Apocalyptic quantum gravity

David Wakeham

UBC Gravity Seminar

April 28, 2021

Why care about quantum gravity?

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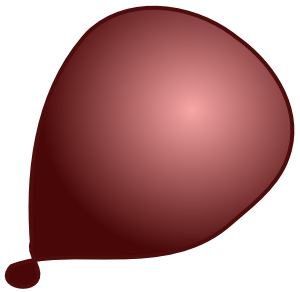

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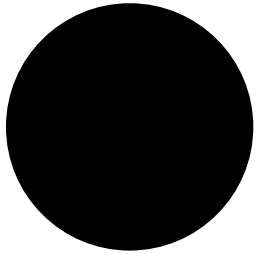

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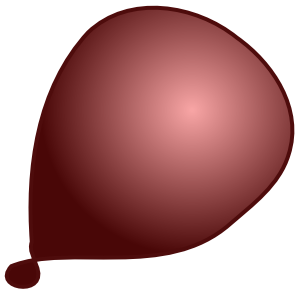

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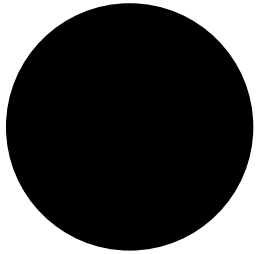

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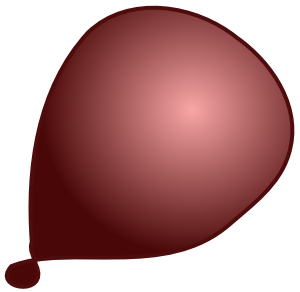

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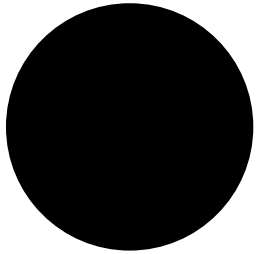

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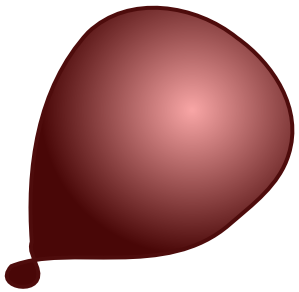

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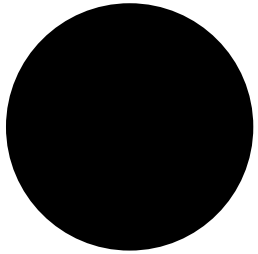

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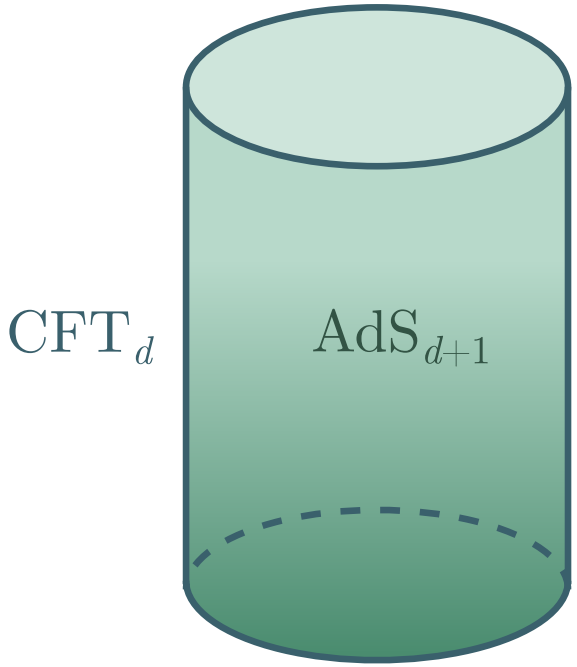

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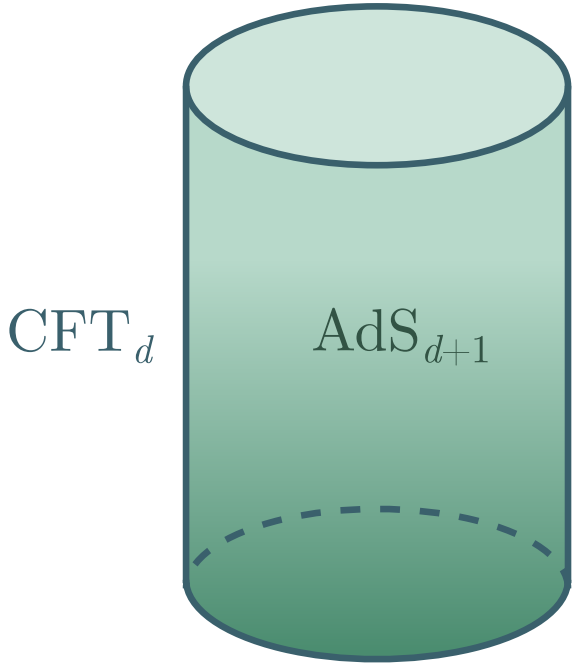

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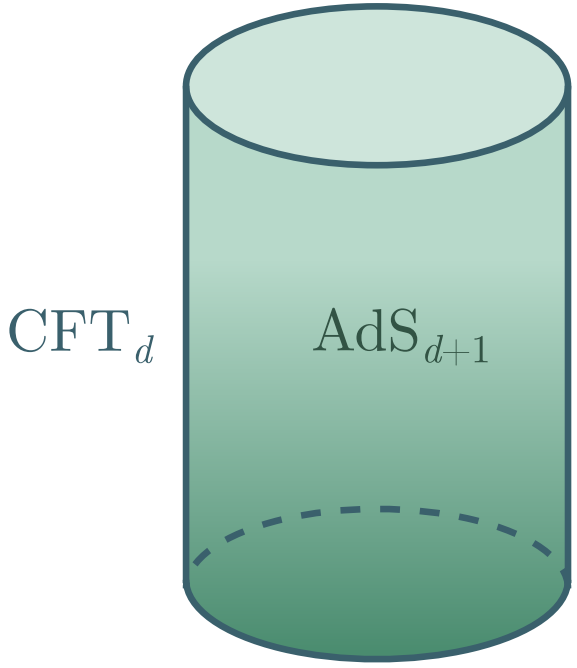

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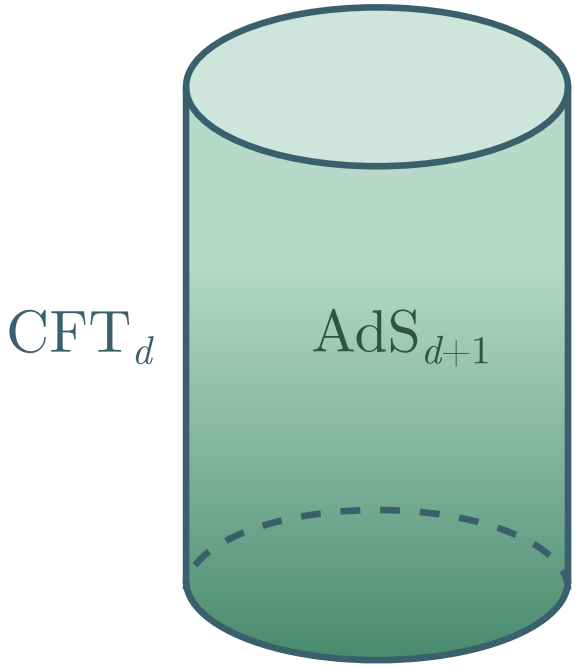

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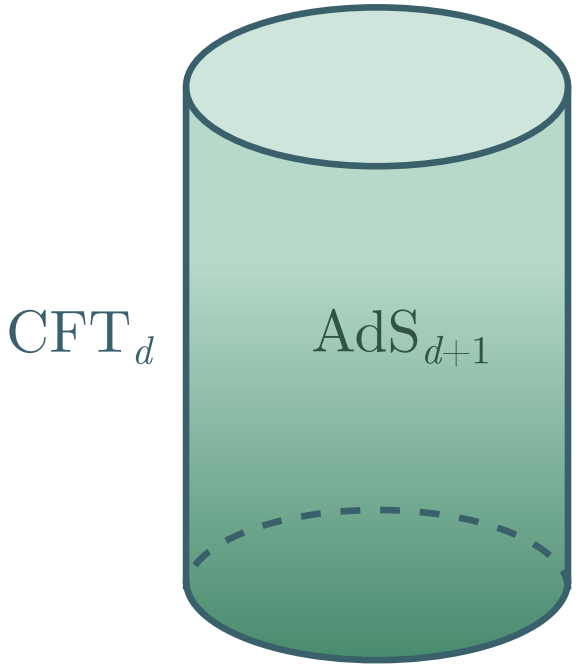

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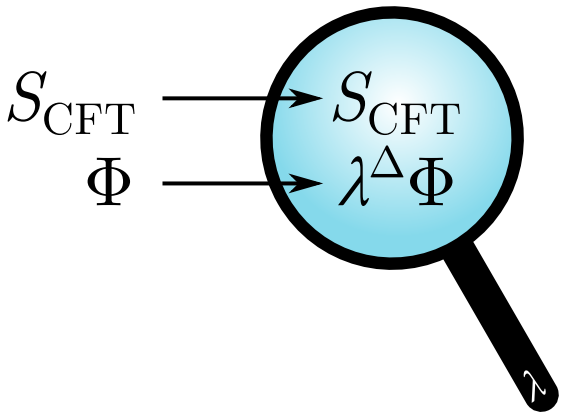

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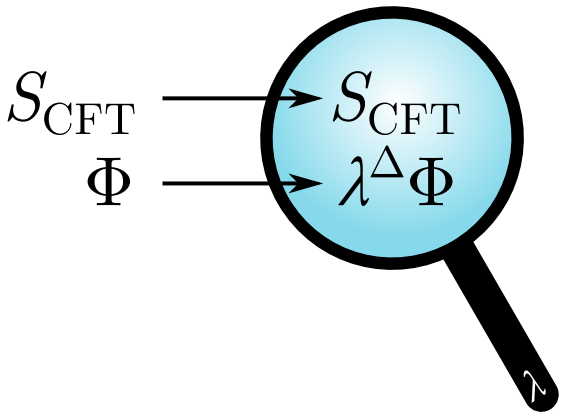

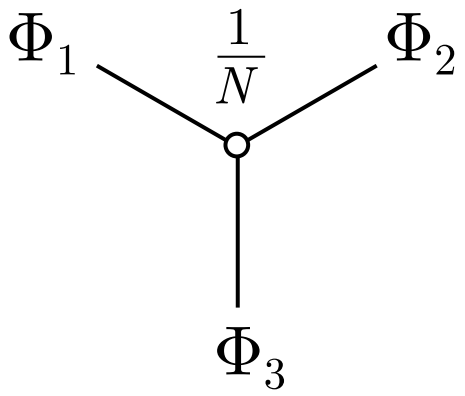

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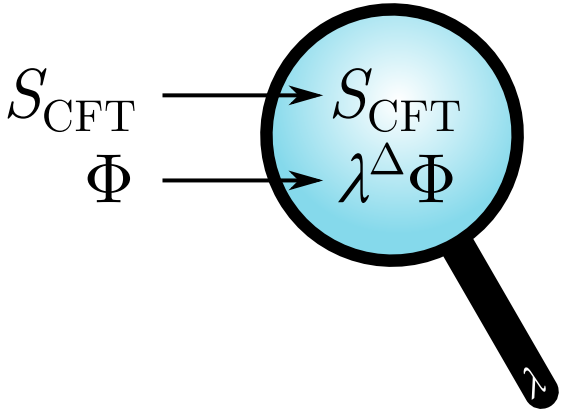

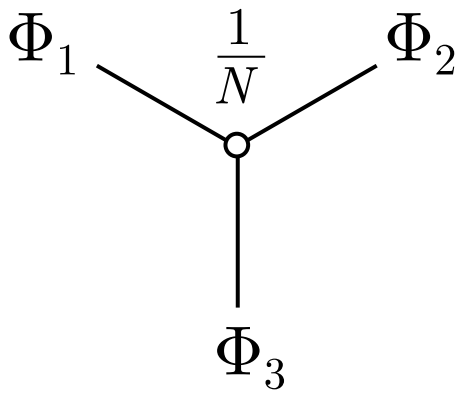

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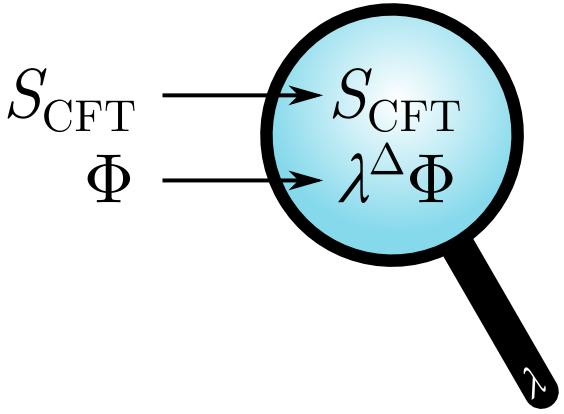

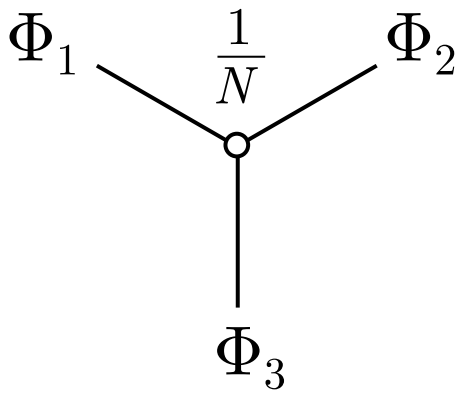

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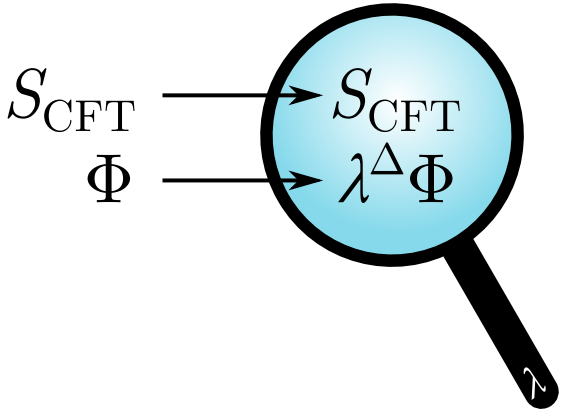

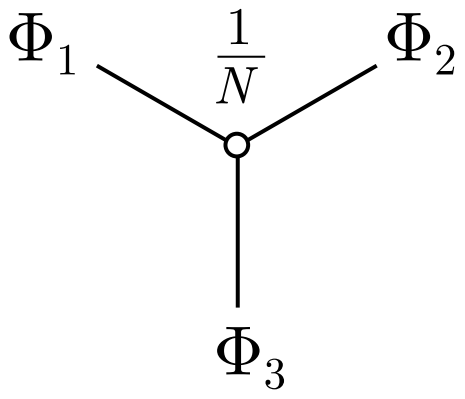

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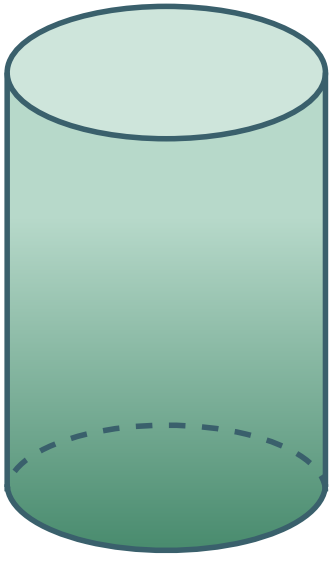

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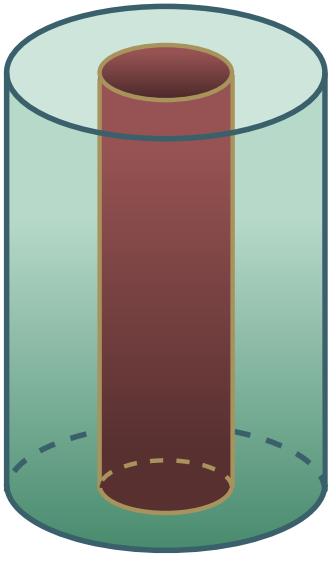

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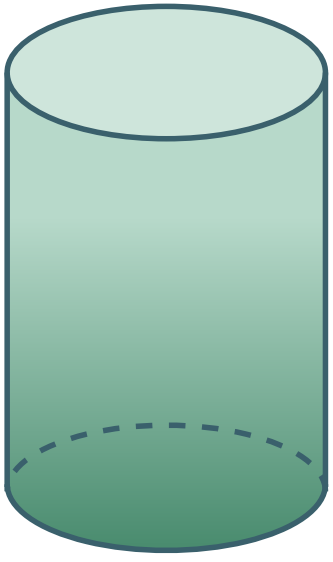

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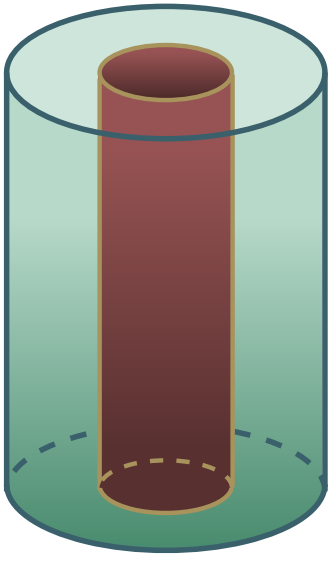

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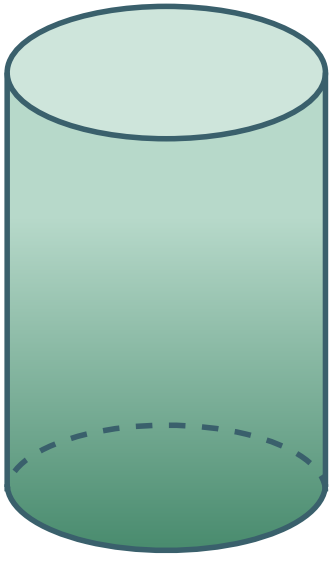

