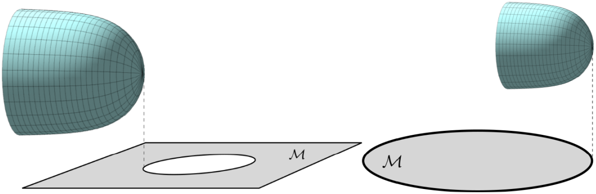
  McNamara/Vafa '19

- Thus, they can contribute to the creation/decay of landscape vacua and their EFT is important for making predictions!

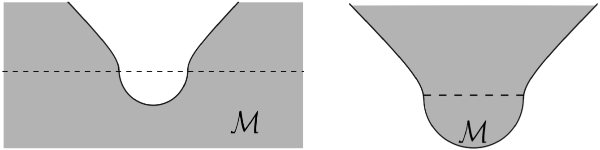
(Witten's) Bubble of Nothing/Something

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

- Euclidean:



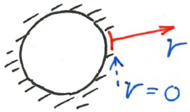
- Lorentzian:



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 ... Blumenhagen/Cribiori/Kneissl/Makridou

- 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

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

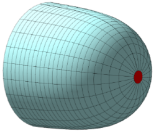
- Crucial: at $r \to 0$ we have $\varphi \to -\infty\,, \;\; f(r) \to 0\,.$

- $\Rightarrow$ 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 at 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.

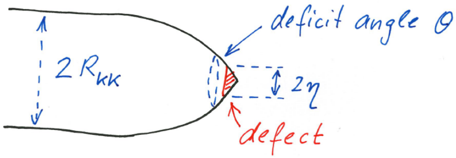
Our goal: Resolve this issue in a universally applicable way.



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:

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

(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

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

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

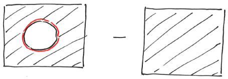
$$T_{4,\, def} = -\left(1 - \frac{\theta}{2\pi}\right) \frac{1}{\sqrt{2\pi\eta^3}} \,.$$

- 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:

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



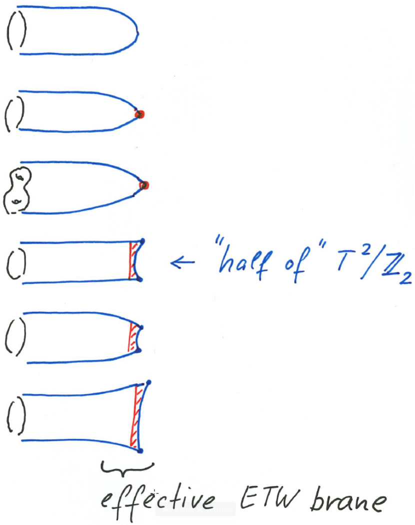
$$\Rightarrow \quad B = \frac{\pi^2 M_P^2 R_{KK}^2}{(1-\theta/2\pi)^2}$$

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

- The result can be phrased purely in 4d terms:

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

More generally: The shrinking space can be anything, including e.g. a CY ...

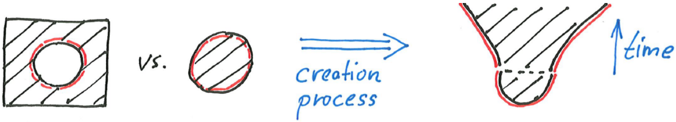


... many different options for the an ETW-brane geometry can be described in our 4d EFT approach ...

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

- Knowing the deficit angle and defect size, the exponent for the corresponding bubble-of-nothing decays can be given explicitly in all these case.

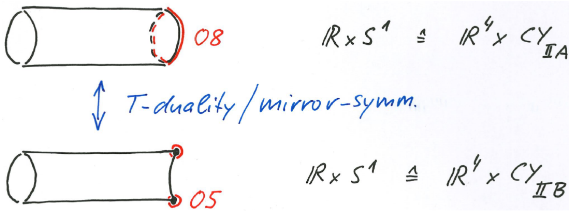
- For sufficiently high defect tension,
  the ETW brane tension T_4 turns positive
  and bubbles of something become possible:



An explicit 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:

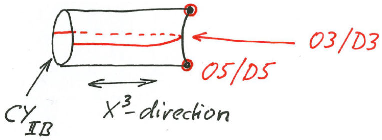


- Alternatively, one may get this by directly orientifolding CY_{IIB}:

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

- To make the vacua realistic, this must be combined with a (conventional) O7/O3 orientifolding of the $\mathrm{CY}_{\mathrm{IIB}}$.

- If only O3s are present, O5/O3 intersections on the ETW-brane are generically avoided:



- If O7s are also present, those will intersect the O5/D5 system sitting at the ETW brane.

