The central dogma and horizons in quantum cosmology

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Cosmology, Quantum Gravity, and Holography
September 14, 2023

Quantum black hole

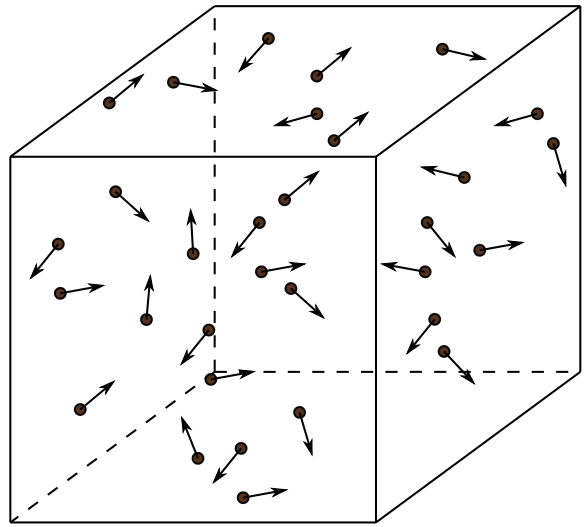
Like a gas in a box, black holes have a **temperature** and an **entropy**:

$$T = \frac{1}{8\pi G M}$$

$$S = \frac{\text{Area}}{4G}$$

Quantum black hole

Boltzmann provided atomic description for gas:



Black hole central dogma: from the outside, a black hole can be described in terms of a quantum system with $\log \dim(\mathcal{H}_{\mathrm{BH}}) = \frac{\mathrm{Area}}{4G}$, which evolves unitarily. [Bekenstein, Hawking, 't Hooft, Susskind,...]

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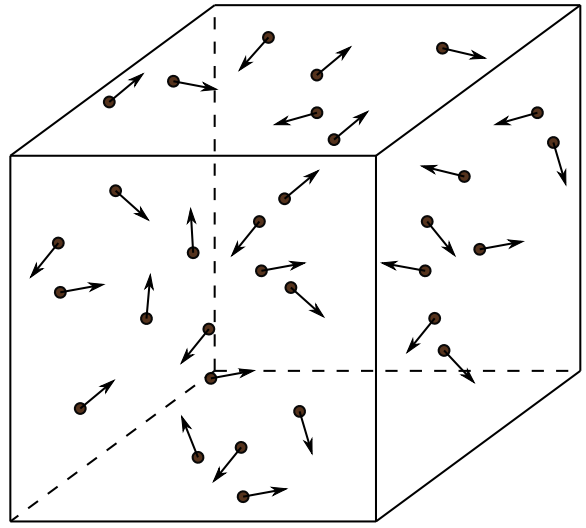

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Region beyond event horizon can be accessed from outside.

Cosmic central dogma

Cosmological horizons have an entropy Area/$4G$ [Gibbons, Hawking]. They radiate and have a temperature. Do they obey a central dogma?

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Will focus on de Sitter spacetime in this talk:

$$ds^2 = -\left(1 - r^2/\ell^2\right) dt^2 + \frac{dr^2}{1 - r^2/\ell^2} + r^2 d\Omega_{d-1}^2$$

$$T = \frac{1}{2\pi\ell}\,, \qquad S = \frac{\ell^{d-1}\mathrm{Area}(S^{d-1})}{4G}$$

