The Landscape and the Swampland: Searching for Consistent Universes

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III ICTEA Research Days - 2026

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Contents

Contents

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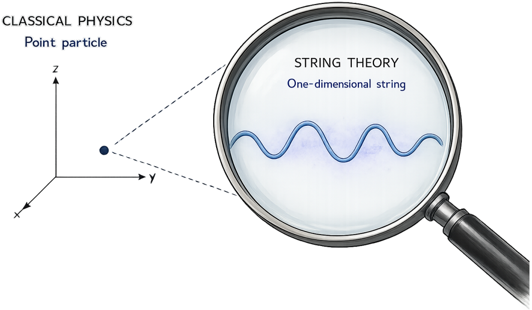

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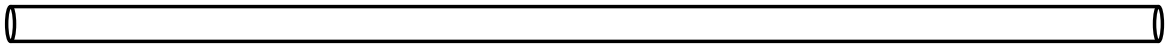

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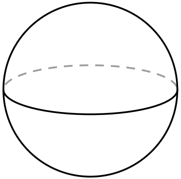

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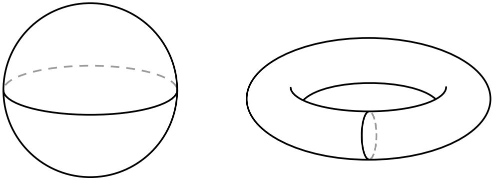

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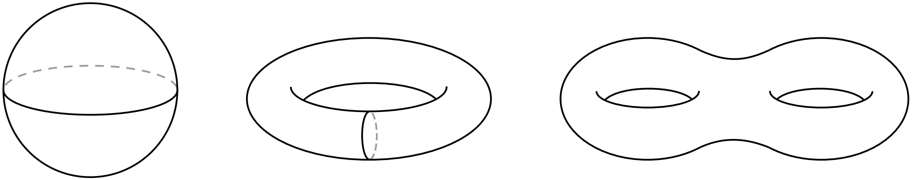

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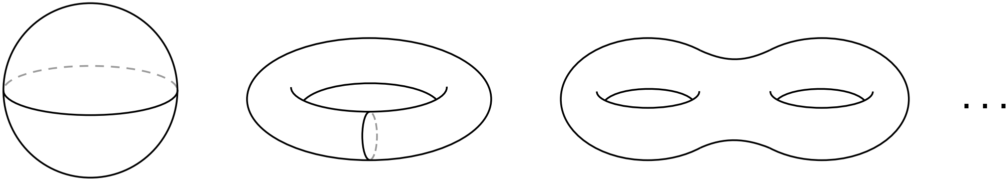

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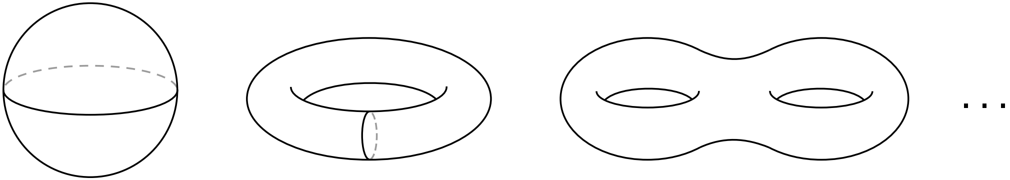

- The number of possible compactifications $10\mathrm{d} \to 4\mathrm{d}$ is vast, leading to a large set of consistent low-energy theories. These effective theories arising from string theory (quantum gravity) are known as the **Landscape**.

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- They are motivated by string theory, but they are expected to hold in any consistent theory of quantum gravity.
- They have been tested in many different setups, but they are still conjectures, they are not proven yet (dealing with quantum gravity is very hard).

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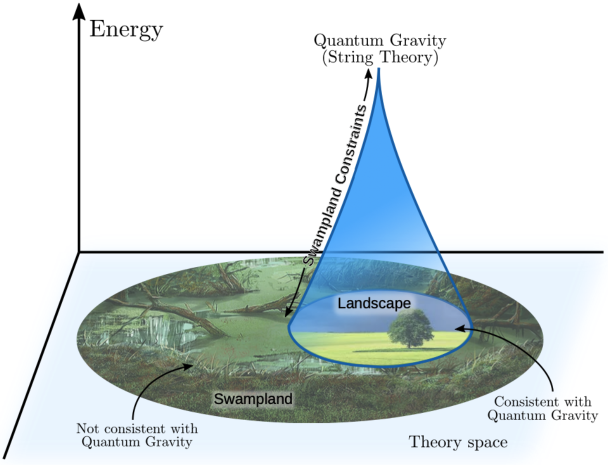

Figure: [van Beest et al., 2022].

