Cobordism, Bubbles of Anything and the Measure Problem

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

(cf. also earlier work with **Xin Gao/Junghans/Schreyer/Venken/Salmhofer/Strauss**)

Outline

- Brief recap of recent issues with metastable de Sitter vacua.
- Cobordism and end-of-the world (ETW) branes:
  4d EFT view of bubbles of nothing/something.
- On the Brown-Dahlen criticism of bubbles of something.
- An explicit ETW brane for the type IIB landscape.
- Bubbles of anything and the 'local Wheeler-DeWitt measure'.

The construction of controlled dS in String Theory remains a key challenge

.....as emphasised e.g. in

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

- Quintessence is certainly an alternative, but technically it runs into similar (or worse) problems....

cf. Cicoli/Pedro/Tasinato '12 .... AH/Skrzypek/Wittner '19 .....

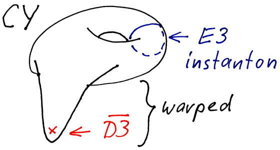
- Thus, the paradigmatic approach of 'AdS-minimum' plus 'Uplift' appears to remain one of the key roads towards controlled string pheno.

- **However....**

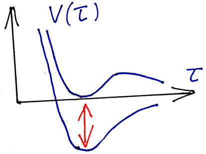
Singular Bulk Problem of KKLT

Carta/Moritz/Westphal '19; Gao/AH/Junghans '20
(see however: Carta/Moritz; McAllister et al. '21...'23)

- Reminder:



$\Rightarrow$



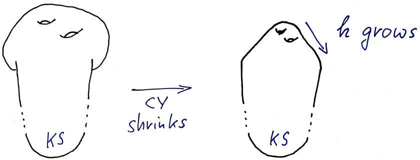
- The dS vacuum relies on the competition of two small quantities:

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

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

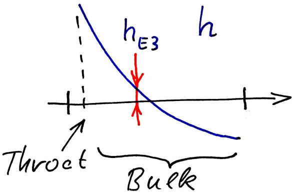
Singular Bulk Problem of KKLT (continued)

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



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

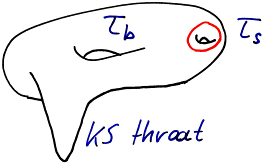
$$ds^2_{10} = h(y)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu$$
$$+h(y)^{1/2}\tilde{g}_{mn}dy^m dy^n$$



(Cf. also 'holographic' criticism in Lüst/Vafa/Wiesner/Xu '22)

Control problems of Large Volume Scenario (LVS)

- Maybe surprisingly
  (in spite of the large volume)
  related control problems affect the LVS.
  Junghans '22



- Control can be maintained if a sufficiently large D3-tadpole is available:
  → LVS Parametric Tadpole Constraint
  Gao/AH/Schreyer/Venken '22

$$|Q_3| > \frac{N_*}{3}(\ln N_* + 8.2 + \cdots) \qquad \text{with} \qquad N_* \sim g_s M^2/5\,.$$

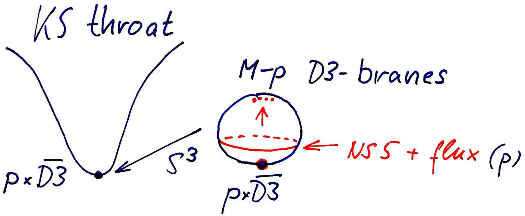
(For $g_s M^2$, metastability bounds of $12 \cdots 46$ have been discussed. See e.g. KPV, Bena et al., Blumenhagen et al. Scalisi et al., Lüst/Randall '22)

- However, things are actually more complicated....

NS5-brane curvature corrections

AH/Schreyer/Venken '22; Schreyer/Venken '22, Schreyer '23

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



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

- Estimating NS5-brane curvature corrections from known D5 results, one finds that control requires

$$g_s M \gtrsim 3.6 \,, \qquad g_s M^2 \gtrsim 150 \,,$$

making the above problems for KKLT/LVS even worse....

Cobordism and the Landscape

- Nevertheless, let's still be optimistic that some form of realistic landscape (not necessarily dS) will eventually be established.

  (My present favorite is F-term uplifting, along the line of Saltman/Silverstein ... Wrase at al. ... AH/Leonhardt ... Krippendorf/Schachner '23)

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

- Due to the cobordism conjecture, end-of-the-world branes are ubiquitous

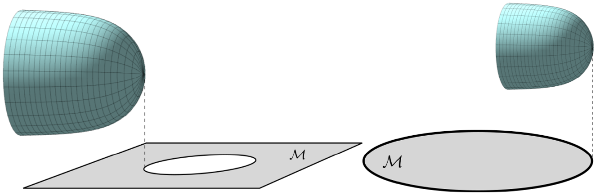
  McNamara/Vafa '19

- Studying their role in 'landscape dynamics' is important!