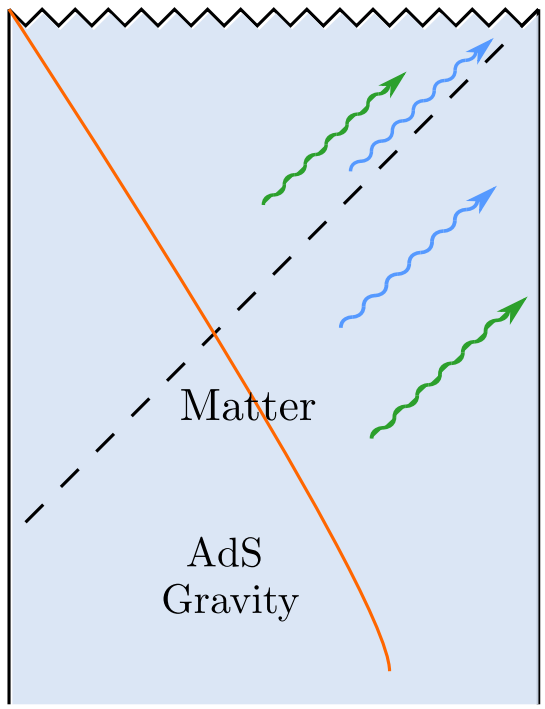
Entanglement entropy in gravity

Entanglement entropy of non-gravitating region R computed by extremizing [Ryu, Takayanagi] [Hubeny, Rangamani, Takayanagi] [Faulkner, Lewkowycz, Maldacena] [Engelhardt, Wall] [Penington] [Almheiri, Engelhardt, Marolf, Maxfield]

$$S_{\mathrm{QG}}(R) = \min \operatorname{ext}_I \left[\frac{\mathrm{Area}(\partial I)}{4G} + S_{\mathrm{QFT}}(I \cup R) \right] .$$

[Penington]

[Almheiri, Engelhardt, Marolf, Maxfield]



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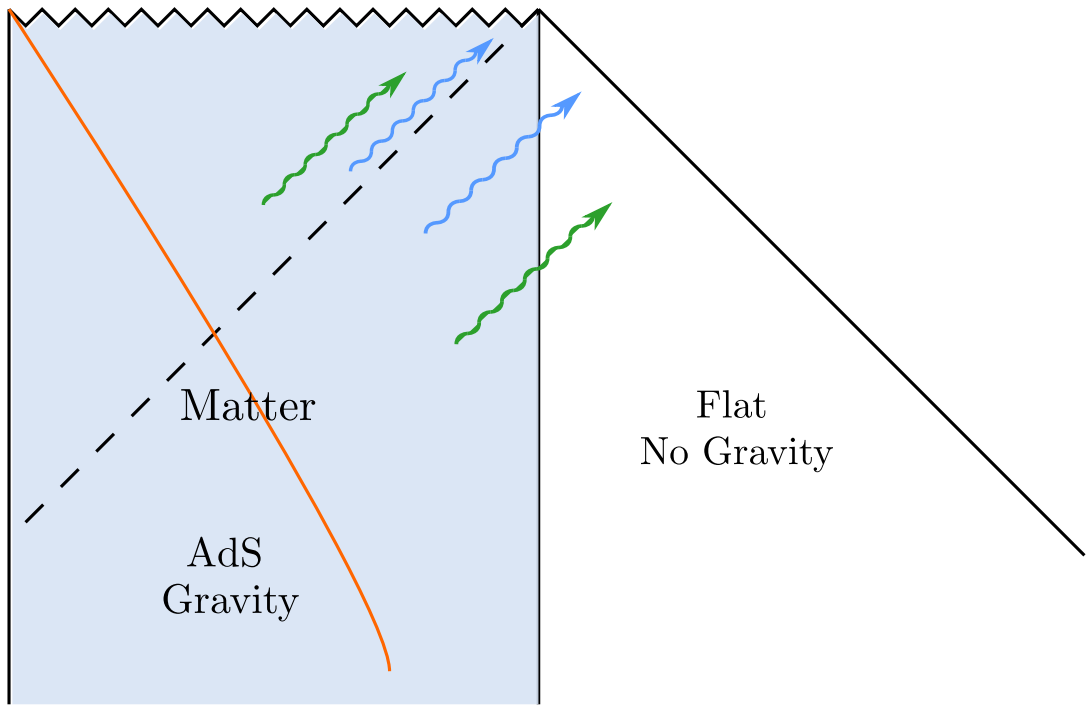