- Nevertheless, in both cases it can be shown that the ETW brane preserves 3d $\mathcal{N} = 1$ SUSY.

- At this level of precision, spacetime is SUSY Minkowski and the ETW-brane tension is zero (no bubbles of either type).

Aside: Explicit $T^6/\mathbb{Z}_2$ model

- Coordinates:

$$Z^i = U^i + iV^i \,, \quad U^i \sim U^i + 2\pi \,, \quad V^i \sim V^i + 2\pi \,, \quad i \in \{1,2,3\}$$

- Orientifold/Orbifold action:

	X^0	X^1	X^2	X^3	U^1	V^1	U^2	V^2	U^3	V^3	
g_1	X^0	X^1	X^2	X^3	$-U^1$	$-V^1$	$-U^2$	$-V^2$	$-U^3$	$-V^3$	$\Omega(-1)^{F_L}$
g_2	X^0	X^1	X^2	$-X^3$	U^1	$-V^1+\pi$	U^2	$-V^2+\pi$	U^3	$-V^3+\pi$	Ω
$g_1 \cdot g_2$	X^0	X^1	X^2	$-X^3$	$-U^1$	$V^1-\pi$	$-U^2$	$V^2-\pi$	$-U^3$	$V^3-\pi$	$(-1)^{F_L}$

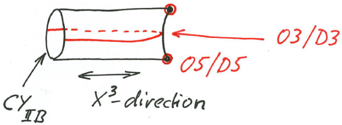
Table 1: Action of the two orientifold generators (of O3 and O5 planes) and of their product.

	X^0	X^1	X^2	X^3	U^1	V^1	U^2	V^2	U^3	V^3
O3	✓	✓	✓	✓	×	×	×	×	×	×
O5	✓	✓	✓	×	✓	×	✓	×	✓	×

Table 2: Summary of dimensions filled by O3/O5 planes (indicated with a ✓).

Back to the generic $CY_{\rm IIB}$-orientifold case....

- Due to corrections, the 4d bulk will not be SUSY-Minkowski but SUSY-AdS or 'SUSY-runaway'.



- One may expect that, by the surviving 3d $\mathcal{N} = 1$ SUSY, the ETW-brane will receive matching corrections making it 'stationary' (in the corrected geometry).

Cvetic/Griffies/Rey/Soleng '92..'96,
Ceresole/Dall'Agata/Giriyavets/Kallosh/Linde '06

- However, 'detuned' (non-stationary) SUSY ETW branes appear to also be possible.

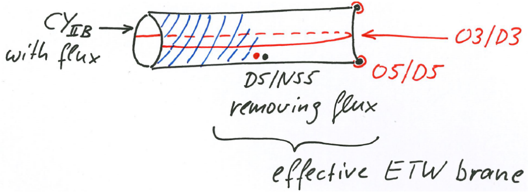
Bagger/Belyaev '02

- Preliminary result: $-M_4/\ell_{AdS} \lesssim T_4 \lesssim M_4/\ell_{AdS}$.

ETW-brane with (non-SUSY) fluxes in 4d....

- Crucially, we really want the bulk vacuum to be a generic, non-SUSY flux vacuum !

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



- Reliably determining the total effective tension is a key outstanding task!

- Once we know T_4, we have the decay/creation rates:

Bubble of nothing:

$$\Gamma \sim e^{-B} \qquad \text{with} \qquad B = \frac{8\pi^2 M_P^6}{T_4^2}$$

Bubble of something:

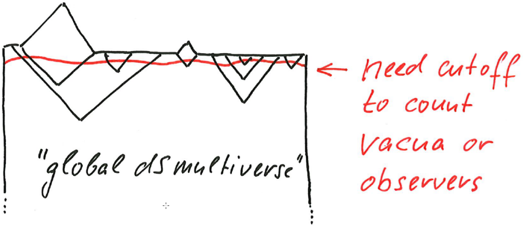
$$\Gamma \sim e^{-B} \qquad \text{with} \qquad B = \mp \frac{8\pi^2 M_P^6}{T_4^2}$$

... depending on the Hartle/Hawking or Linde/Vilenkin sign choice. In the latter case, the bubble of something may be the dominating creation process!

Measure problem and why we should care about creation processes

- Standard view: 'Bubbles 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/Zell - to appear

A 'Local Wheeler-DeWitt Measure'

- Cosmological Central Dogma:

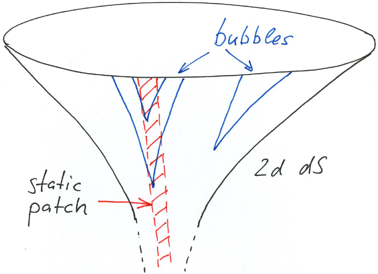
  dS space is a finite system with $\dim(\mathcal{H}) = e^S$.