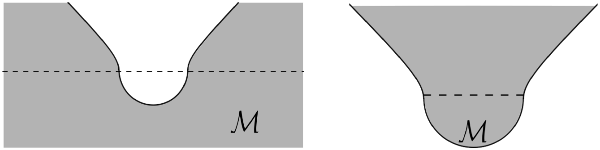
(Witten's) Bubble of Nothing/Something

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

- Euclidean:



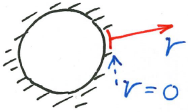
- Lorentzian:



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

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

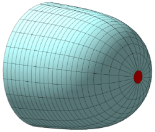
- Crucial: at $r \to 0$ we have $\varphi \to -\infty \,, \;\; f(r) \to 0 \,.$

- $\Rightarrow$ 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.

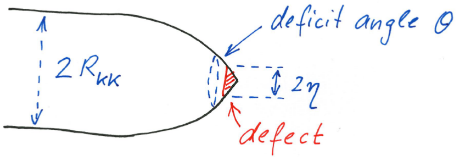
Our goal: Resolve this issue in a universally applicable way.



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:

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

(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

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

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

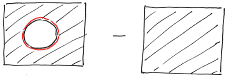
$$T_{4,\,\eta} = -\left(1 - \frac{\theta}{2\pi}\right)\frac{1}{\sqrt{2\pi\eta^3}}\,.$$

- 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.)

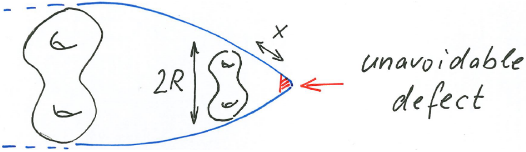
Bubble of nothing / ETW-brane – General case

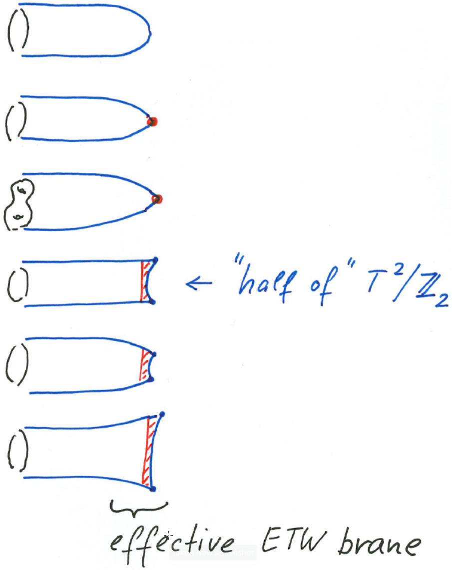
- Our 4d EFT approach can be easily generalized:

  – 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:

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





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

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

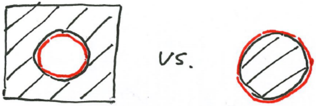
- The exponent for the corresponding bubble-of-nothing decay can be given explicitly in all these case.

- For expample, 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.



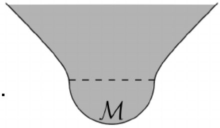
Bubble of something – a small detour

(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.

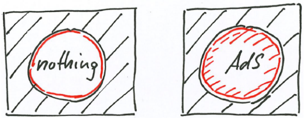
- Fundamental criticism has been raised based on an analogy to up-tunneling from AdS.
  Brown/Dahlen '98



- I want to spend some time to dismiss these concerns.

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.

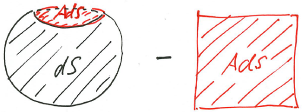
- Technically, one takes $\ell_{AdS} \to 0$ together with $T_{DW} \to \infty$, to recover precisely the ETW-brane result with finite

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

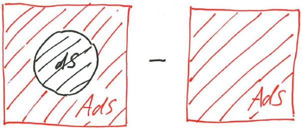
- This works analogously for the decay of dS to nothing or to AdS.

On the Brown-Dahlen argument (continued)

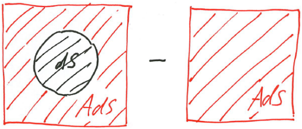
- B/D propose to use the same instanton for up-tunneling from AdS to dS, subtracting full AdS as a backround:



- 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:



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.

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.

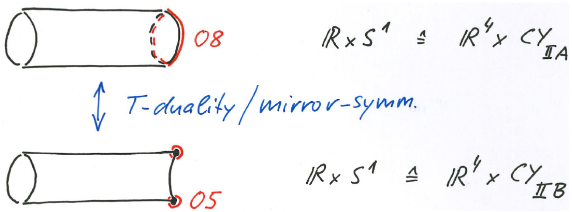
  – This allows for a straightforward calculation of 'tunneling exponents' for bubbles of something/nothing.