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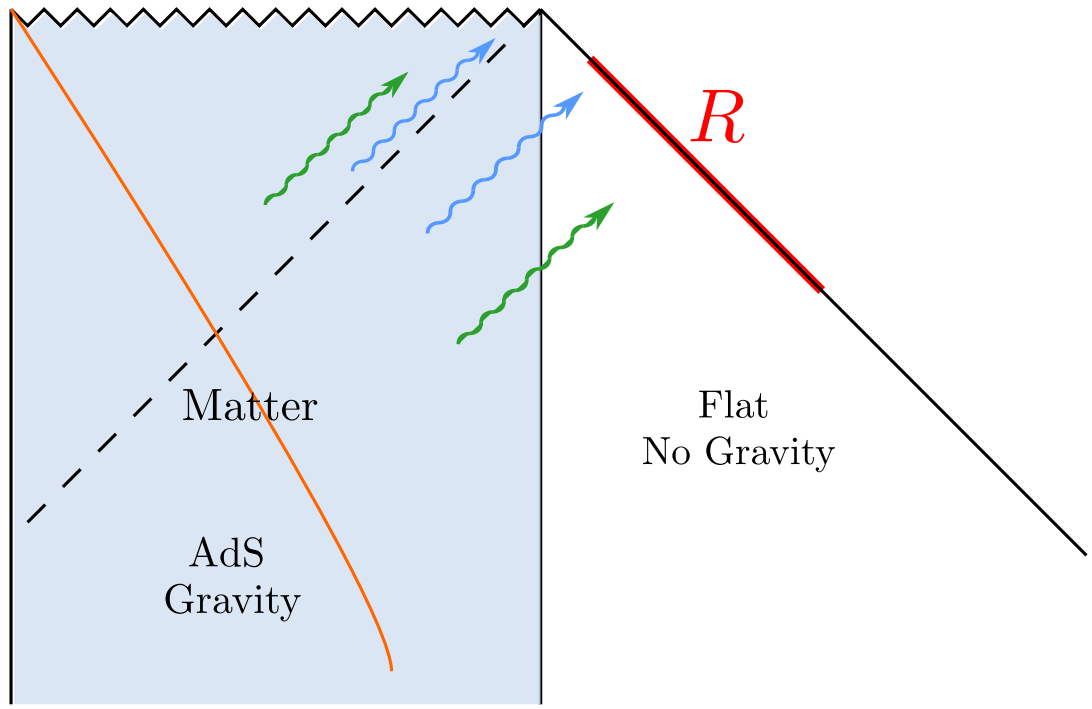

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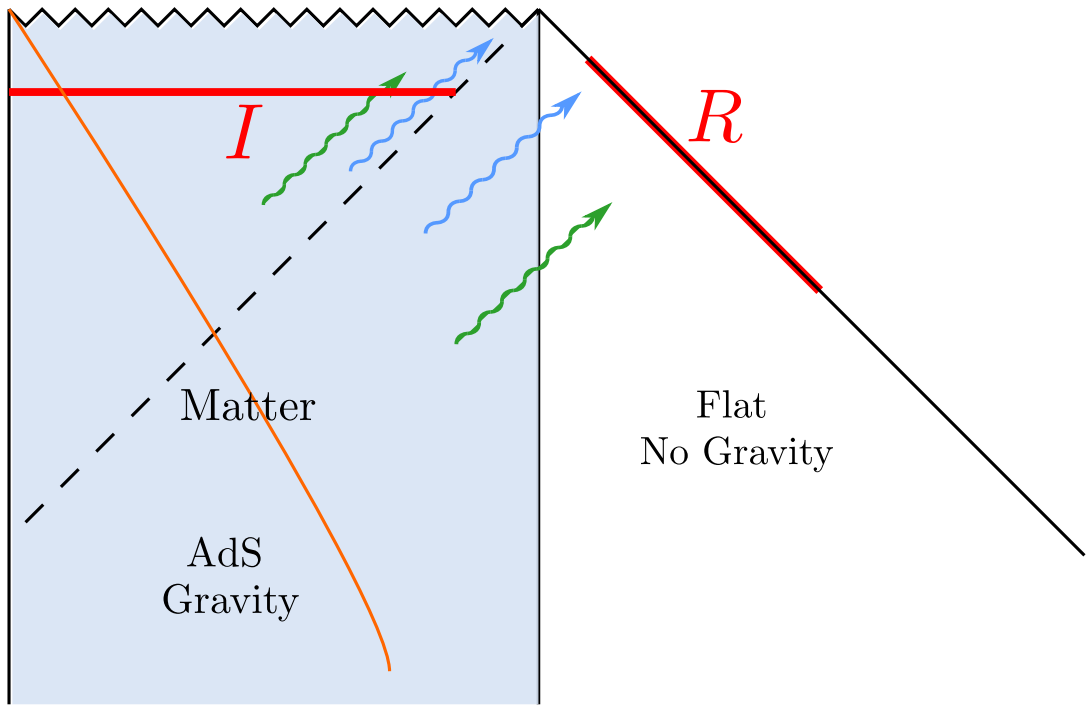