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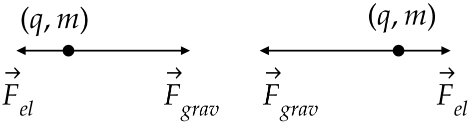

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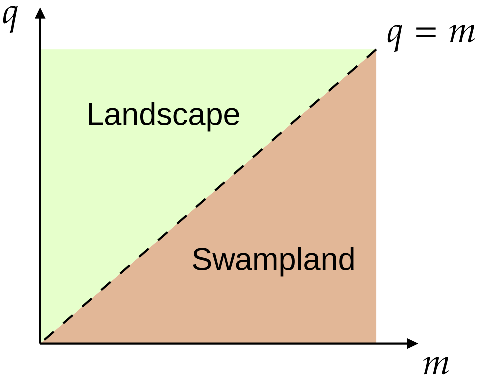

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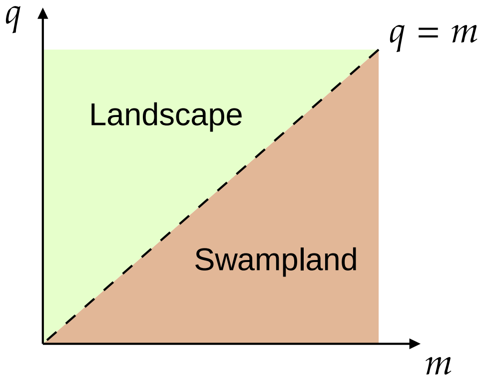

We conclude that in order to be in the Landscape, the mass should depend on the charge:

$$m = m(q) = m_n(g)$$

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The Swampland Distance Conjecture [`Ooguri & Vafa, 2006`]

At infinite distance in moduli space $\{\vec{\phi}\}$, an infinite tower of states becomes exponentially light as

$$m_n(\vec{\phi}) \xrightarrow[|\vec{\phi}|\to\infty]{} ne^{-|\vec{\phi}|}$$

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  - **Testing Global Robustness:** Validating the SDC not just in simple limits, but across complex arrangements of the moduli space.
  - **Sliding Towers:** Observing how a rich structure for the towers (sliding) emerges throughout the moduli space, while still satisfying the conjectures.

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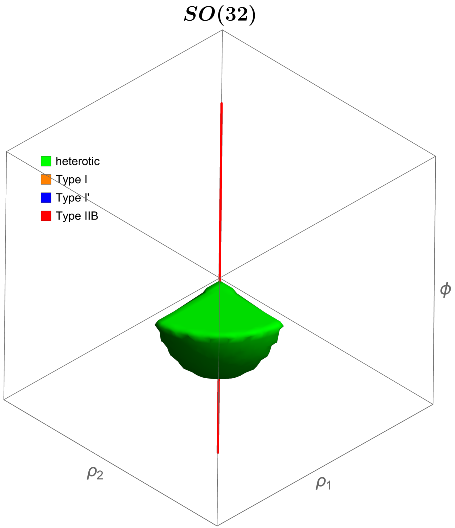
The **moduli space** of heterotic string theory on a 2-torus: the dilaton and two radii.



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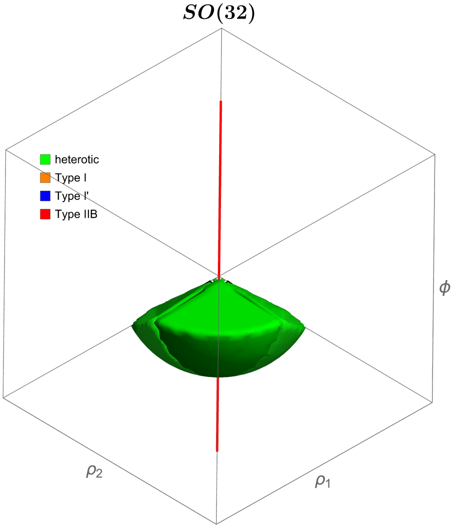

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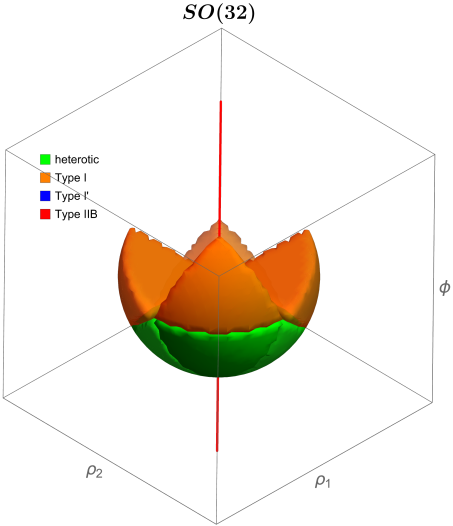