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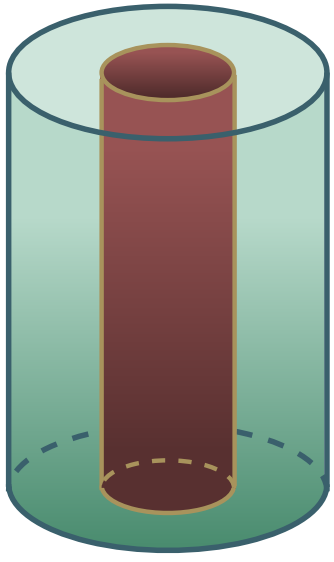

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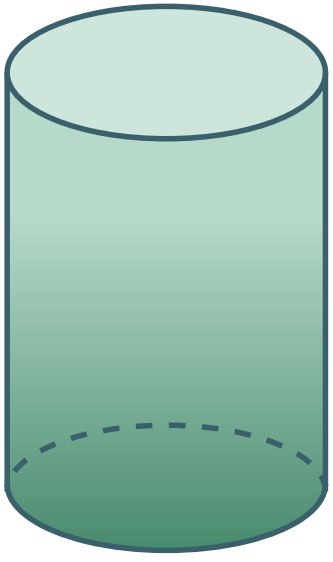

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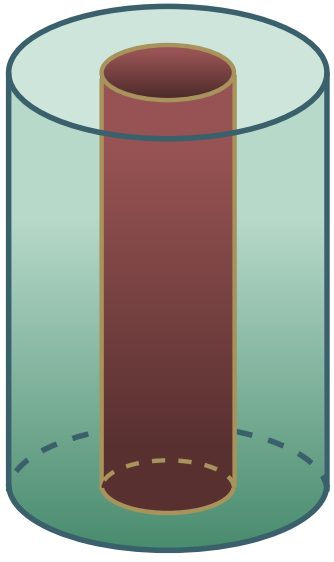

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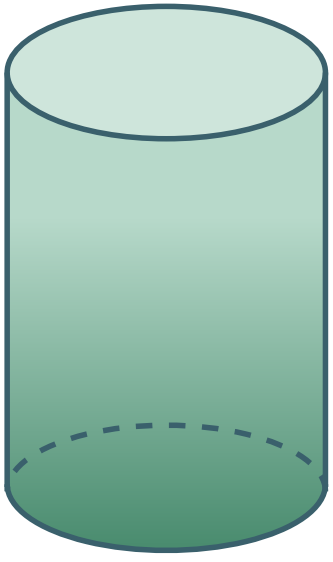

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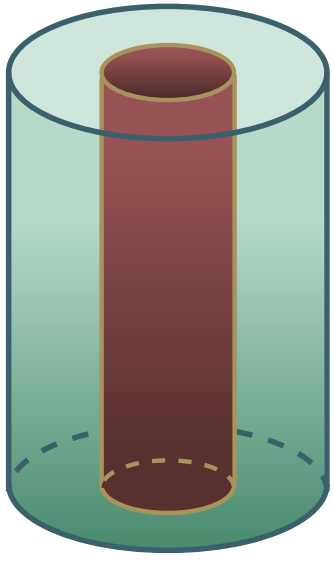

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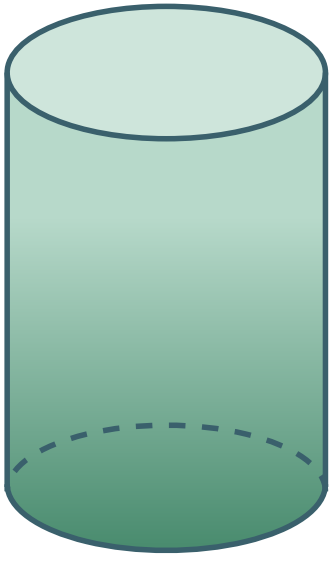

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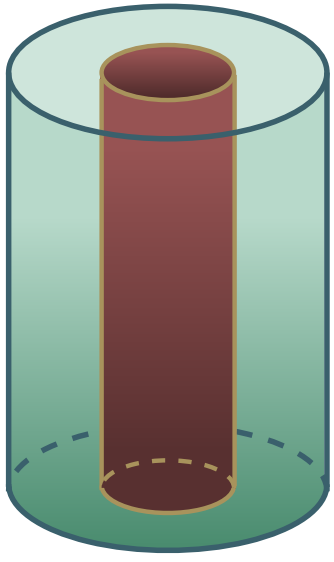

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- This turns out to be dual to an AdS black hole![3]

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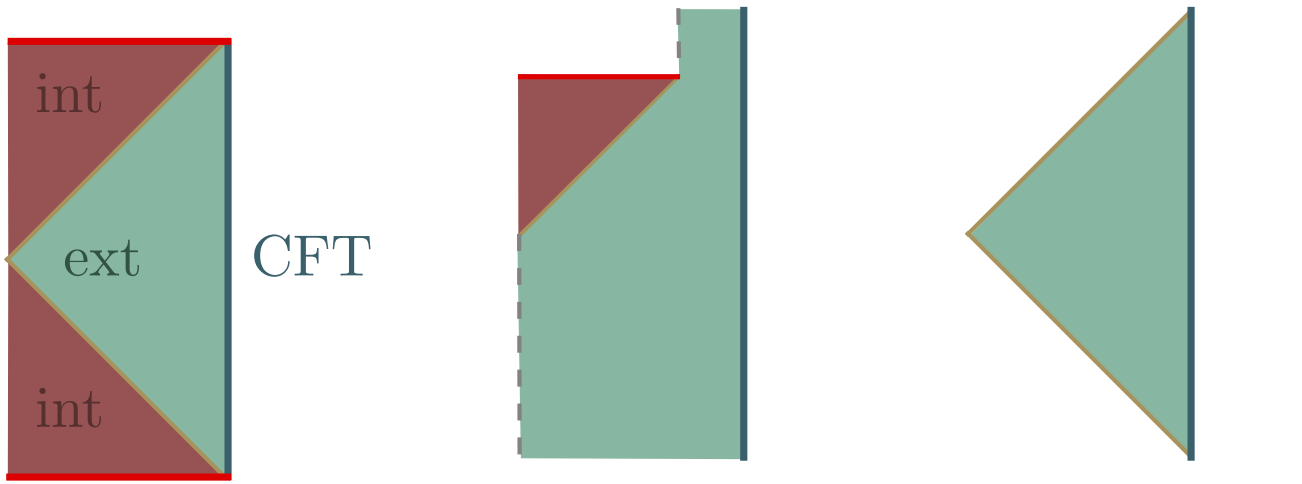

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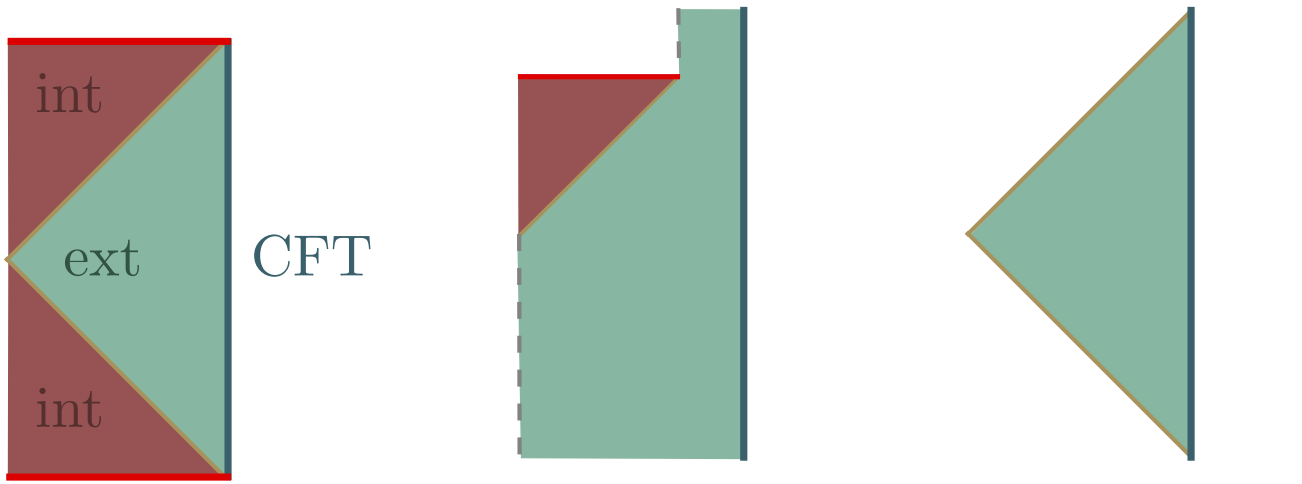

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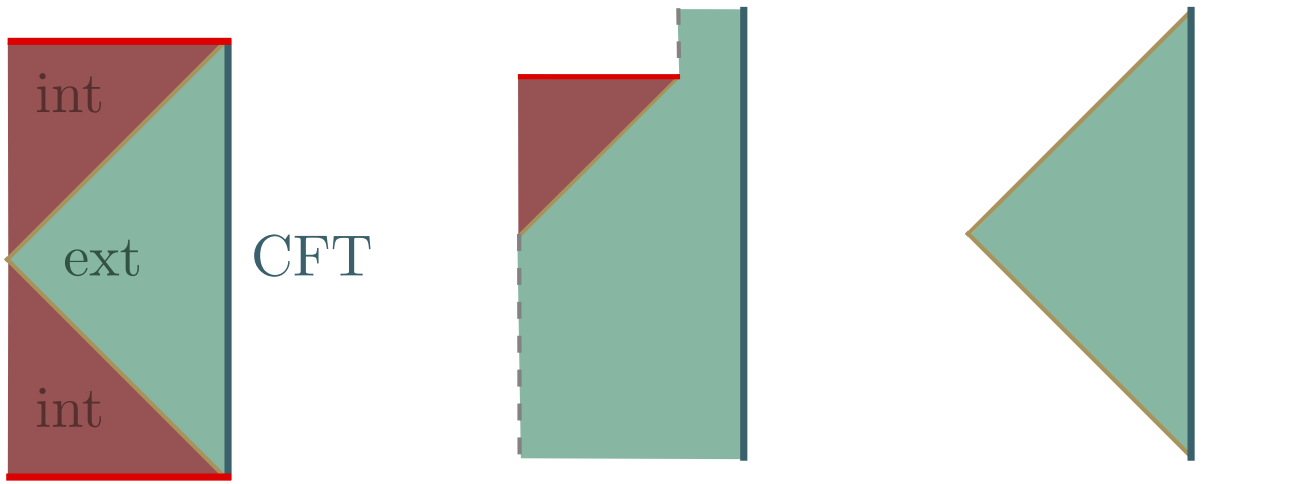

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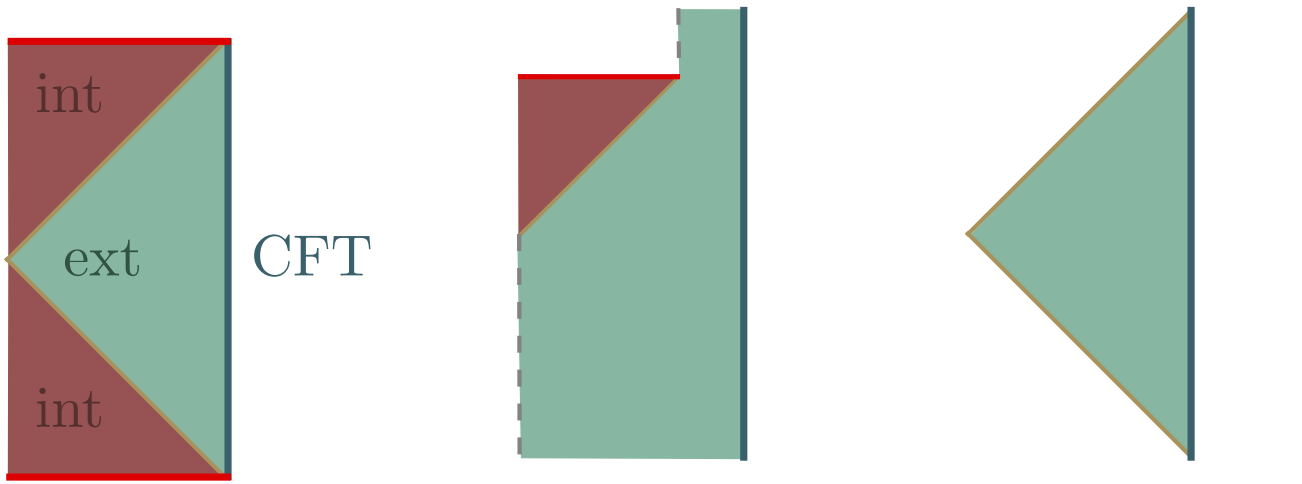

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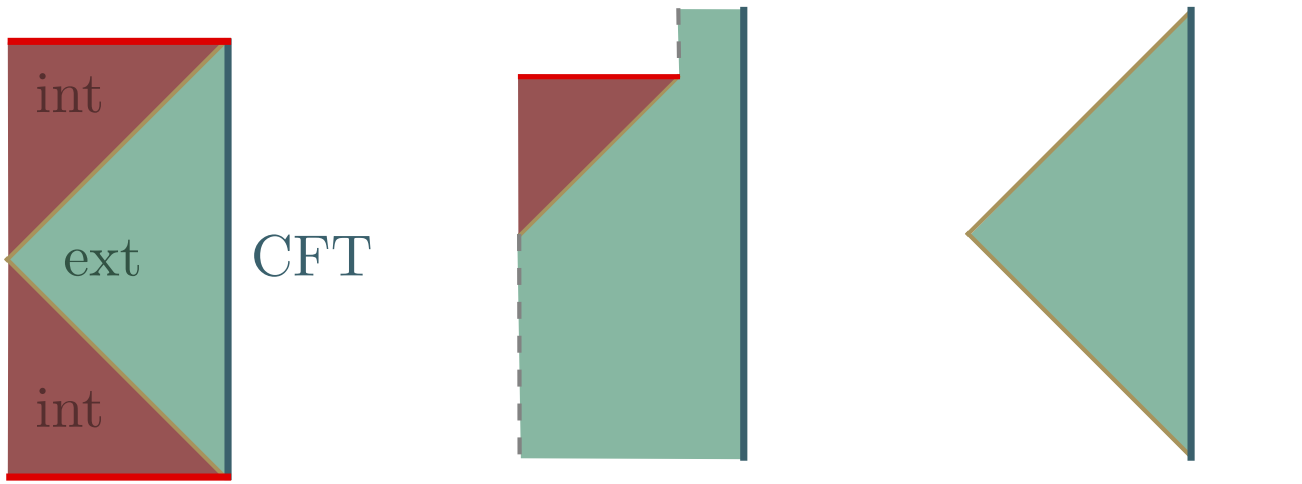

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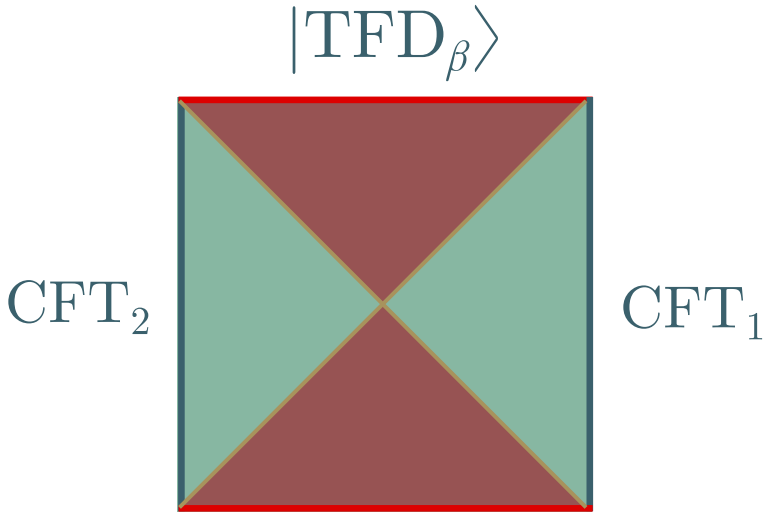

$$\rho_\beta = \mathrm{Tr}_2\left[|\mathrm{TFD}_\beta\rangle\langle\mathrm{TFD}_\beta|\right]$$

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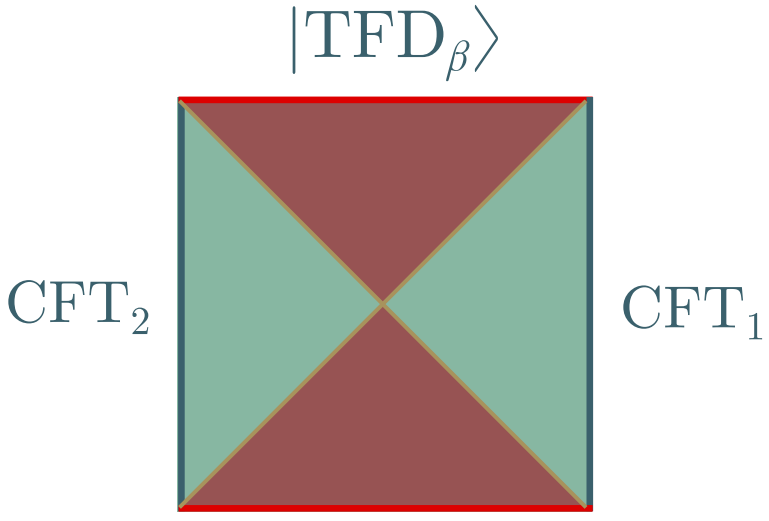