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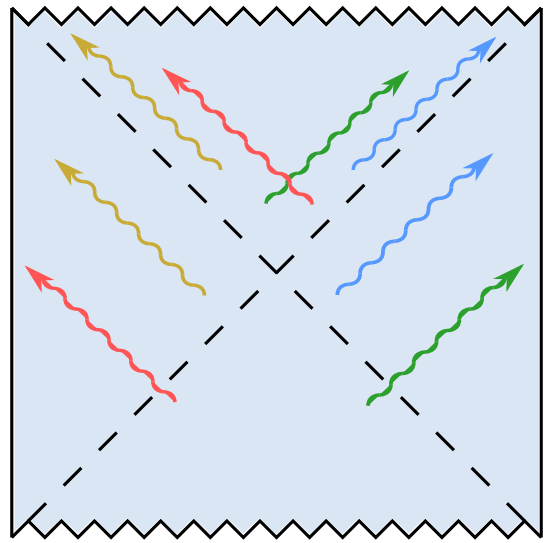

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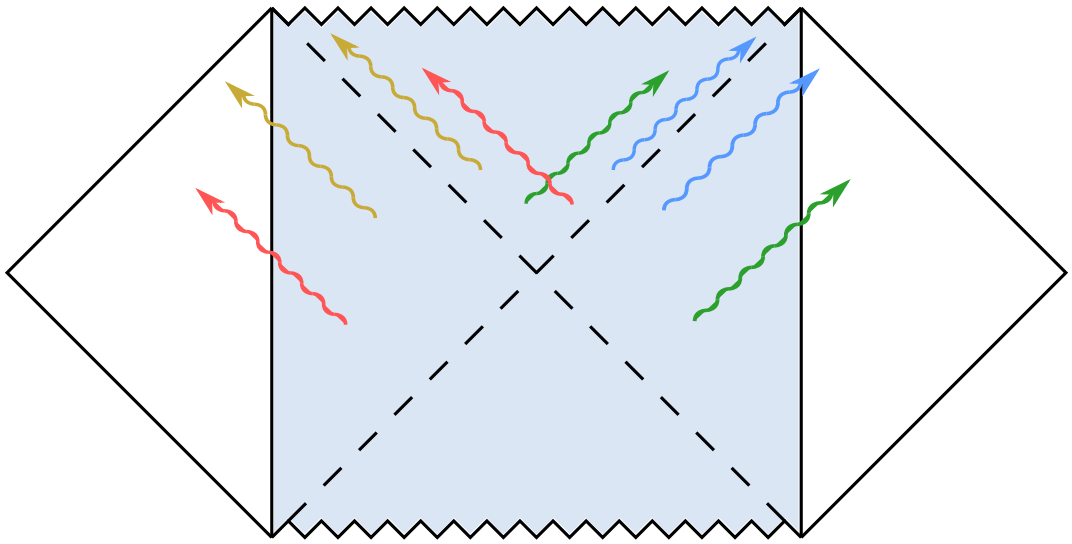