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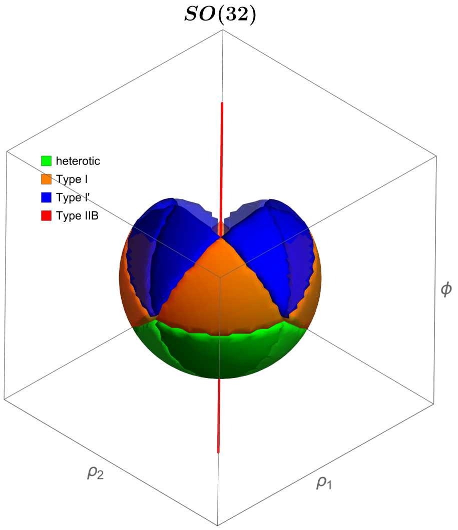

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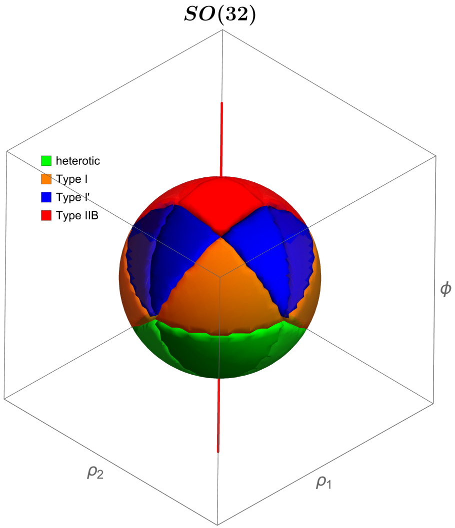

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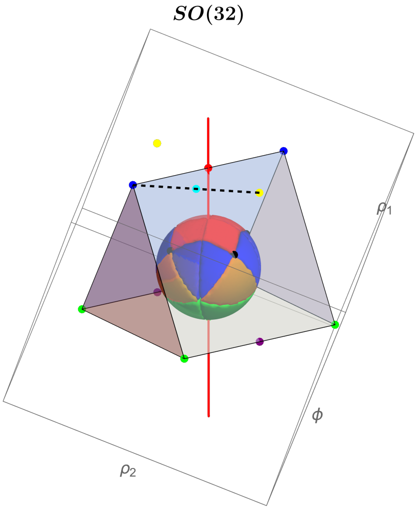
The SDC at work: Light towers of states.



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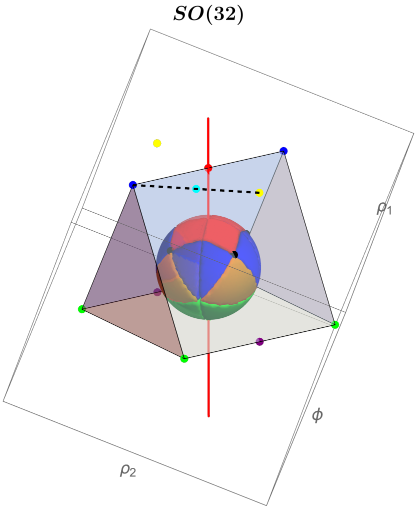

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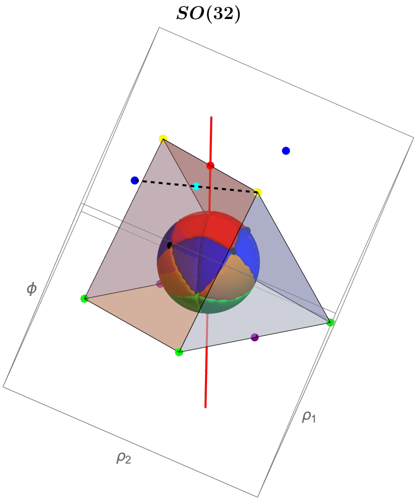

Contents

1. String Theory and the Swampland Program
2. Some Swampland Conjectures
3. **Conclusions**
4. Bibliography

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- We work on **testing** and **sharpening** these conjectures.

The End

`Thank you for your attention!`

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Contents

References I

[1] Nima Arkani-Hamed et al. “The String landscape, black holes and gravity as the weakest force”. In: *JHEP* 0706 (2007), p. 060. DOI: `10.1088/1126-6708/2007/06/060`. arXiv: `hep-th/0601001 [hep-th]`.

[2] Marieke van Beest et al. “Lectures on the Swampland Program in String Compactifications”. In: *Phys. Rept.* 989 (2022), pp. 1–50. DOI: `10.1016/j.physrep.2022.09.002`. arXiv: `2102.01111 [hep-th]`.

[3] Muldrow Etheredge et al. “Running decompactification, sliding towers, and the distance conjecture”. In: *JHEP* 12 (2023), p. 182. DOI: `10.1007/JHEP12(2023)182`. arXiv: `2306.16440 [hep-th]`.

[4] Hirosi Ooguri and Cumrun Vafa. “On the Geometry of the String Landscape and the Swampland”. In: *Nucl.Phys.* B766 (2007), pp. 21–33. DOI: `10.1016/j.nuclphysb.2006.10.033`. arXiv: `hep-th/0605264 [hep-th]`.