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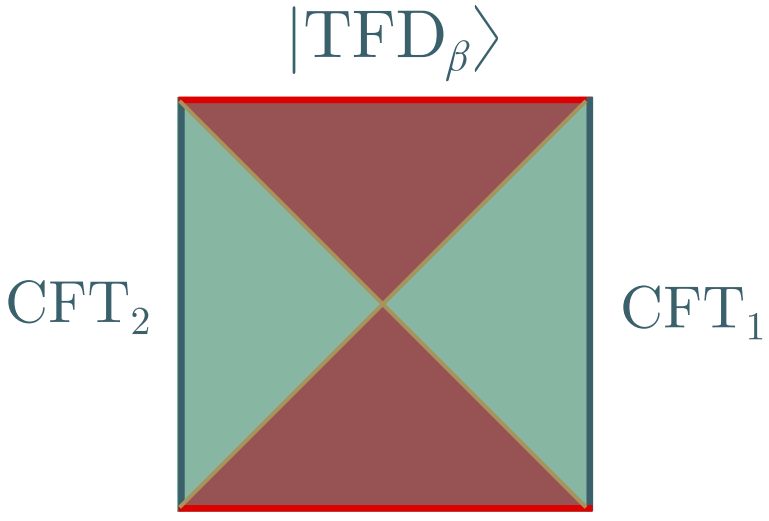

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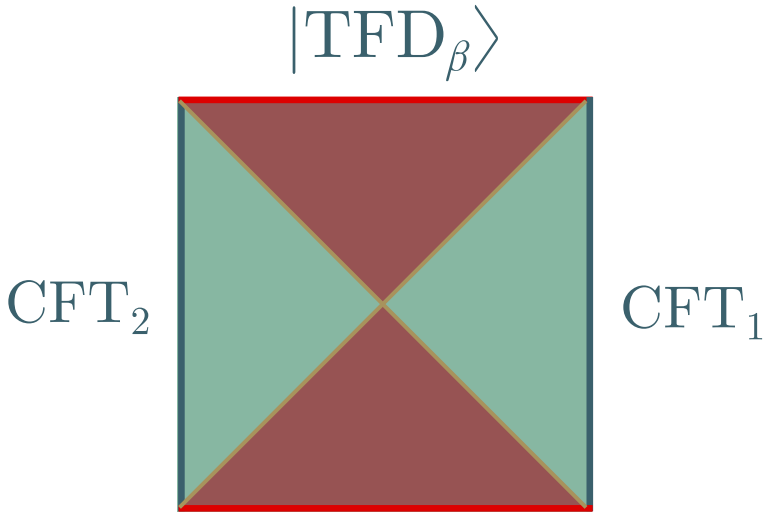

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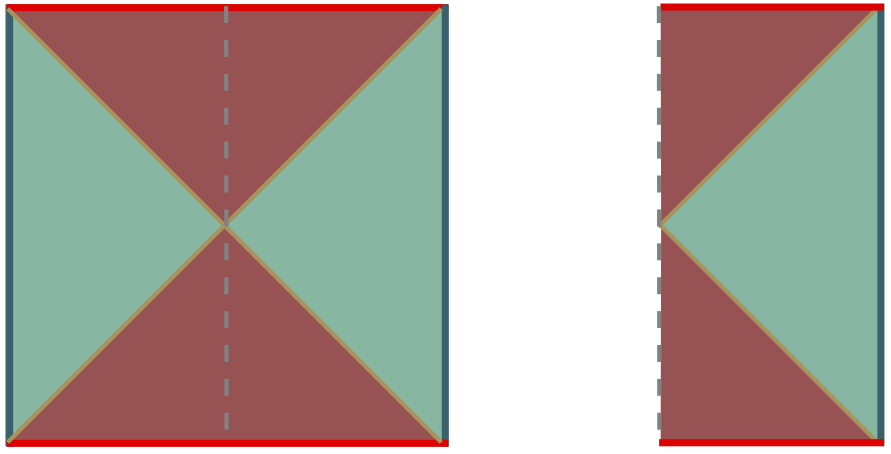

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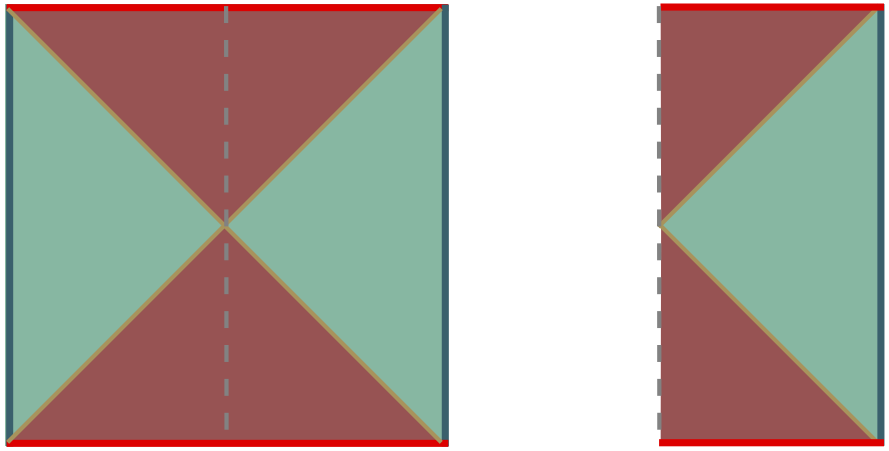

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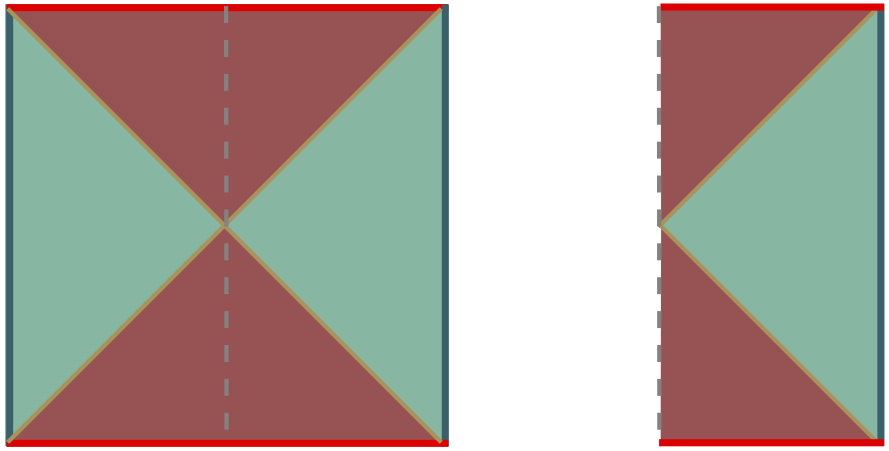

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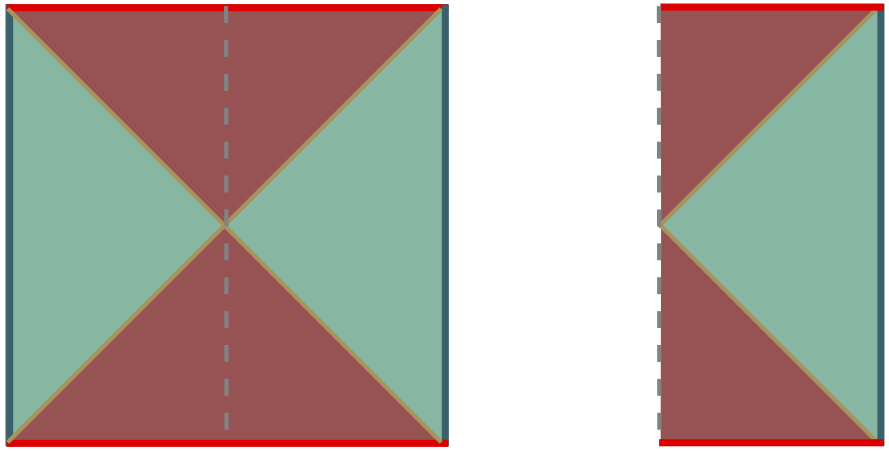

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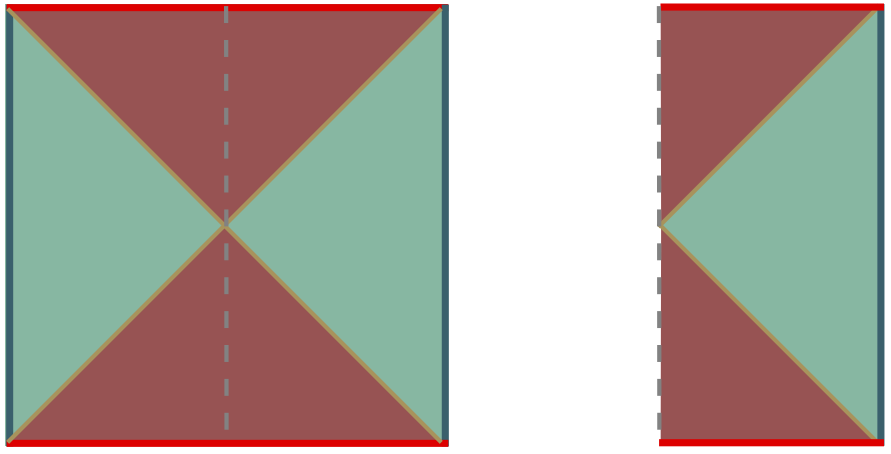

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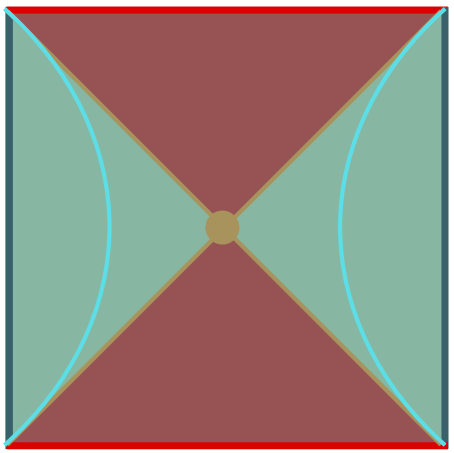

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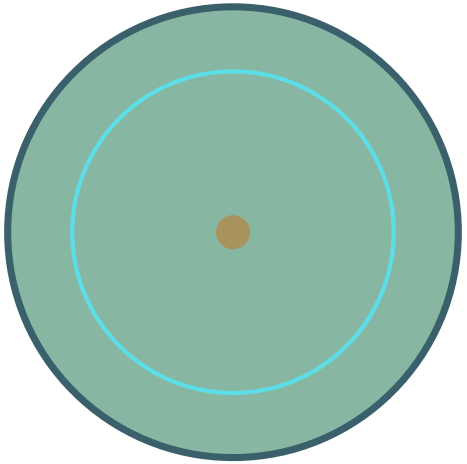

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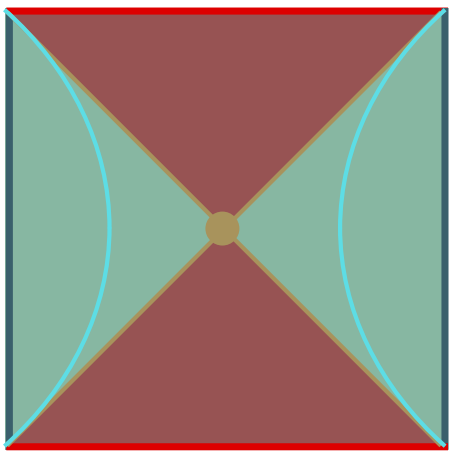

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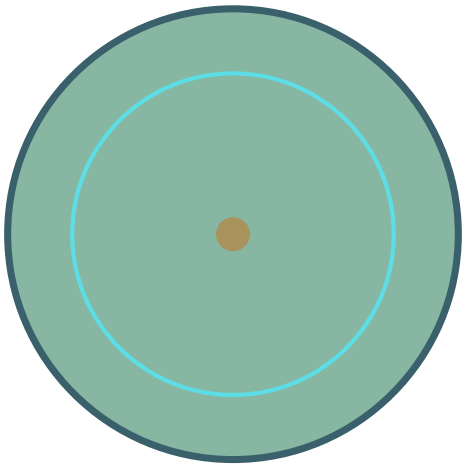

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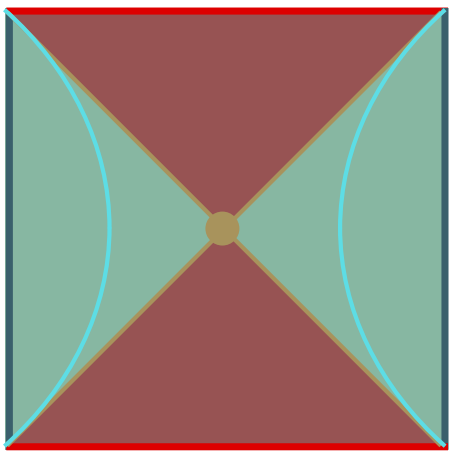

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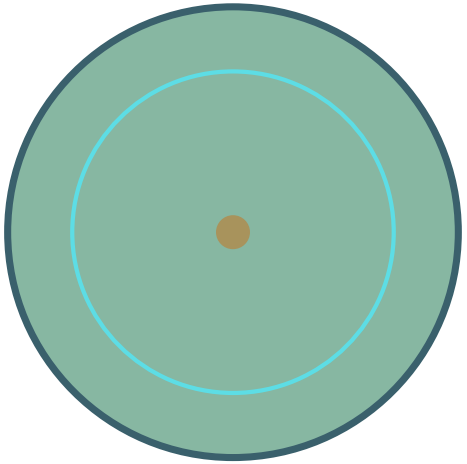

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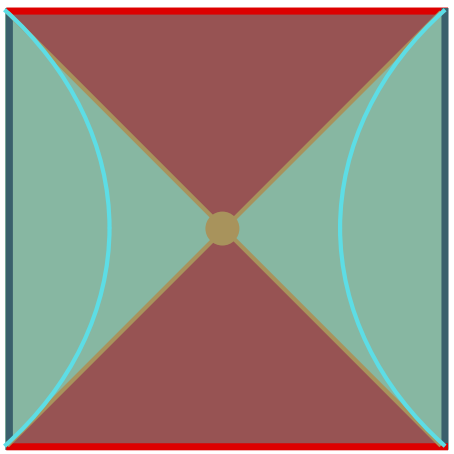

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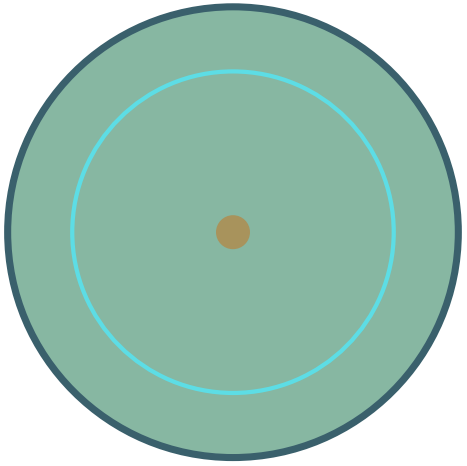

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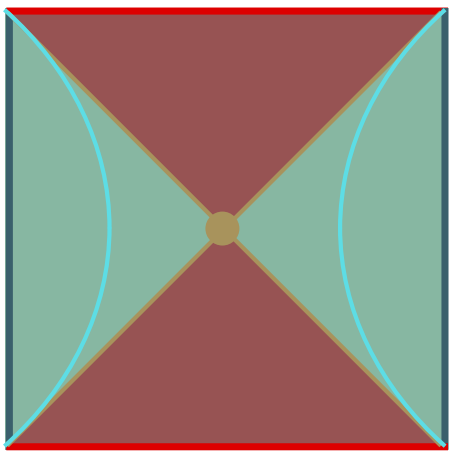

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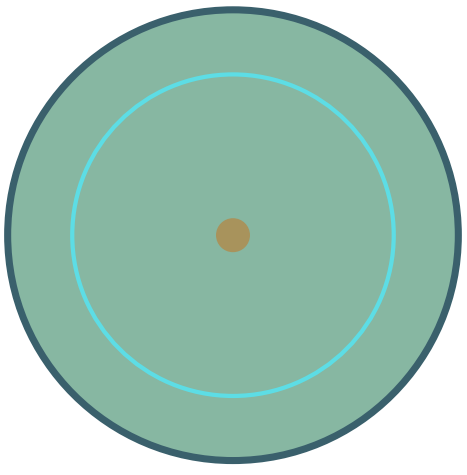

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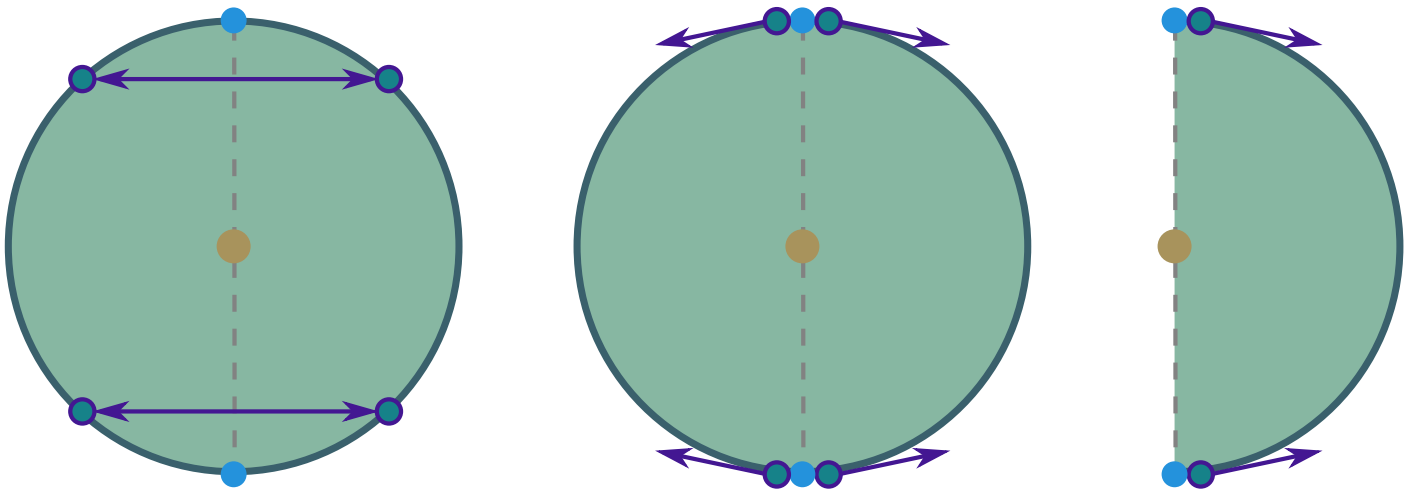