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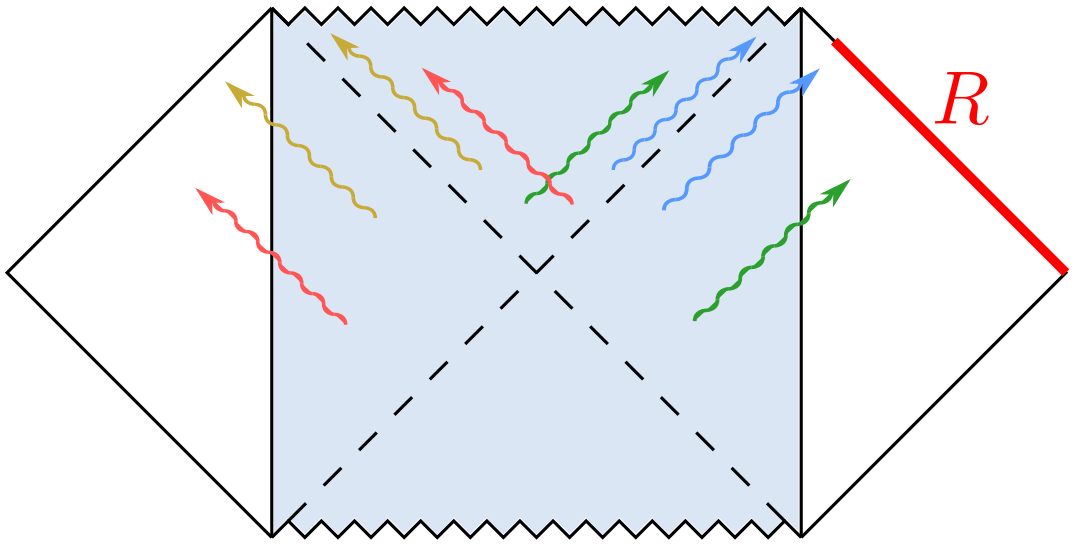

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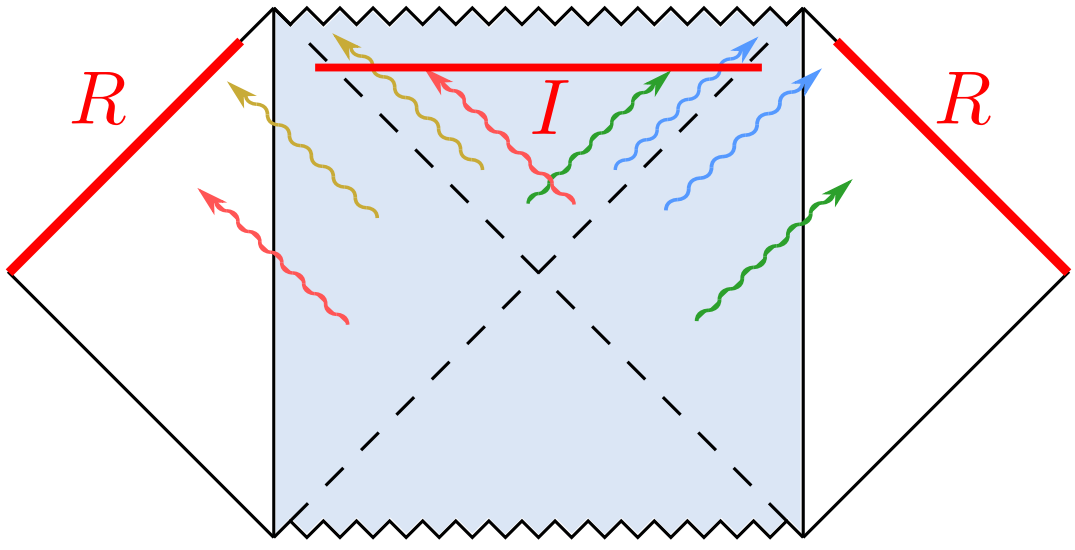