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

- Wheeler-DeWitt equation must have a source term:

  $H\psi = \chi$

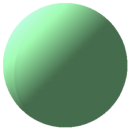
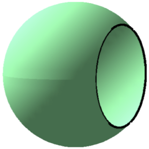
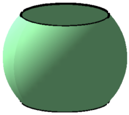
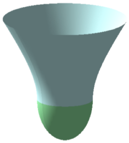
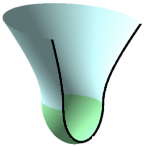
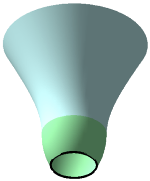
- This source term is sensitive to bubbles of something!



Situation is similar to certain 'local measures',
cf. Garriga/Vilenkin/... '05...'11, Nomura '11, Hartle/Hertog '16

Summary and the additional ‘Boundary Proposal’

- Once we consider ‘creation from nothing’ with ETW branes, a new possibility naturally arises:

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

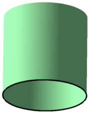
The 'Boundary Proposal' – continued

- Interesting fact: For the Linde-Vilenkin sign-choice and small ETW-tension, the 'Boundary process' dominates.

- Finally, one may consider the creation of torus rather than spherical universes.

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

- Assuming the existence of zero-tension ETW-brane (e.g. 'O8 + 4 D8') $\Rightarrow$ possible creation process without any 'off-shell' region and hence with no action cost!



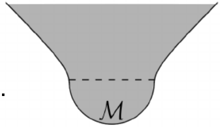
Summary / Conclusions

- We have developed a universally applicable 4d EFT approach to ETW branes associated with shrinking compact space.
- We have proposed a simple, explicit geometry suitable as an ETW brane for the type-IIB flux landscape.
- It's precise tension is a key research goal (needed to quantify Bubble-of-Something processes).
- Note: 'Quantum measures' based on the Wheeler-DeWitt-equation (and many local measures) rely on understanding the 'creation from nothing' quantitatively.
- New idea: Creation process using purely spacelike ETW brane ('Boundary proposal').

Bubble of something – brief comments

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

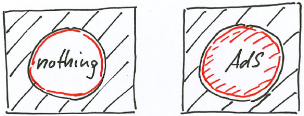
- They have been studied since quite some time....
  Hawking/Turok '98, Garriga '98, Bousso/Chamblin '98,
  Blanco-Pillado/Ramadhan/Shlaer '11, Cespedes/de Alwis/Muia/Quevedo '23, ...
- A key difference compared to the 'non-boundary' creation à la Hartle-Hawking/Linde-Vilenkin is the applicability to Minkowski/AdS.
- Fundamental criticism has been raised based on an analogy to up-tunneling from AdS.
  Brown/Dahlen '98



- We have quantitatively analysed and dismissed this criticism (cf. our paper and backup slides below).

On the Brown-Dahlen argument against bubbles of something

- Note first that tunneling from Minkowski to nothing or AdS is indeed very similar:



- Reason: Most of the AdS volume is near the boundary and may be absorbed in a 'renormalized' wall tension.

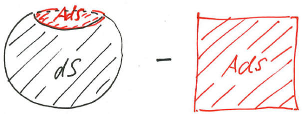
- Technically, one takes $\ell_{AdS} \to 0$ together with $T_{DW} \to \infty$, to recover precisely the ETW-brane result with finite

$$T_{eff} = T_{DW} - 2/\ell_{AdS} \,.$$

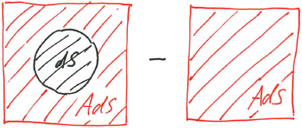
- This works analogously for the decay of dS to nothing or to AdS.

On the Brown-Dahlen argument (continued)

- B/D propose to use the same instanton for up-tunneling from AdS to dS, subtracting full AdS as a backround:

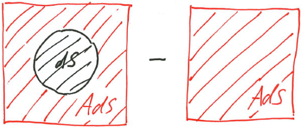


- This is divergent and they conclude that both up-tunelling from AdS to dS and, by analogy, the bubble of something are forbidden.
- We argue instead that, following Coleman-De-Luccia, one must glue in a bubble of dS into infinite AdS:



Backup:

On the Brown-Dahlen argument (continued)



- The result of this calculation is finite and allows for the desired limit of an 'effective' bubble of something:

$$T_{eff} = T_{DW} + 2/\ell_{AdS} \quad \text{with} \quad \ell_{AdS} \to 0\,, \;\; T_{DW} \to -\infty\,.$$

- Due to the negative domain wall tension, we do not claim this to be a reliable model for a bubble of something.

- However, we also see that, using AdS as a model for nothing, the bubble of something can not be ruled out.