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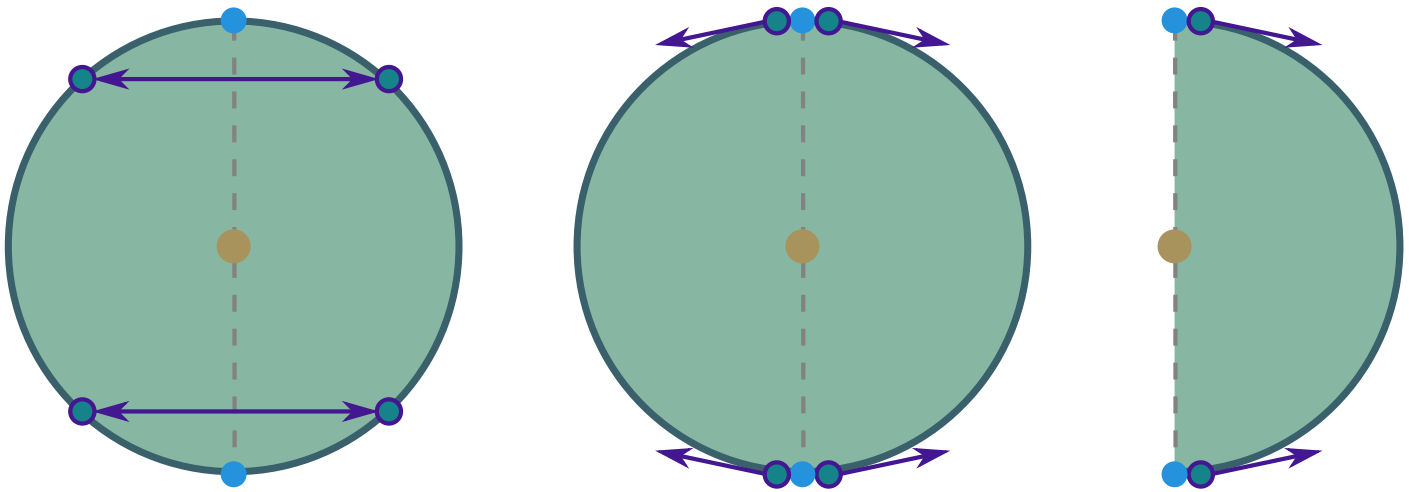

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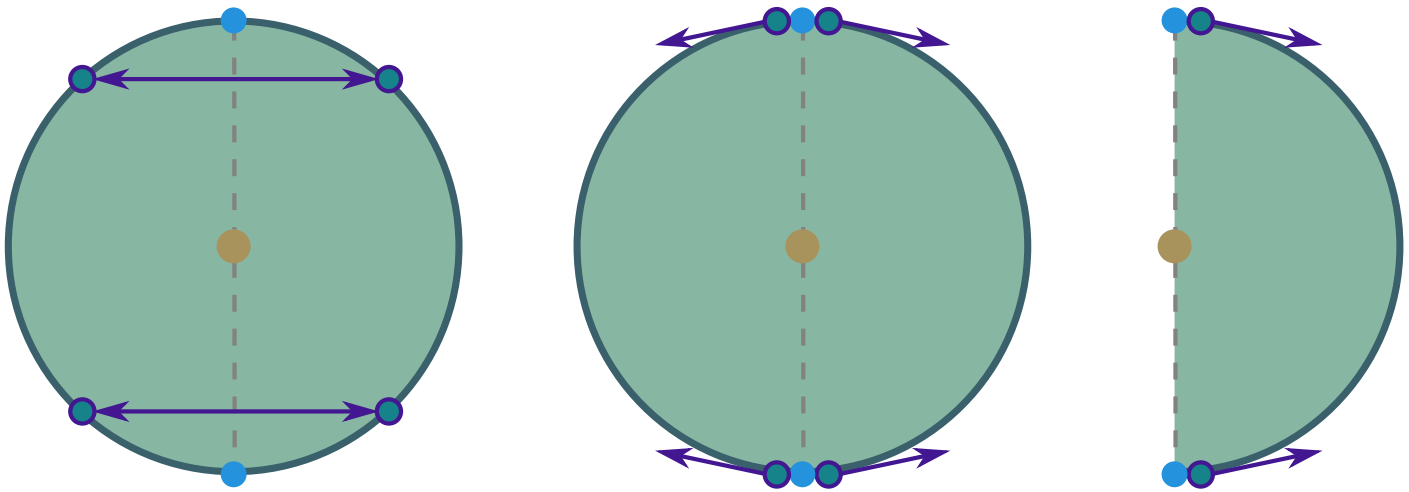

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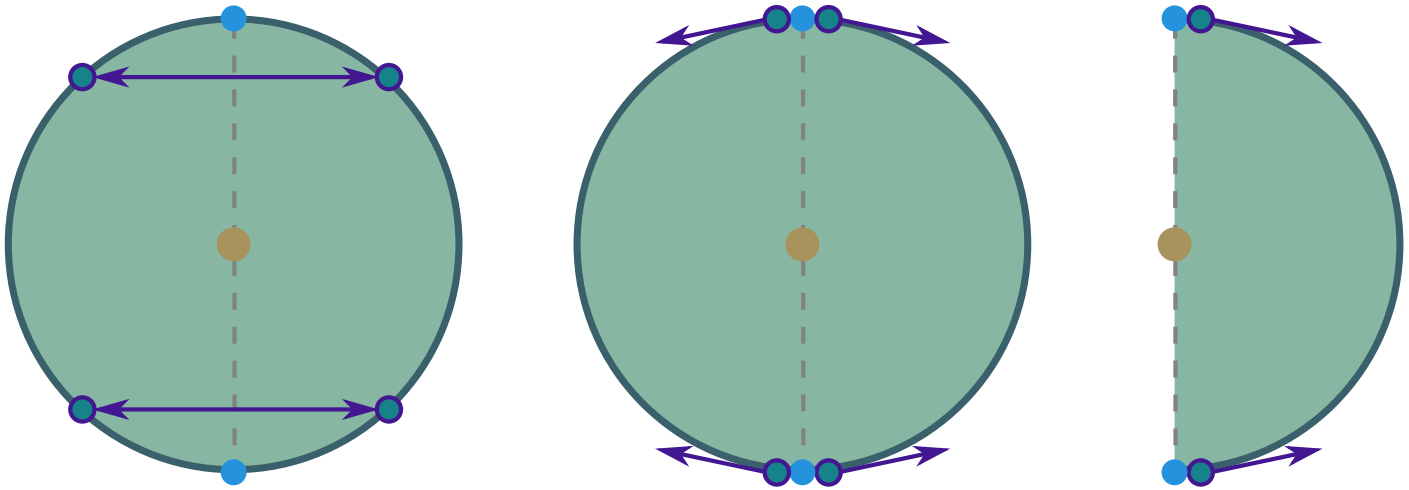

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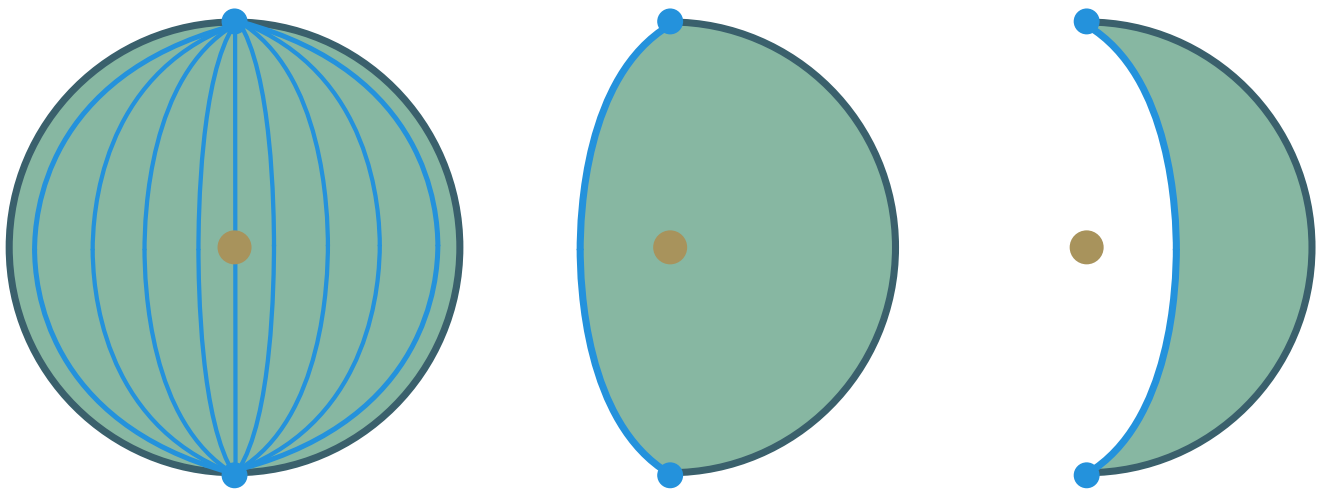

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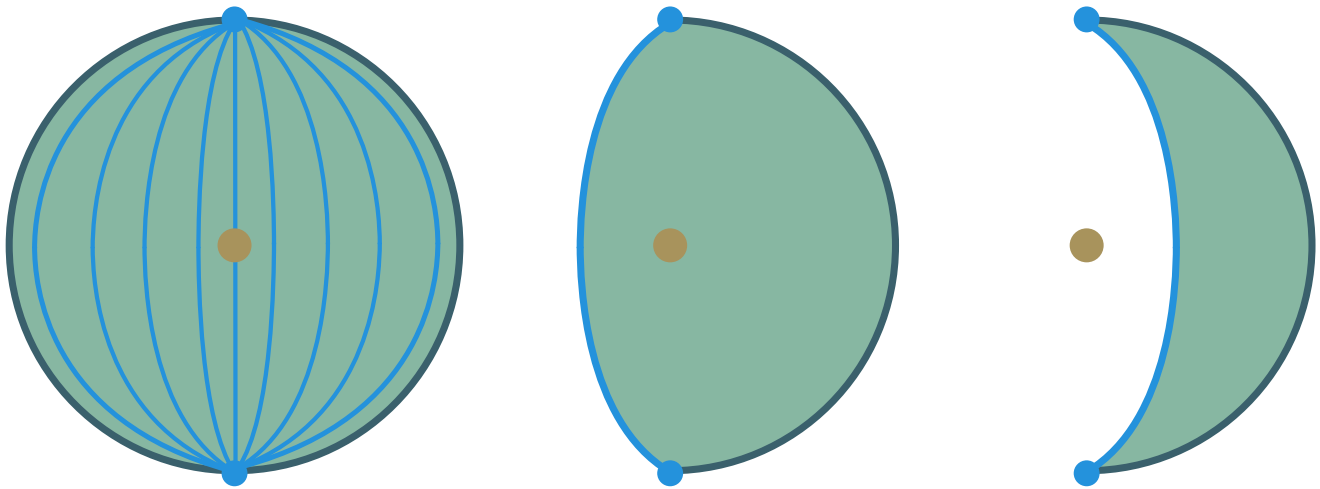

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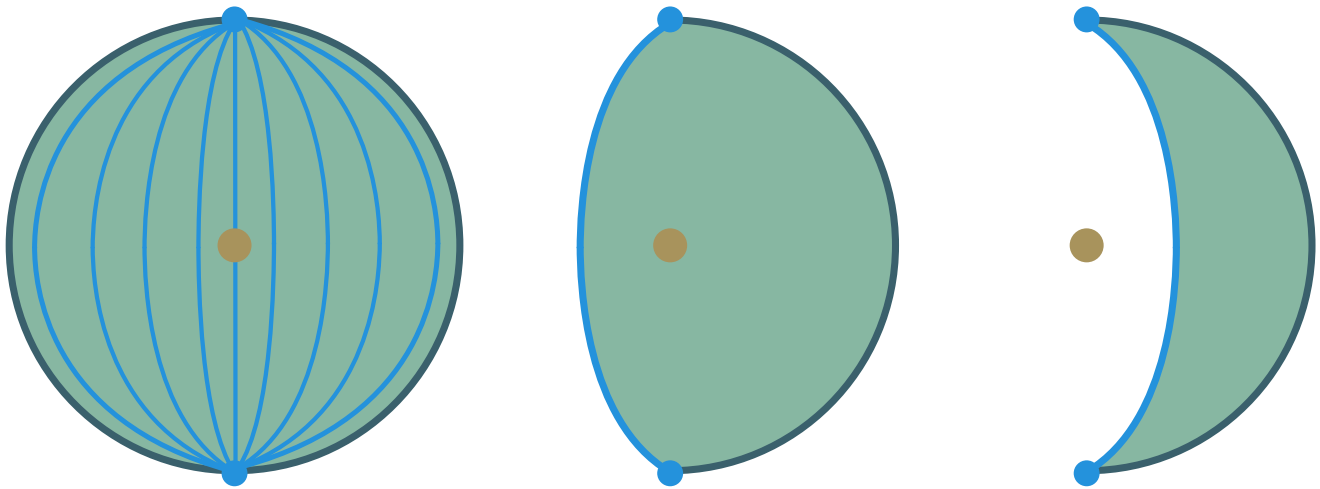

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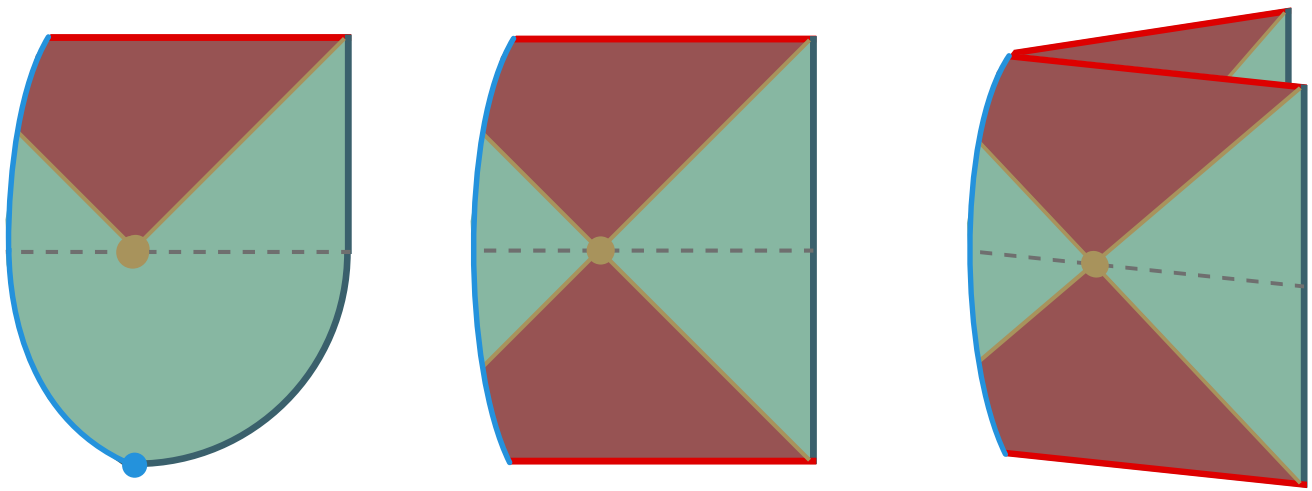

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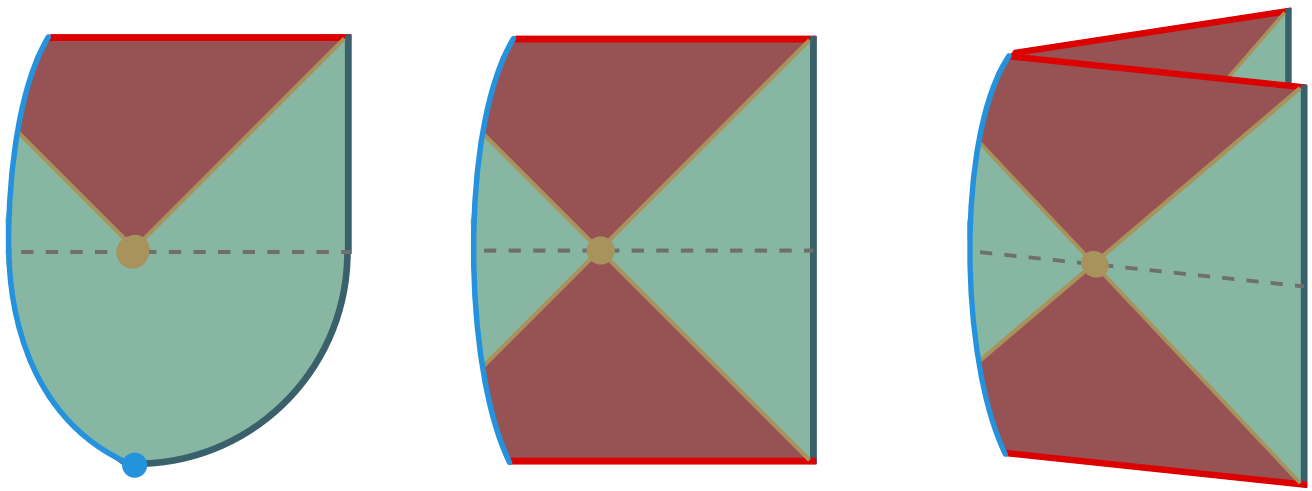