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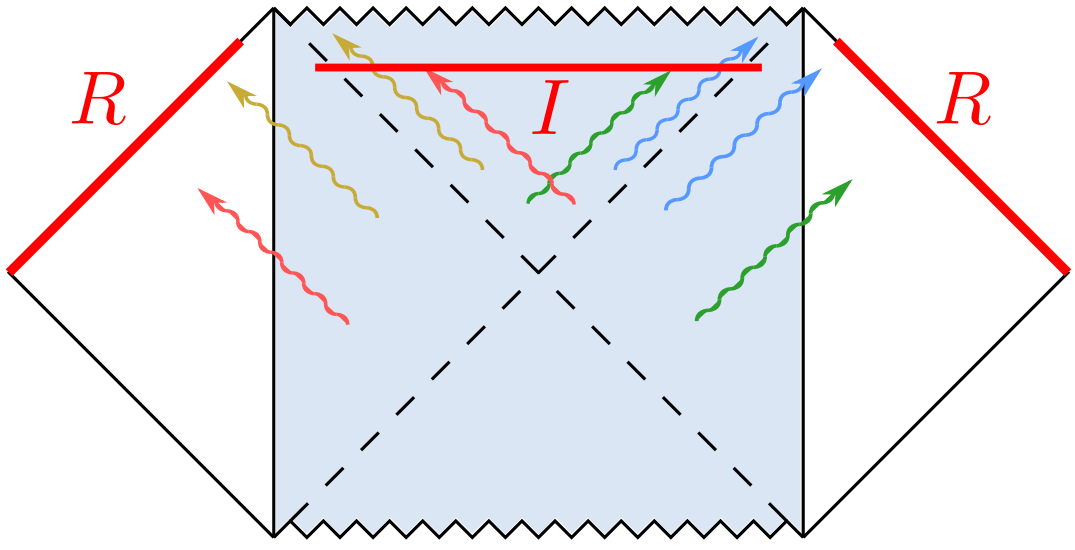

I is encoded in R in the sense of entanglement wedge reconstruction.

Can we encode beyond cosmic horizon?

Use gravity path integral to study cosmology – should give clues about holography [Harlow, ES]

Islands in de Sitter?

Do islands appear in de Sitter?

For pure de Sitter + CFT in the Hartle-Hawking state: **no**.

Must decorate de Sitter somehow: modify the geometry (e.g. exit from inflation) and/or the quantum state (e.g. a mixed state).

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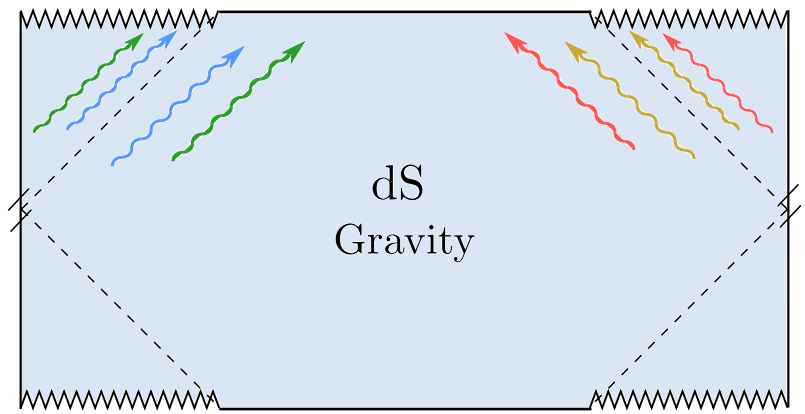
Fundamental issues that need to be faced:

- no region of weak gravity on time slice of de Sitter; if $\mathcal{I}^+$ is used must refer to meta-observer/inflation exit. (Related: can't collect horizon radiation without backreaction.)
- matter entropy in HH state grows like area. Need large matter entropy for appearance of islands!
- potential no-cloning violation.

[Hartman, Jiang, ES]

[Chen, Gorbenko, Maldacena]



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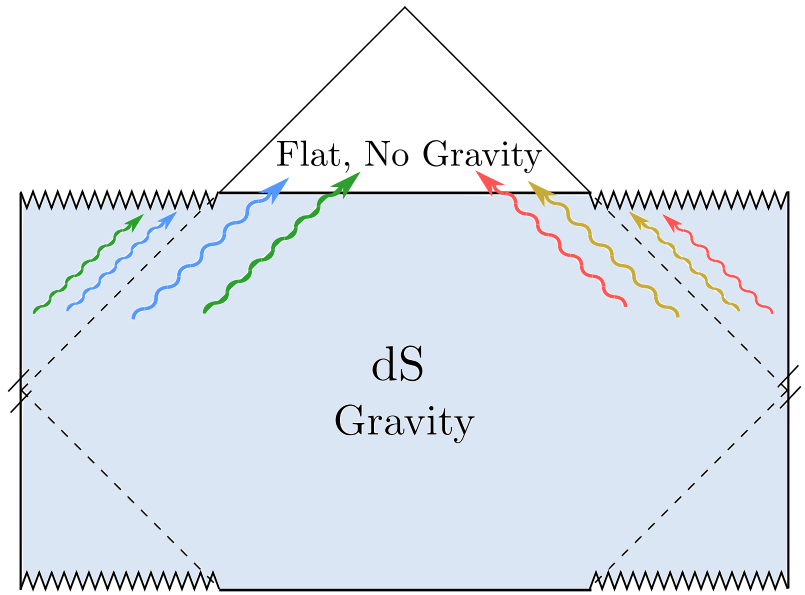