  (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:

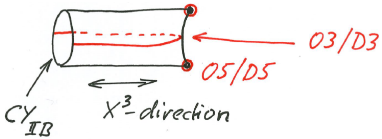


- Alternatively, one may get this by directly orientifolding $\mathrm{CY}_{\mathrm{IIB}}$:

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

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

- 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	$-X^3$	$-U^1$	$V^1-\pi$	$-U^2$	$V^2-\pi$	$-U^3$	$V^3-\pi$	$(-1)^{F_L}$

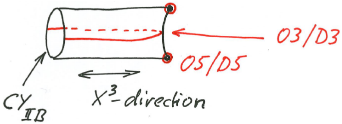
Table 1: Action of the two orientifold generators (of O3 and O5 planes) and of their product.

	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 $\mathrm{CY}_{\mathrm{IIB}}$-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

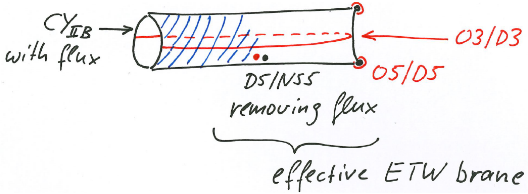
- However, 'detuned' (non-stationary) SUSY ETW branes appear to also be possible.

Bagger/Belyaev '02

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

ETW-brane with (non-SUSY) 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:

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

(also after 'uplifting')

- The decay/creation rates are:

Bubble of nothing:

$$\Gamma \sim e^{-B} \qquad \text{with} \qquad B = \frac{8\pi^2 M_P^6}{T_4^2} \sim \frac{(R_{KK} M_{10})^8}{\epsilon^2}$$

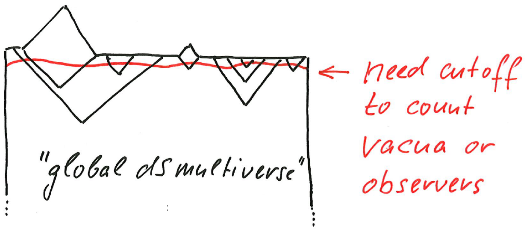
Bubble of something:

$$\Gamma \sim e^{-B} \qquad \text{with} \qquad B = \mp\frac{8\pi^2 M_P^6}{T_4^2} \sim \mp\frac{(R_{KK} M_{10})^8}{\epsilon^2}$$

... 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 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 fundemantal, quantum-mechanical measure.

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

Towards a 'Quantum-Measure'

- Cosmological Central Dogma:

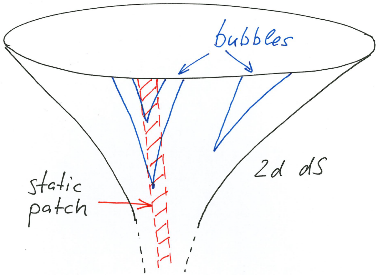
  dS space is a finite system with $\dim(\mathcal{H}) = e^S$.

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

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

  $H\psi = \chi$

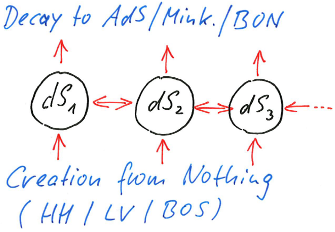
- Crucially, a source term for the creation from nothing is unavoidable.



The ‘Local Wheeler-DeWitt Measure’

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

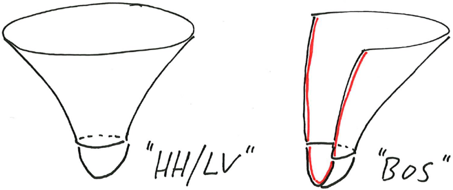
- Formally, we have $H\psi = \chi$,
  with the probability for vacuum dS_i given by $p_i = \left\| \psi|_i \right\|^2$.
- In practice, this reduces to rate equations for a
  ‘flow through the landscape’:



The outcome is similar to certain ‘local measures’,
cf. Garriga/Vilenkin/... ’05...’11, Nomura ’11, Hartle/Hertog ’16

'Local Wheeler-DeWitt Measure' – Importance of ETW brane

- Key point in our context:
  - No late-time attractor.
  - Creation from nothing is needed.
  - Creation rates directly affect predictions.



$\Rightarrow$ $\Gamma \sim e^{\pm 24\pi^2 M_P^4/\Lambda}$ Hartle-Hawking / Linde-Vilenkin

$\Gamma \sim e^{\pm 8\pi^2 M_P^6/T^2}$ Bubble-of-something rate

- For example, if the Linde-Vilenkin sign is right and positive-tension branes are easier to get than high-Λ dS, then the "BOS" will dominate!

Summary / Conclusions

- Predictions in the landscape need a measure.
  I argued that, in a proper quantum approach, this is sensitive to 'Creation from Nothing' processes.
- This is even more so if there is no de Sitter and quintessence-type potentials rule the landscape.
- Given the Cobordism Conjecture, a key ingredient in these creation processes are ETW branes, allowing for 'BOS's.
- We derived a 4d EFT approach for obtaining ETW effective tensions (accepting the singular shrinkage of the compact space and using a generalized deficit angle).
- We suggested a concrete O5-plane-based ETW brane for the type-IIB landscape. Its tension is a worthy research target!