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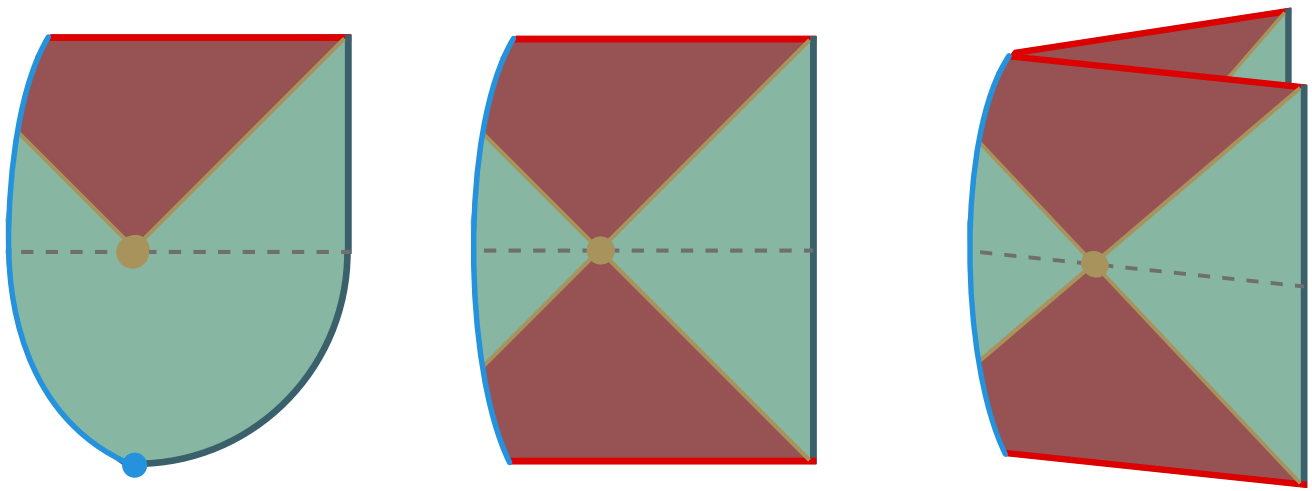

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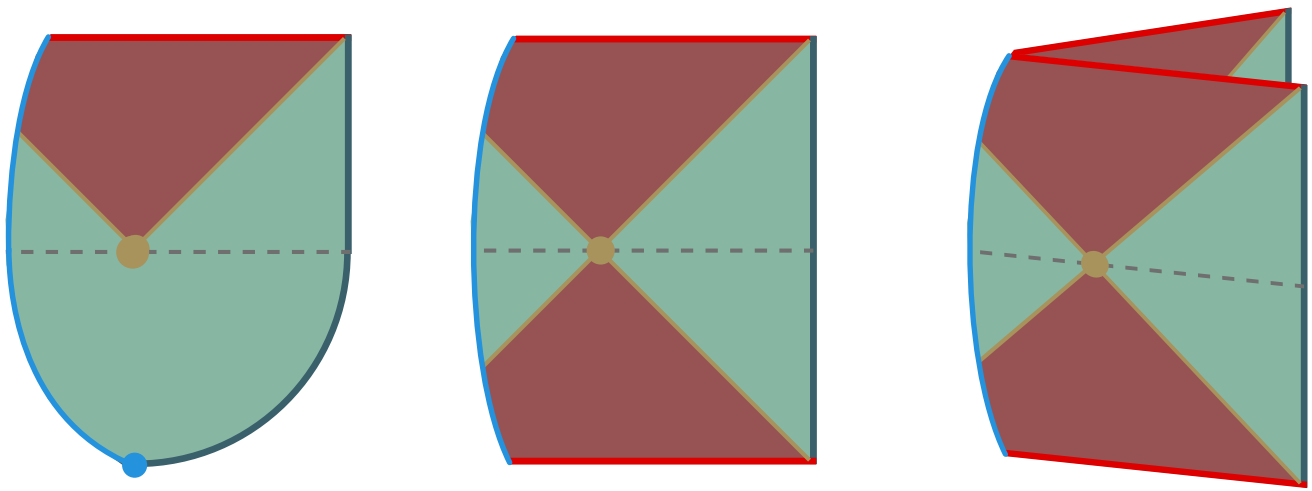

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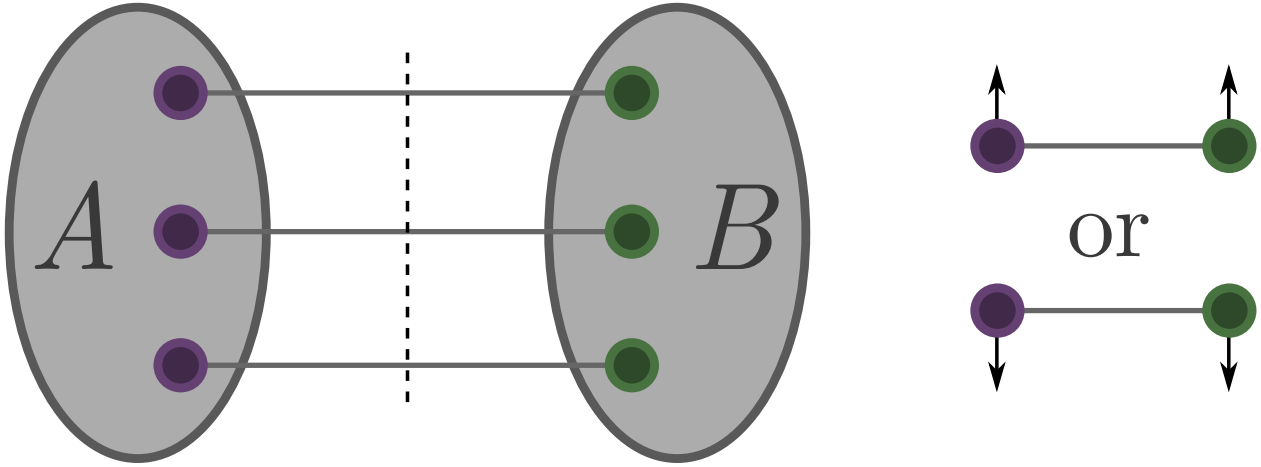

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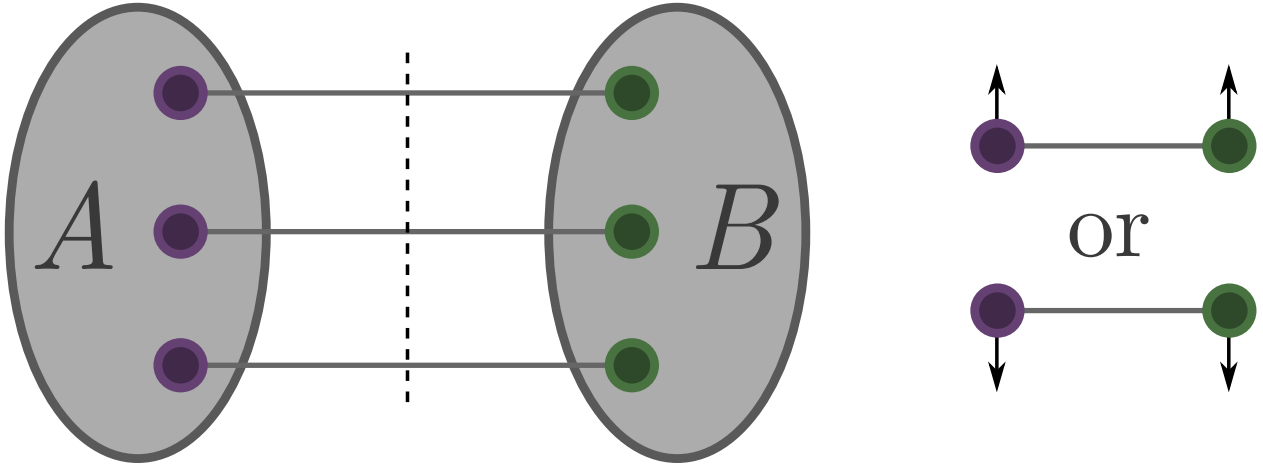

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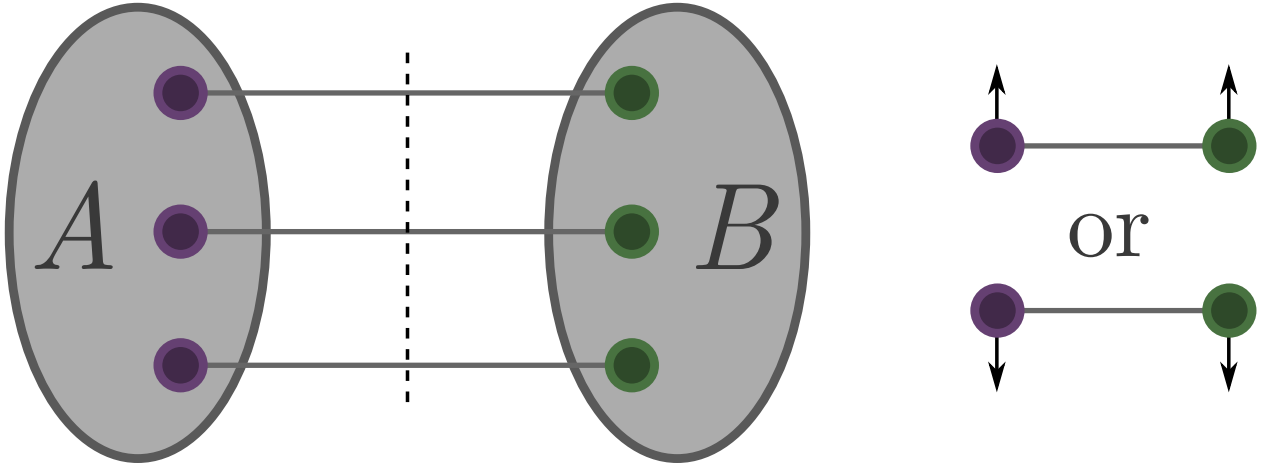

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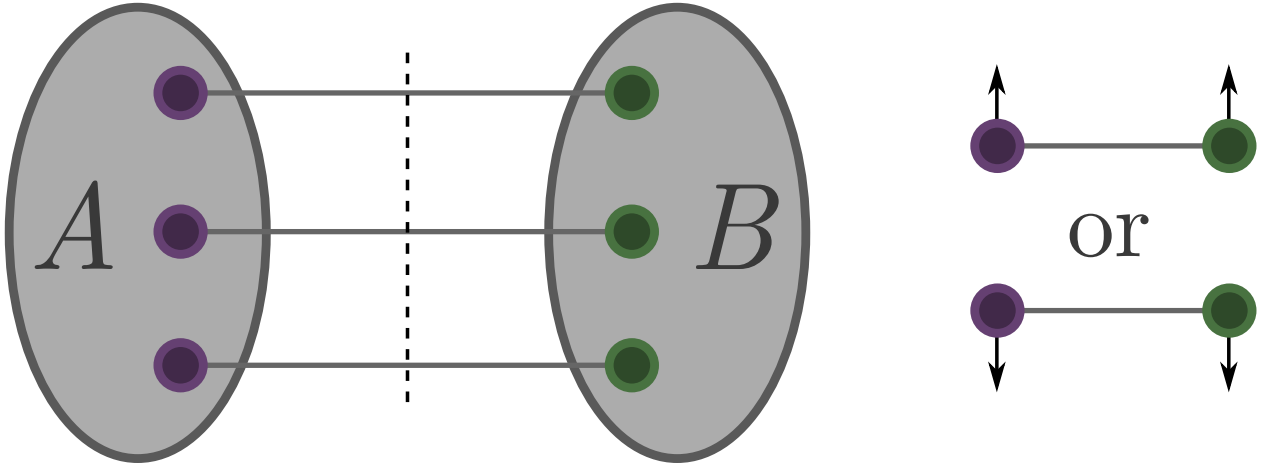

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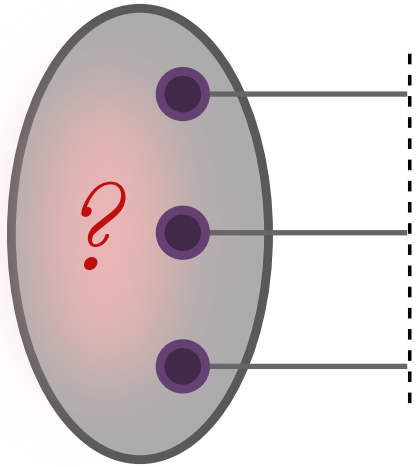

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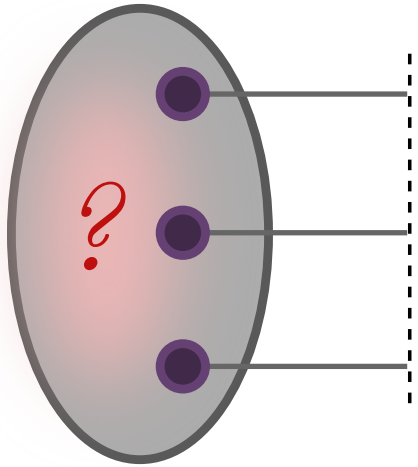

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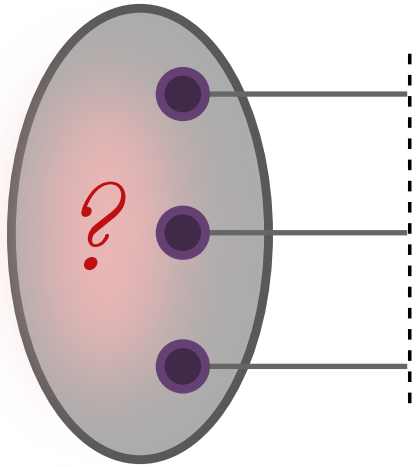
- A good measure is the entanglement entropy[6] $S[\rho_A]$.

Entanglement entropy

- Given a density matrix ρ_A for system A, uncertainty can come from (a) entanglement and (b) classical entropy.
- Either way, we have uncertainty about the state on A.



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- A good measure is the entanglement entropy[6] $S[\rho_A]$. (It's just the Shannon entropy for the distribution over states.)

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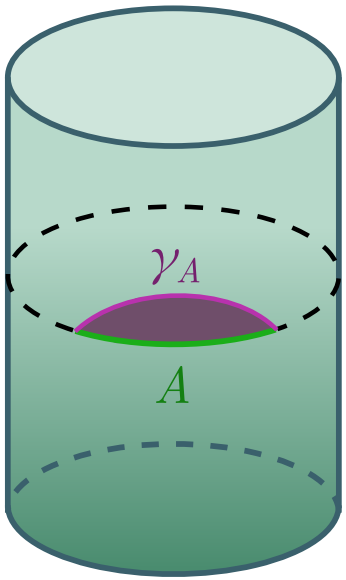

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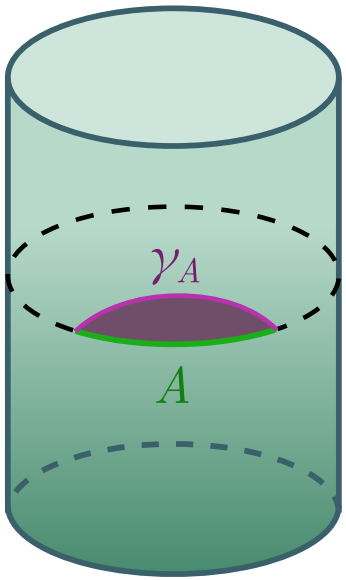

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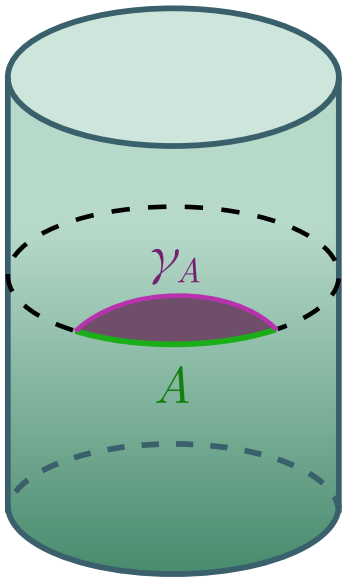

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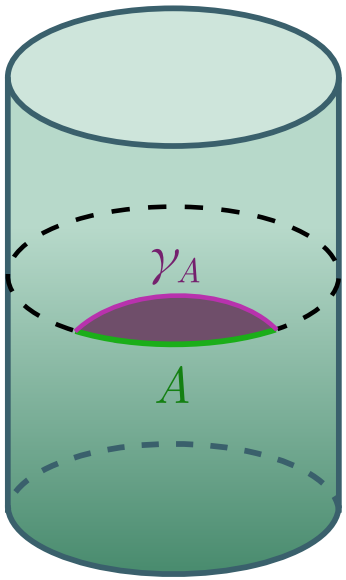

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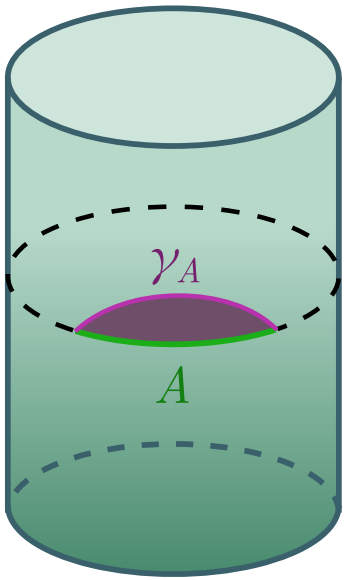

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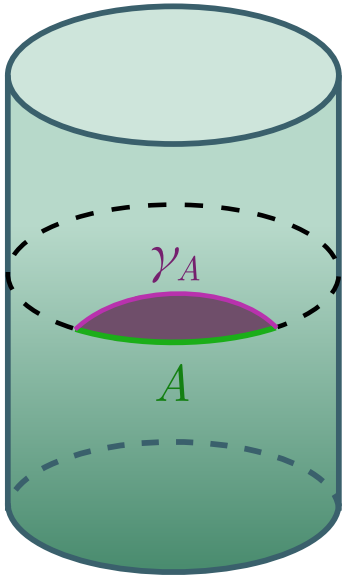

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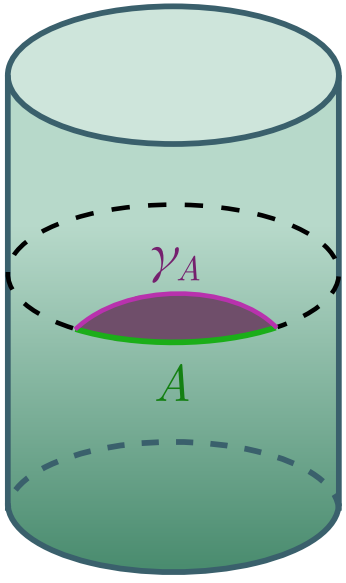