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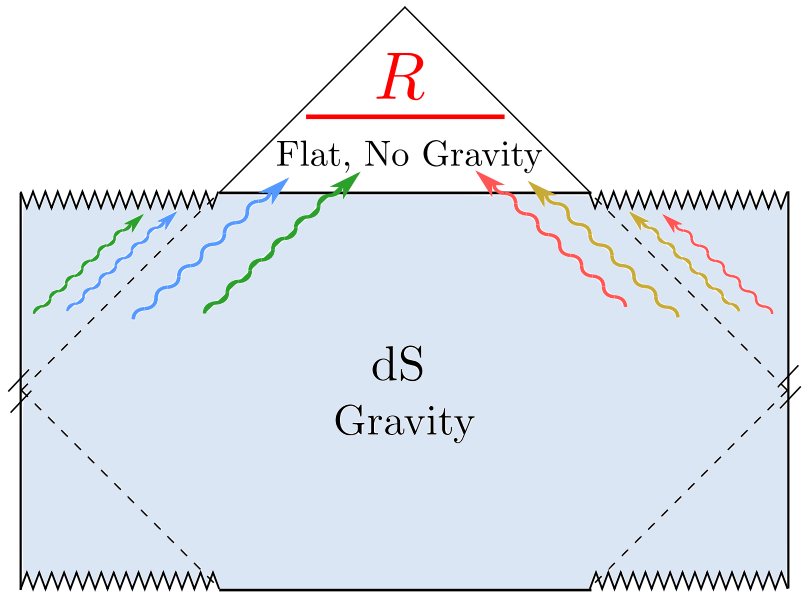

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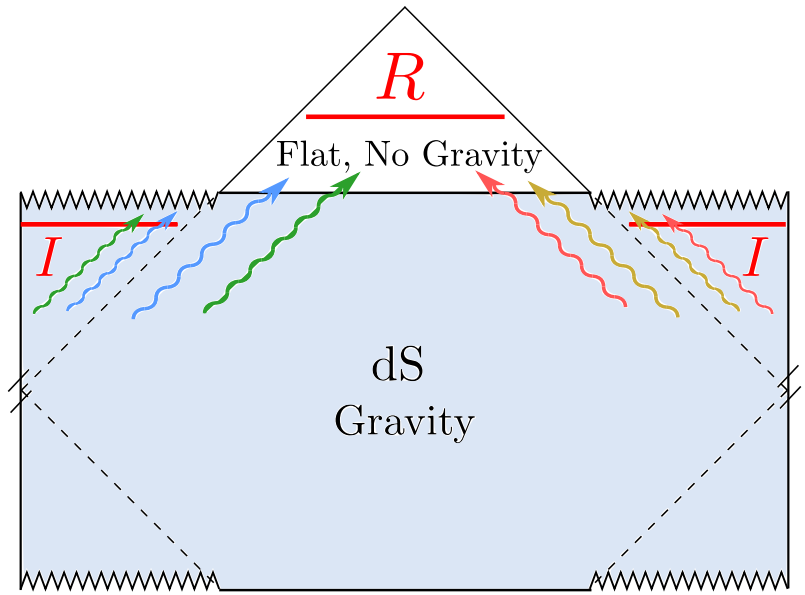