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- The purple entanglement wedge is encoded by ρ_A.[8]

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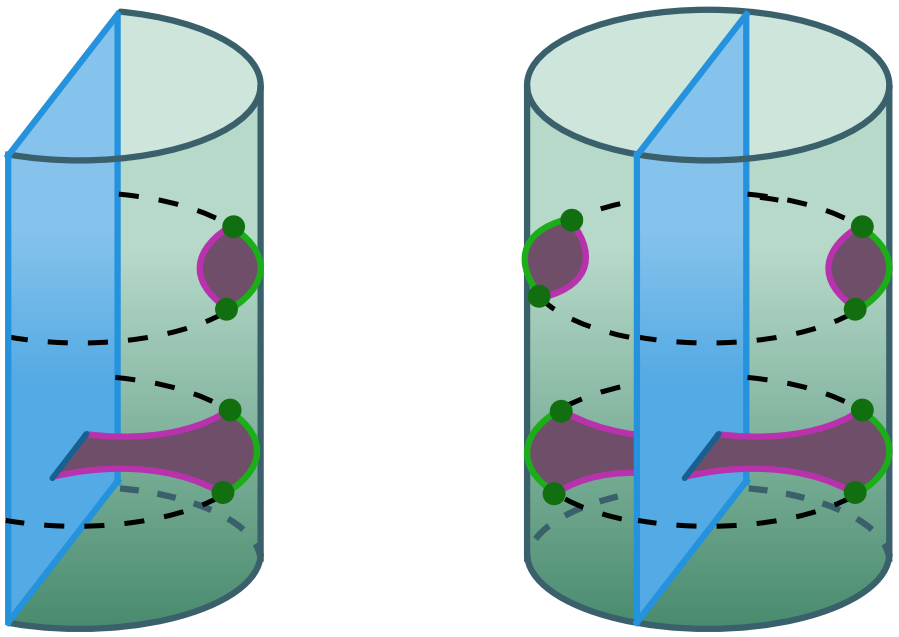

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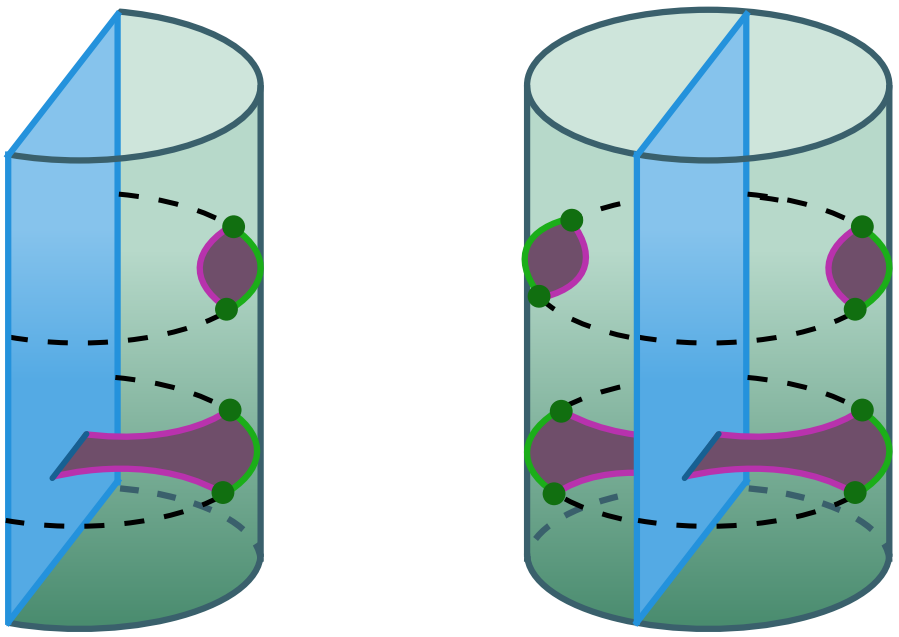

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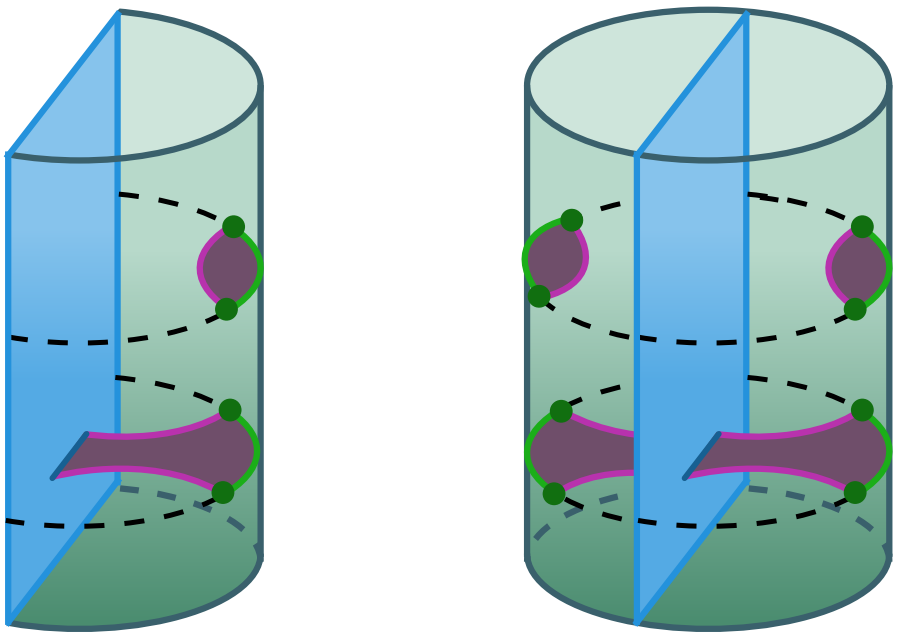

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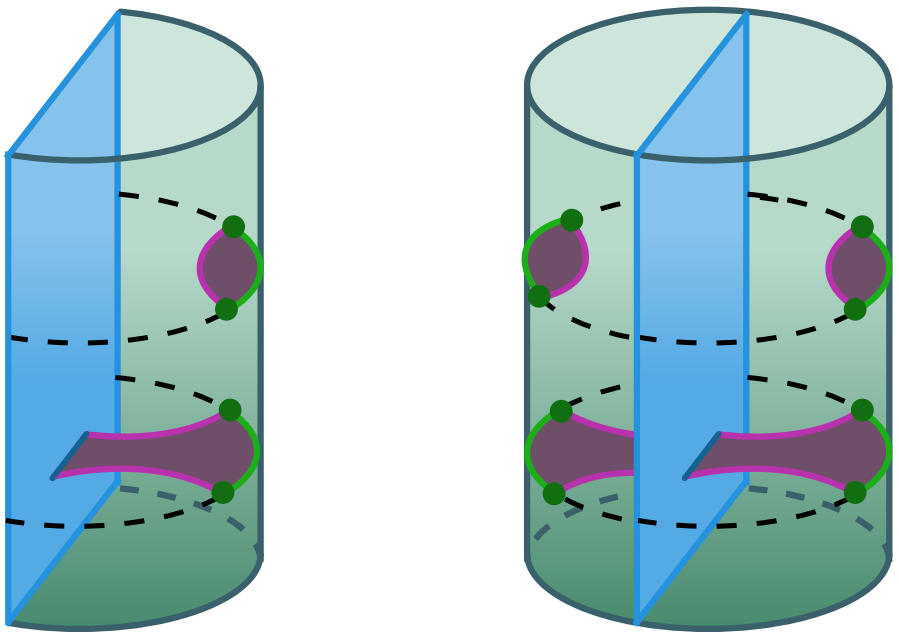

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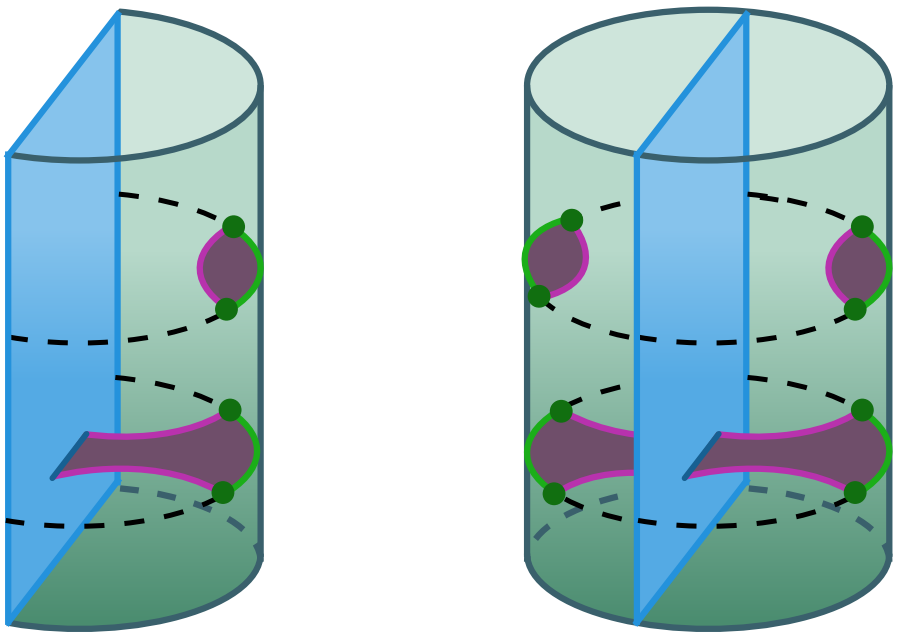

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- (It's the method of images for quantum gravity.)

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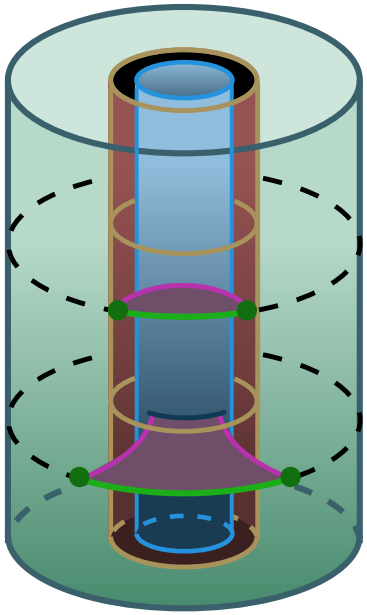

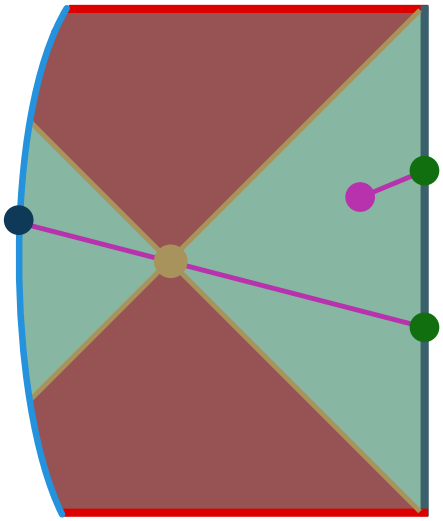

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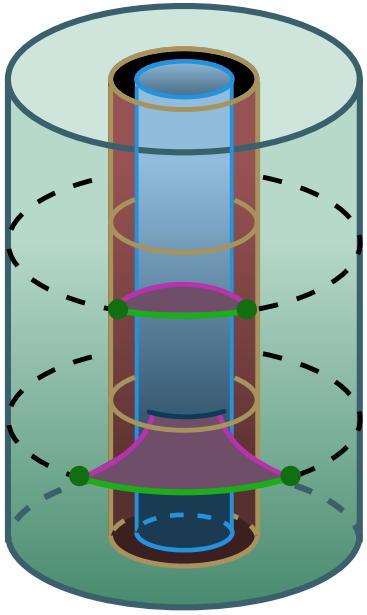

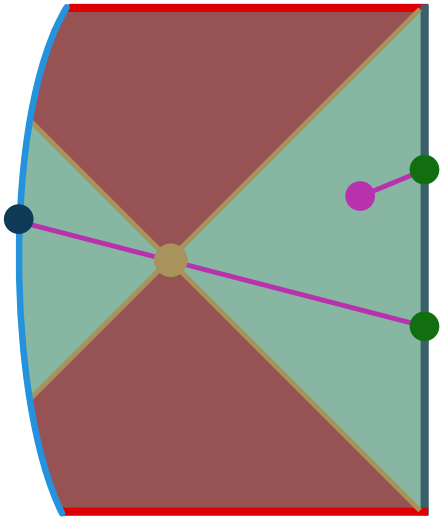

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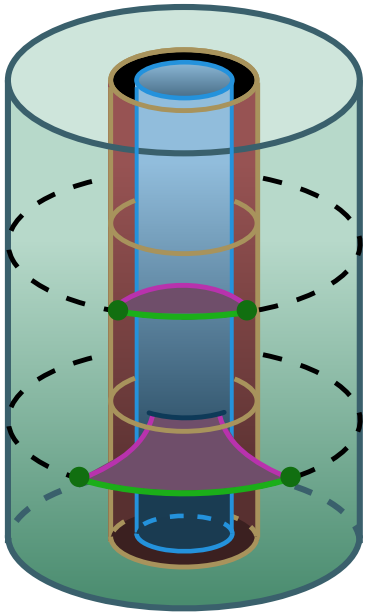

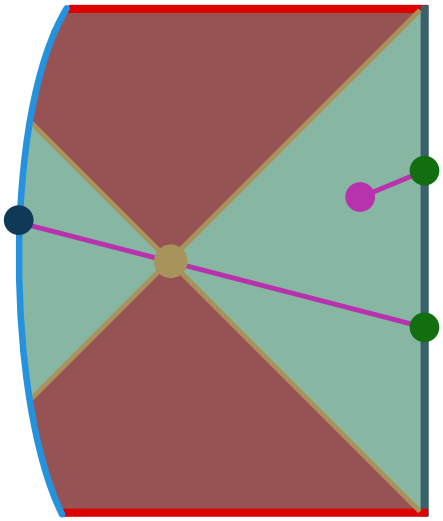

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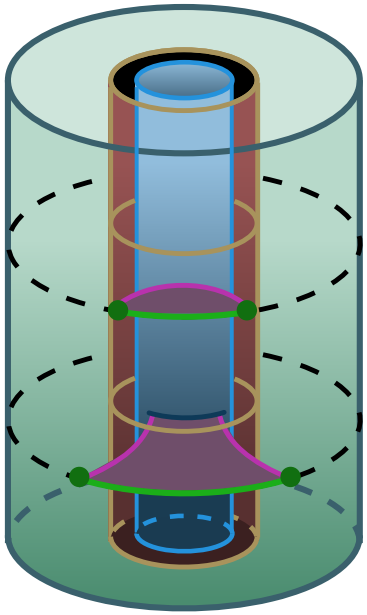

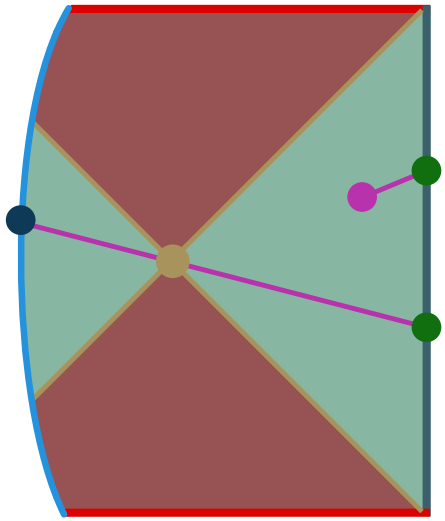

- We did explicit calculations[9] to find regimes γ_A falls in. You need large A and a close enough brane to hit it.

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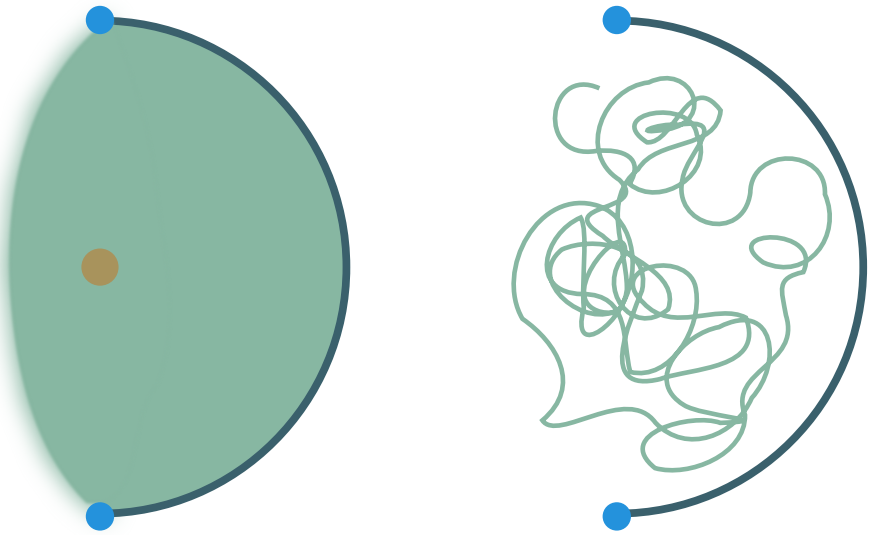

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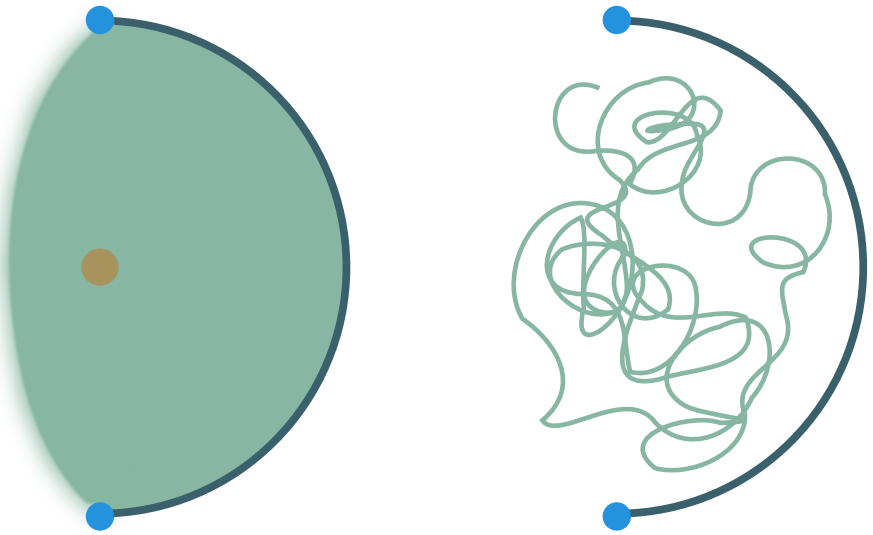

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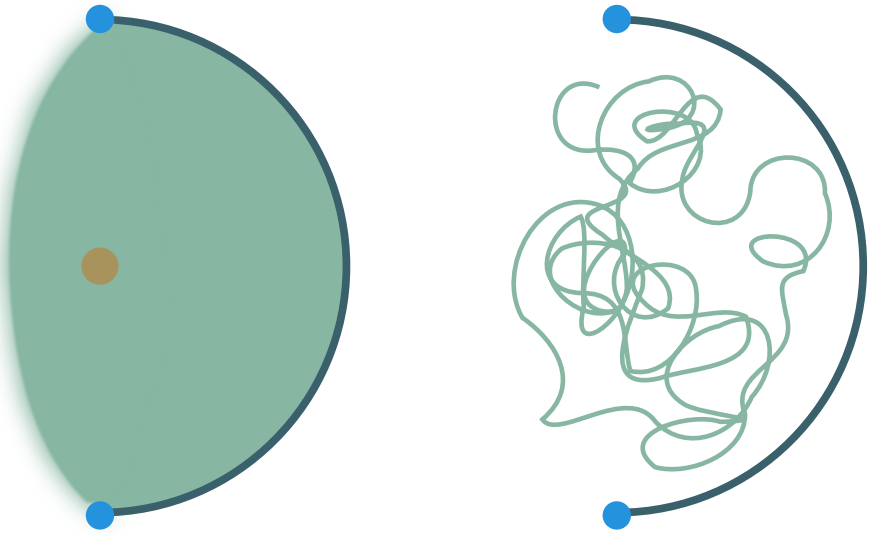

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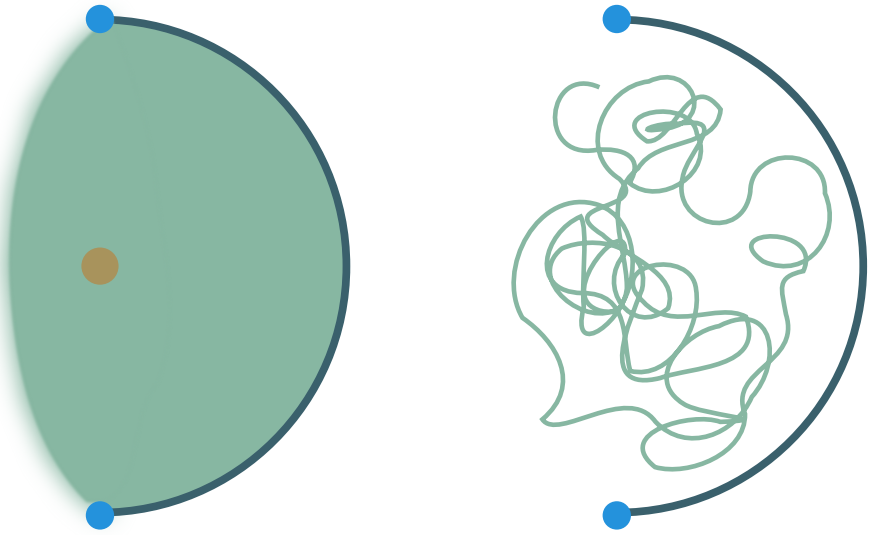

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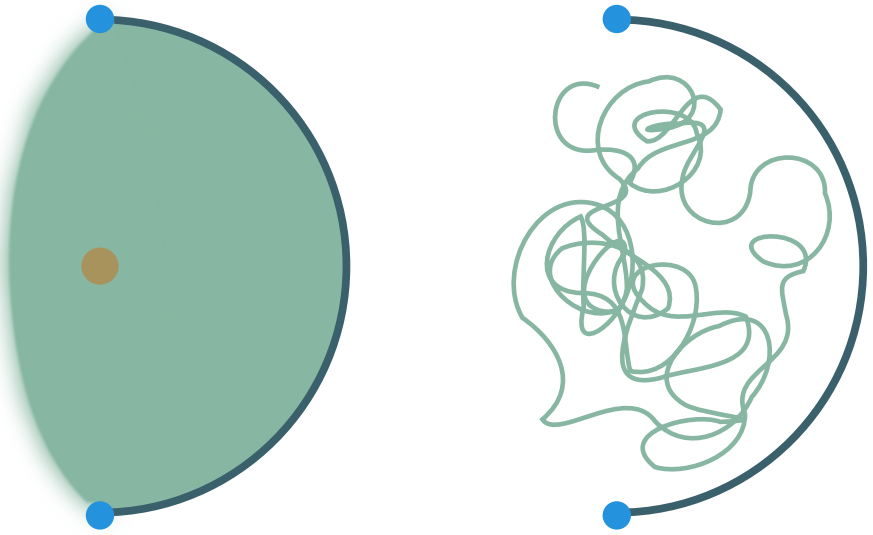

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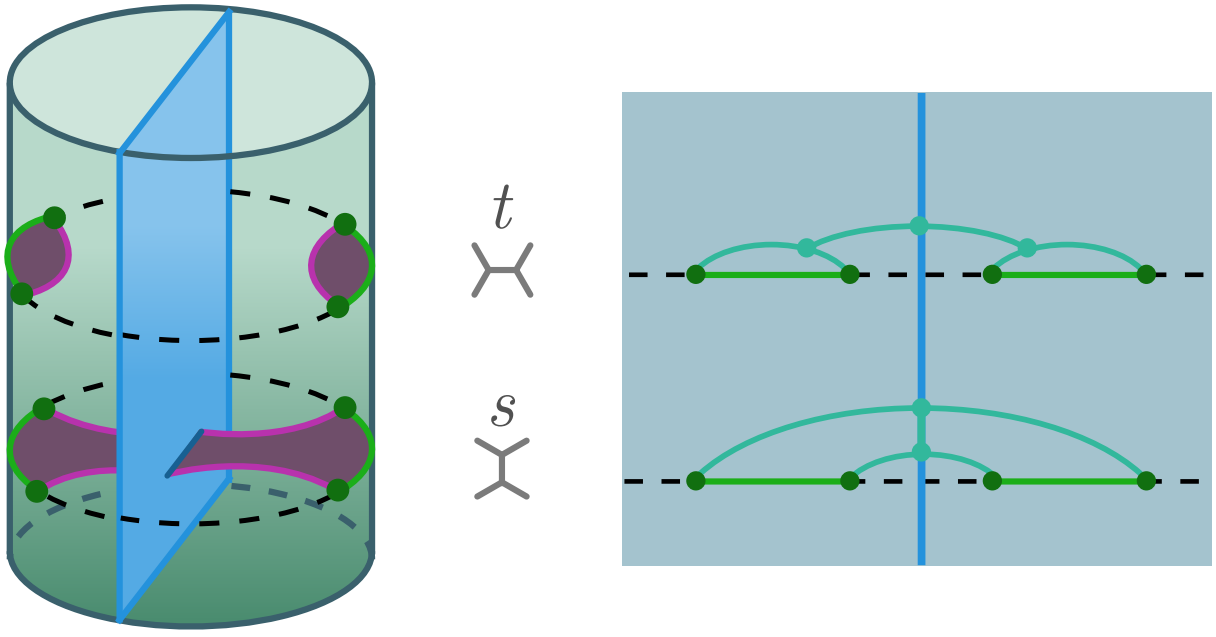

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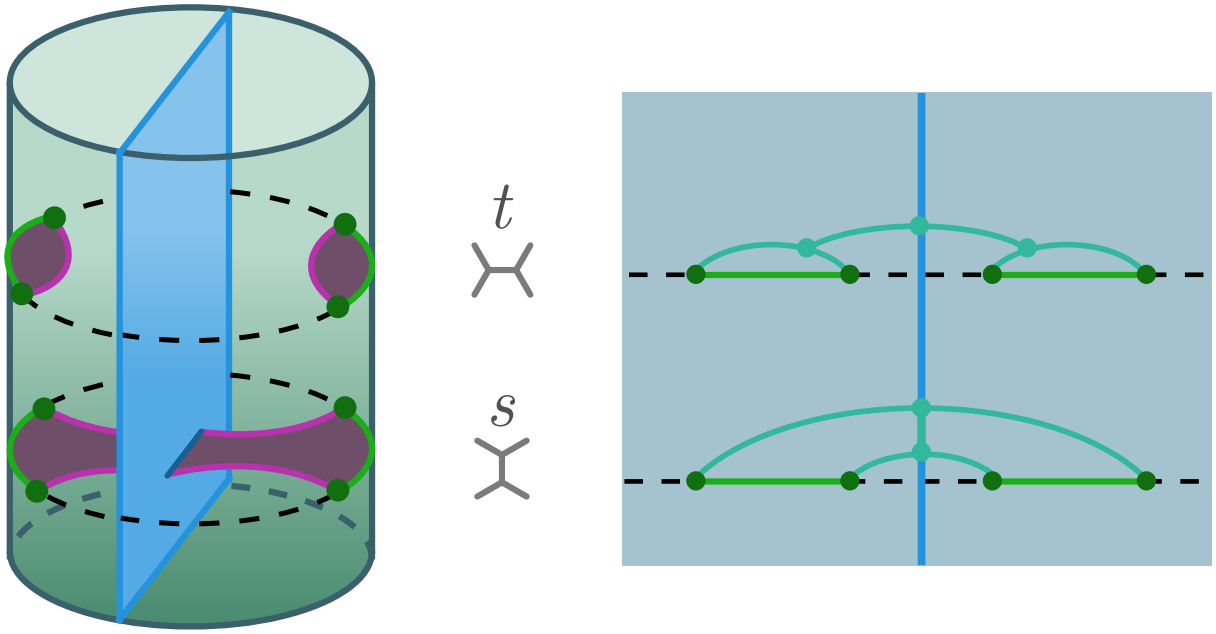

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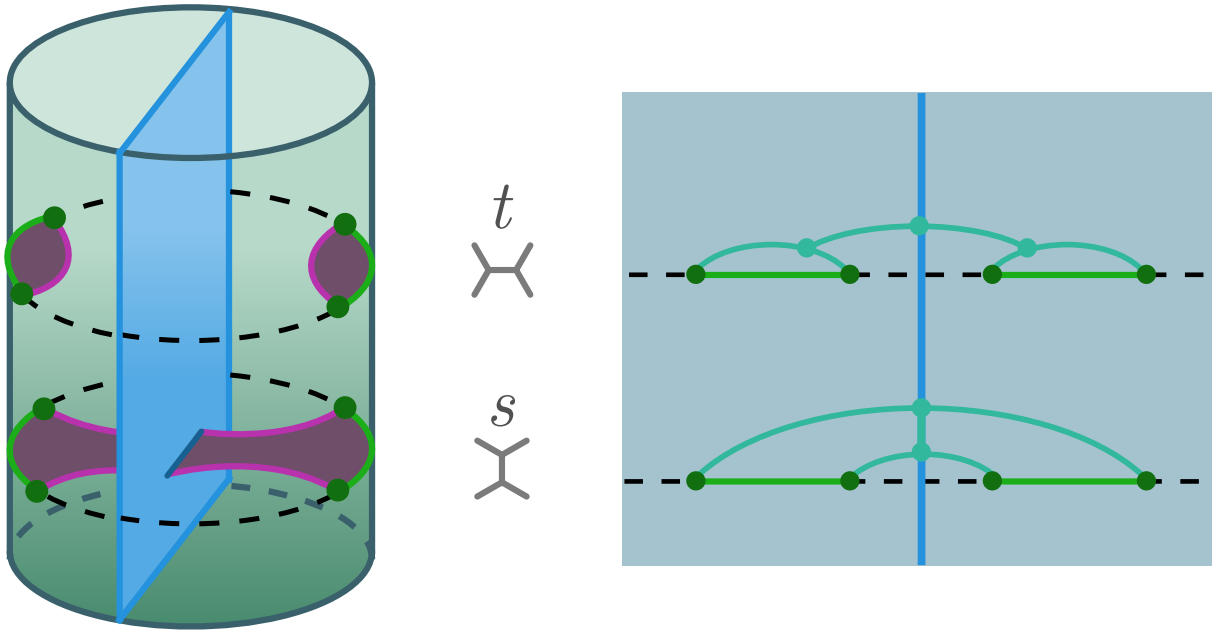

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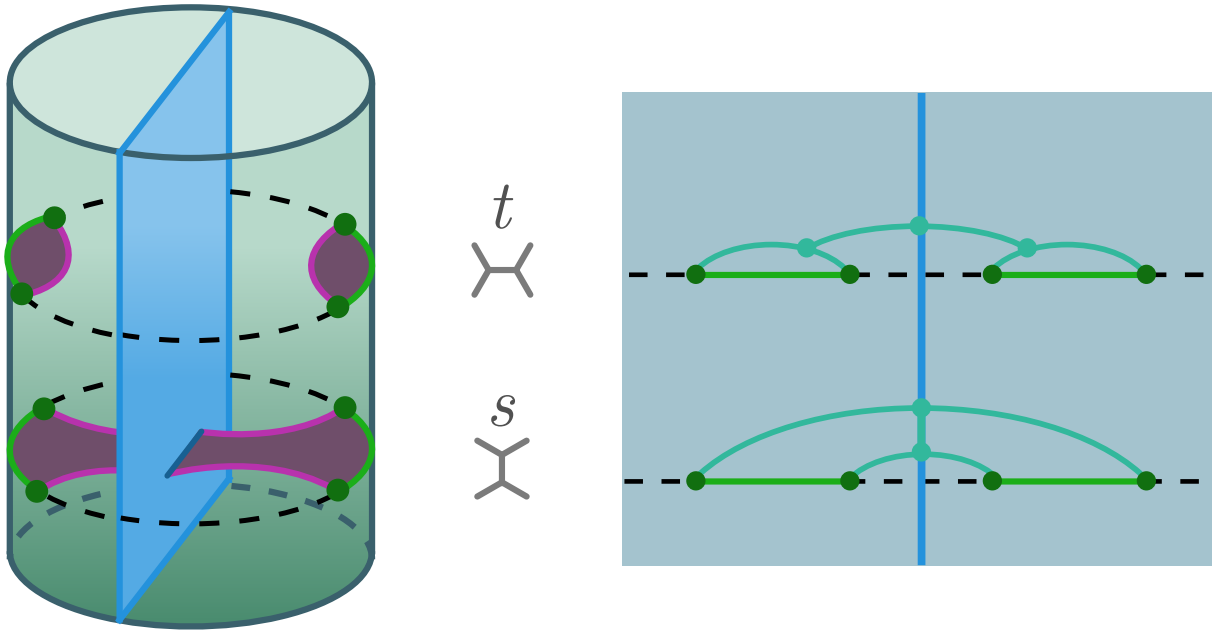

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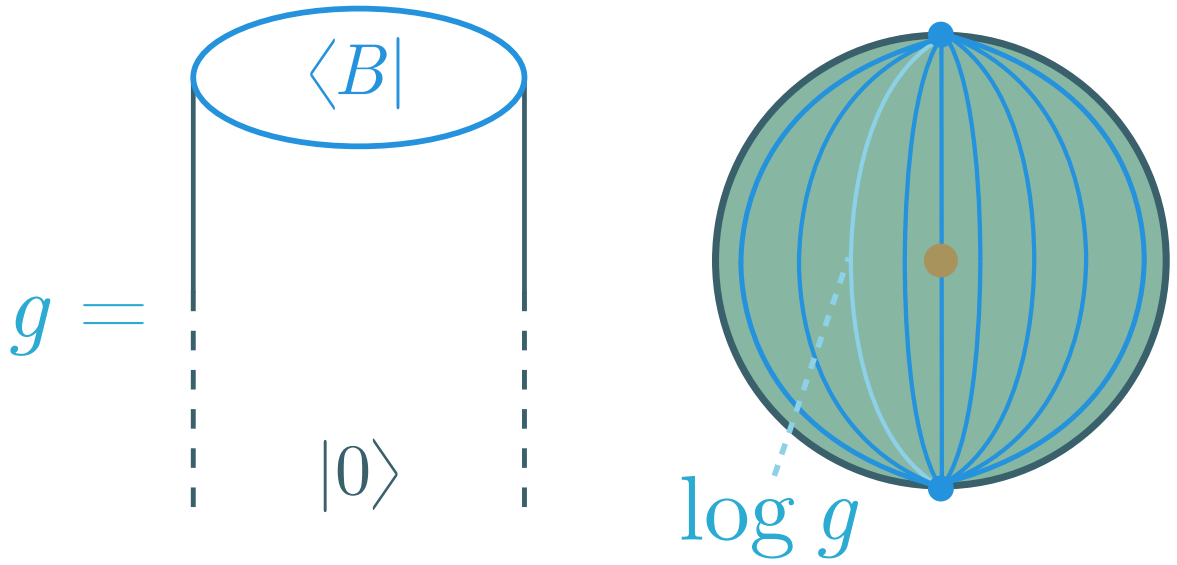

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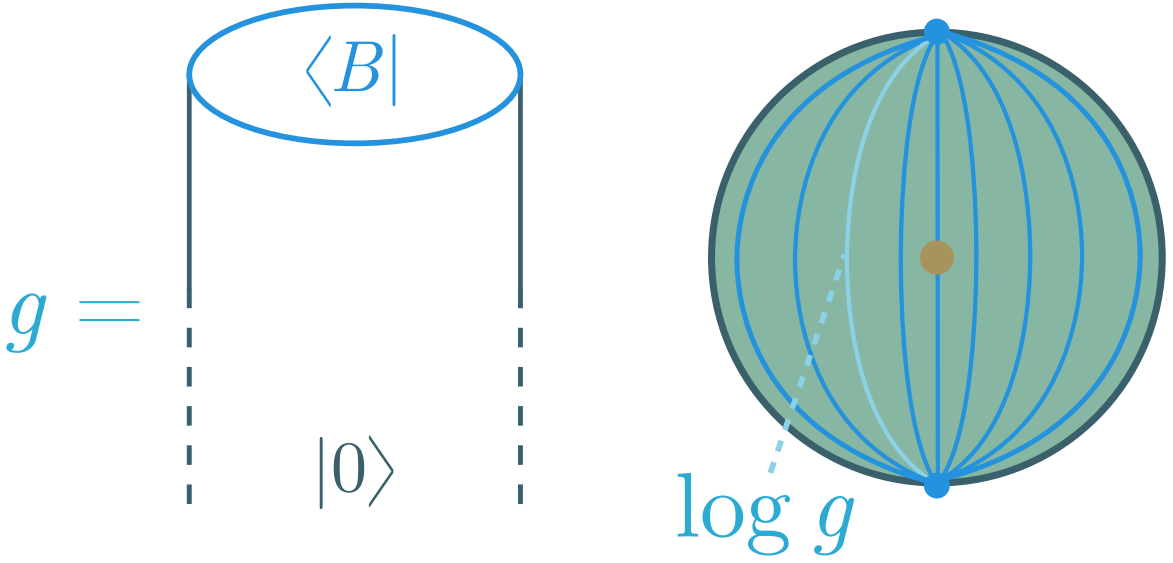

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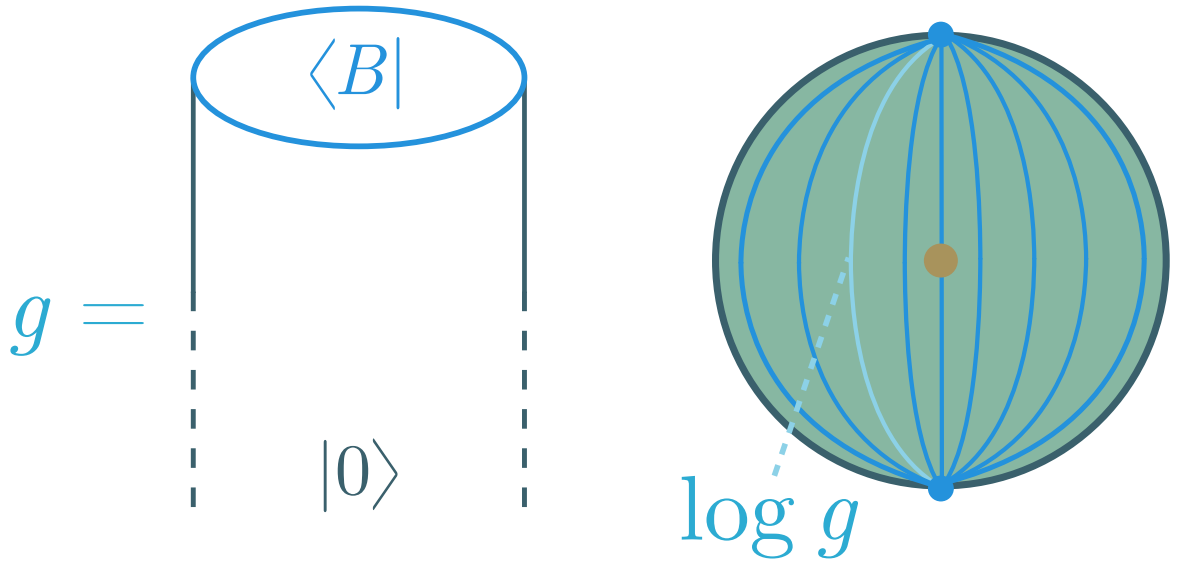

- This validates the apocalyptic RT formula and gives us a microscopic handle on the black hole interior.

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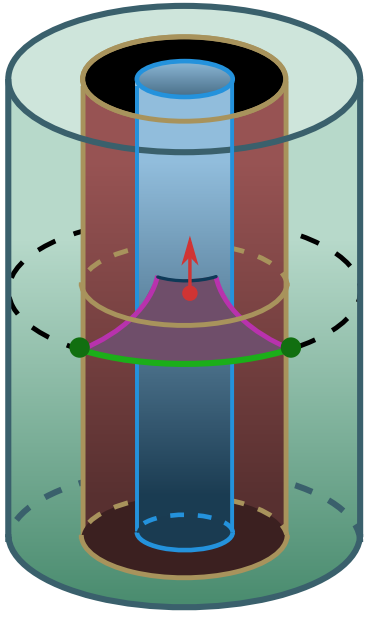

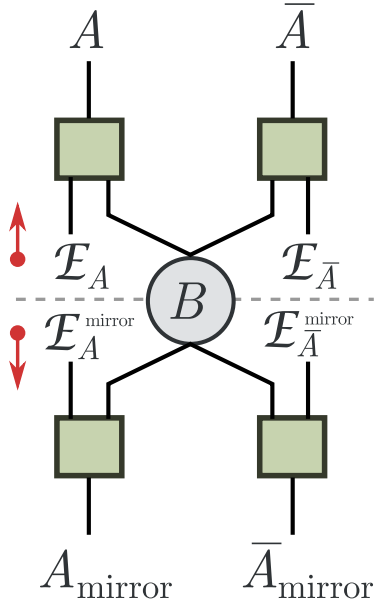

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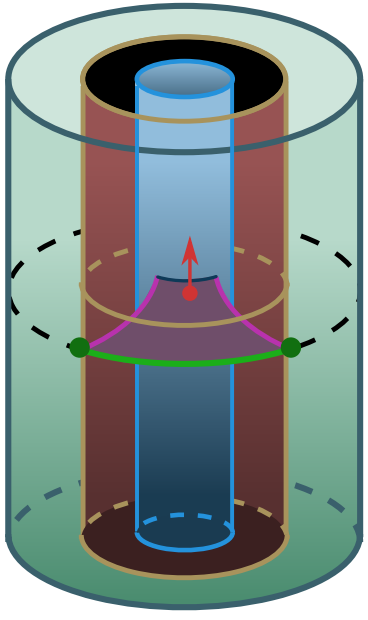

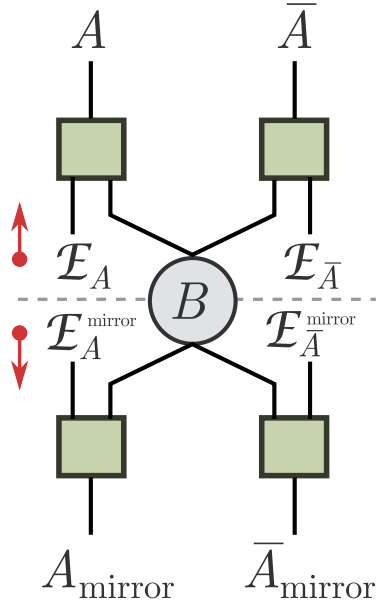

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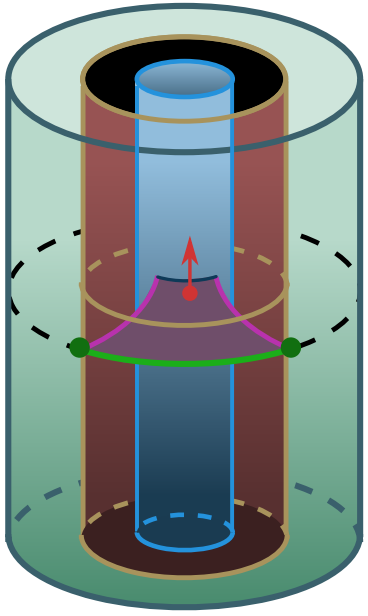

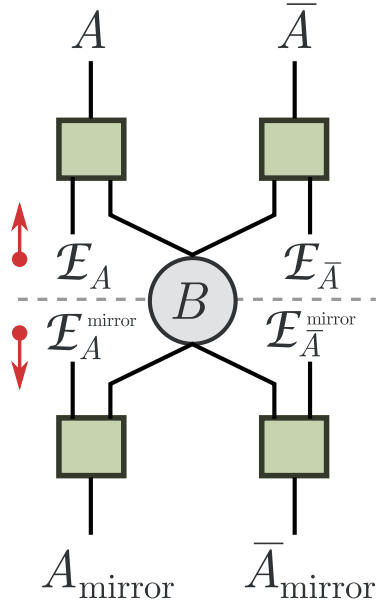

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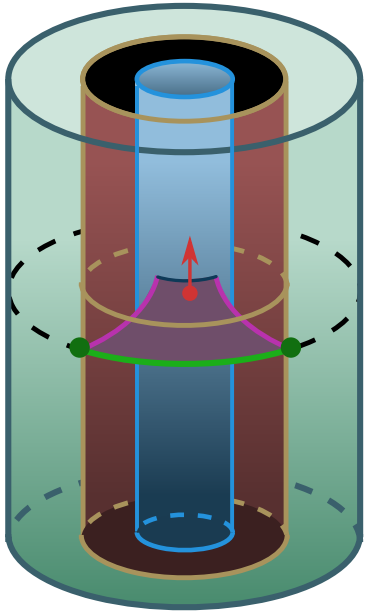

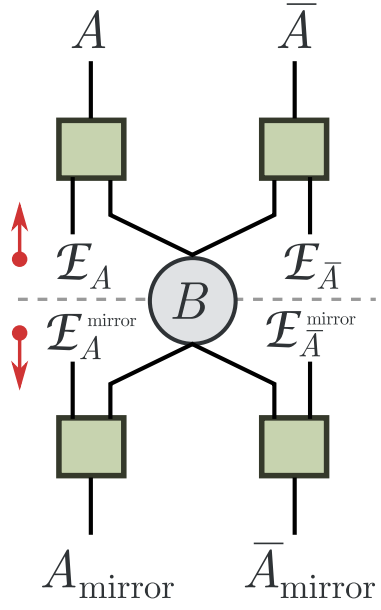

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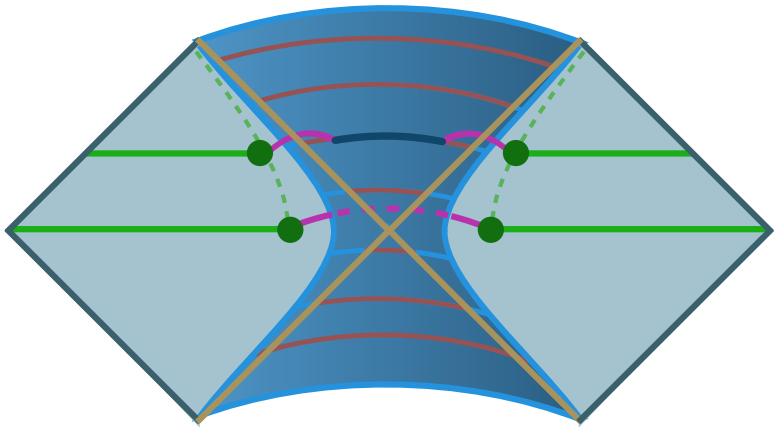

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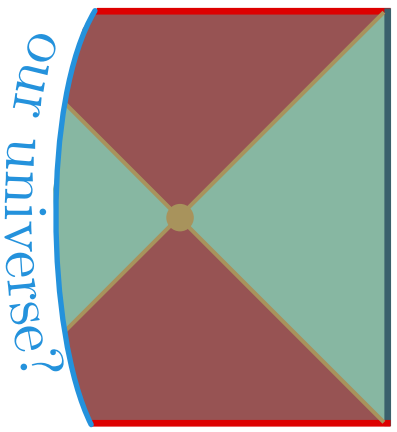

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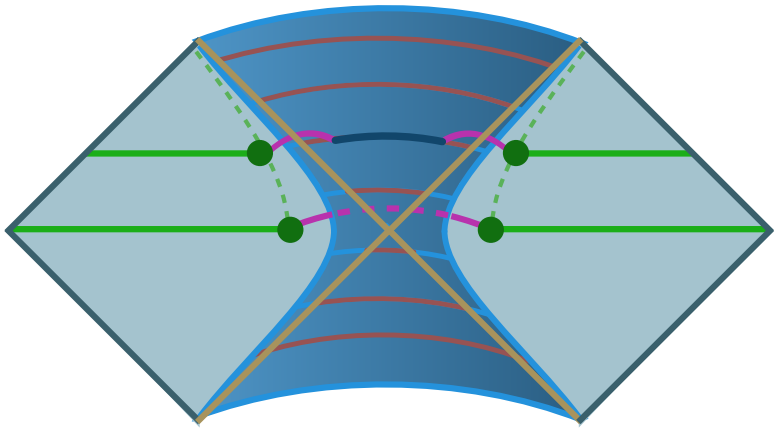

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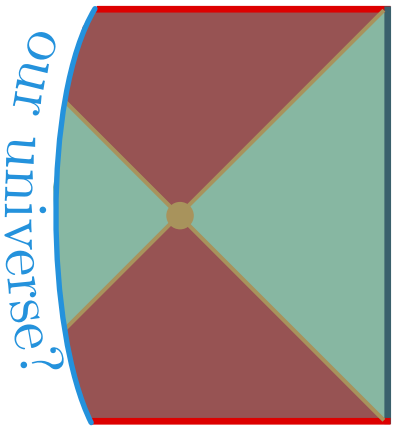

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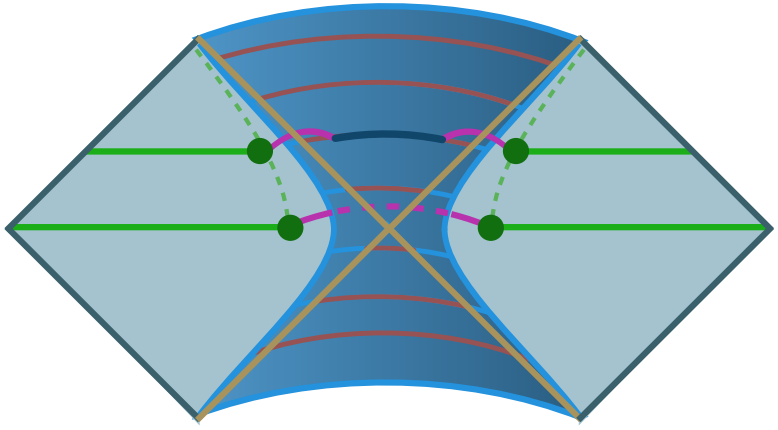

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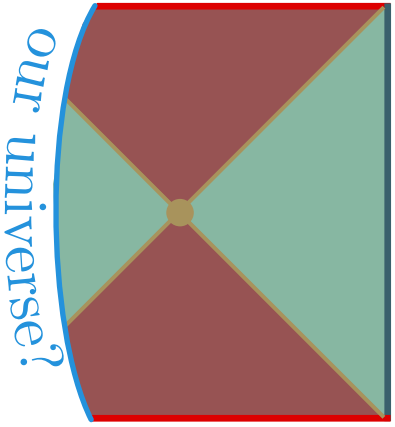

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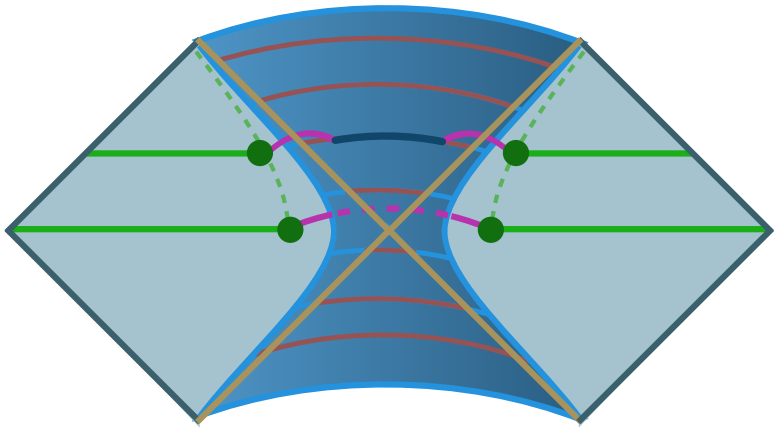

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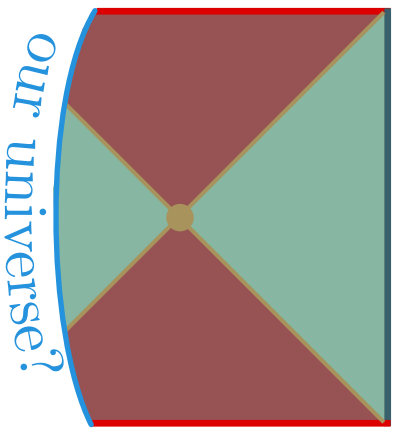

cosmology!

- Circling back round to our initial motivation, the brane itself looks like a Big Bang/Big Crunch cosmology.
- The trick is to localize gravity to the brane.[14]

Conclusion

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Thanks for listening!

References

1. Maldacena 97; Witten 98; Gubser, Klebanov, Polyakov 98.
2. 't Hooft 74.
3. Witten 98.
4. Hawking 75.
5. Israel 76; Maldacena 01.
6. Von Neumann 36; Shannon 48.
7. Ryu, Takayanagi 06; Hubeny, Rangamani, Takayanagi 07.
8. Czech, Karczmarek, Nogueira, Van Raamsdonk 12; Dong, Harlow, Wall 16.
9. Cooper, Rozali, Swingle, Van Raamsdonk, Waddell, DW 18.
10. Hartman 13; Sully, Van Raamsdonk, DW 20.
11. Affleck, Ludwig 91; Takayanagi 12.
12. Almheiri 18.
13. Rozali, Sully, Van Raamsdonk, Waddell, Wakeham 19.
14. Antonini, Swingle 19.