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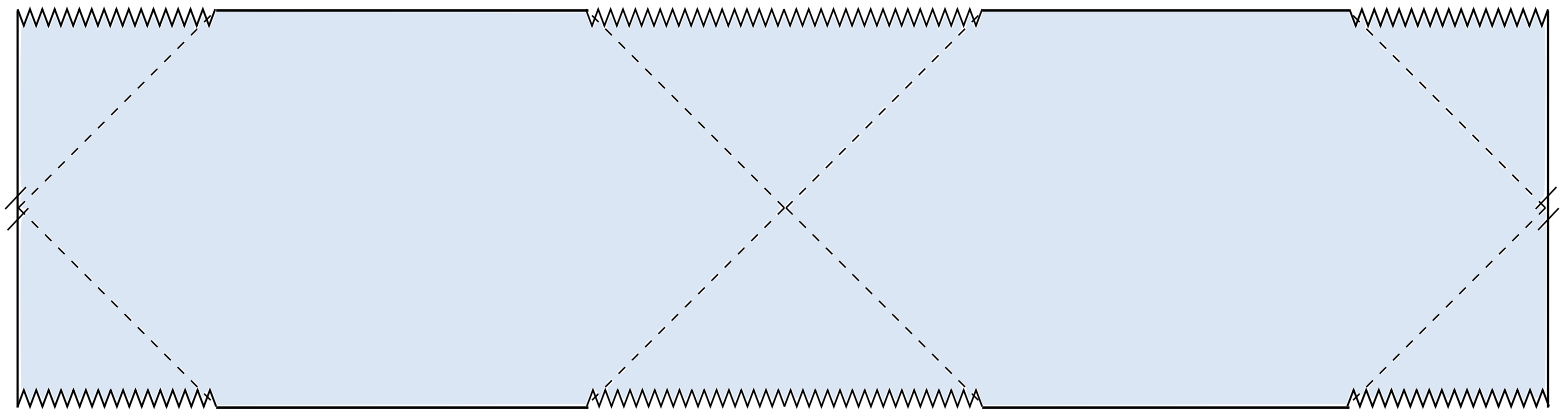

See also [Aguilar-Gutierrez, Chatwin-Davies, Hertog, Pinzani-Fokeeva, Robinson]

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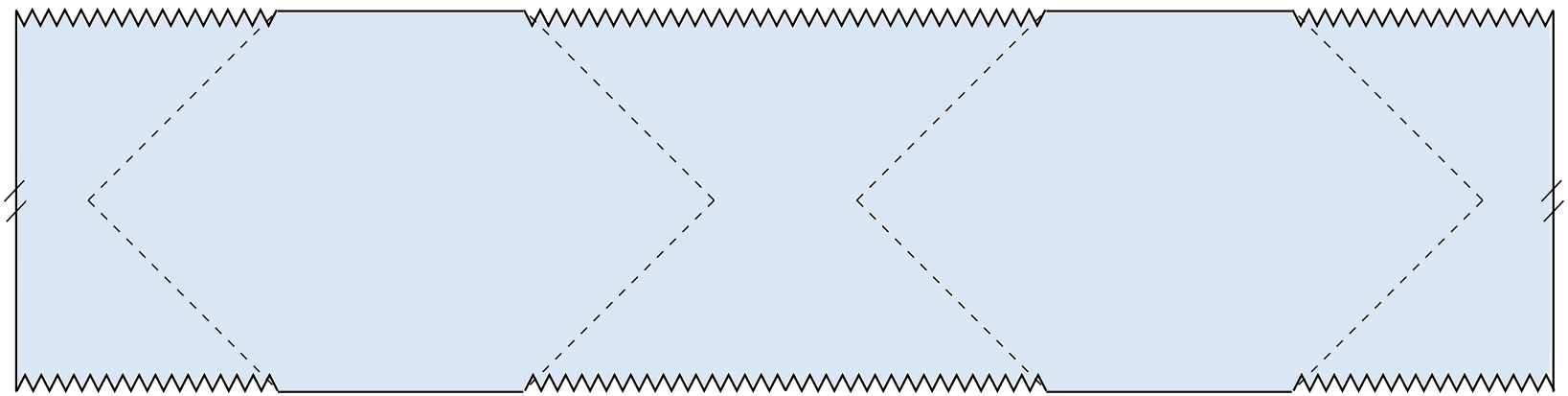

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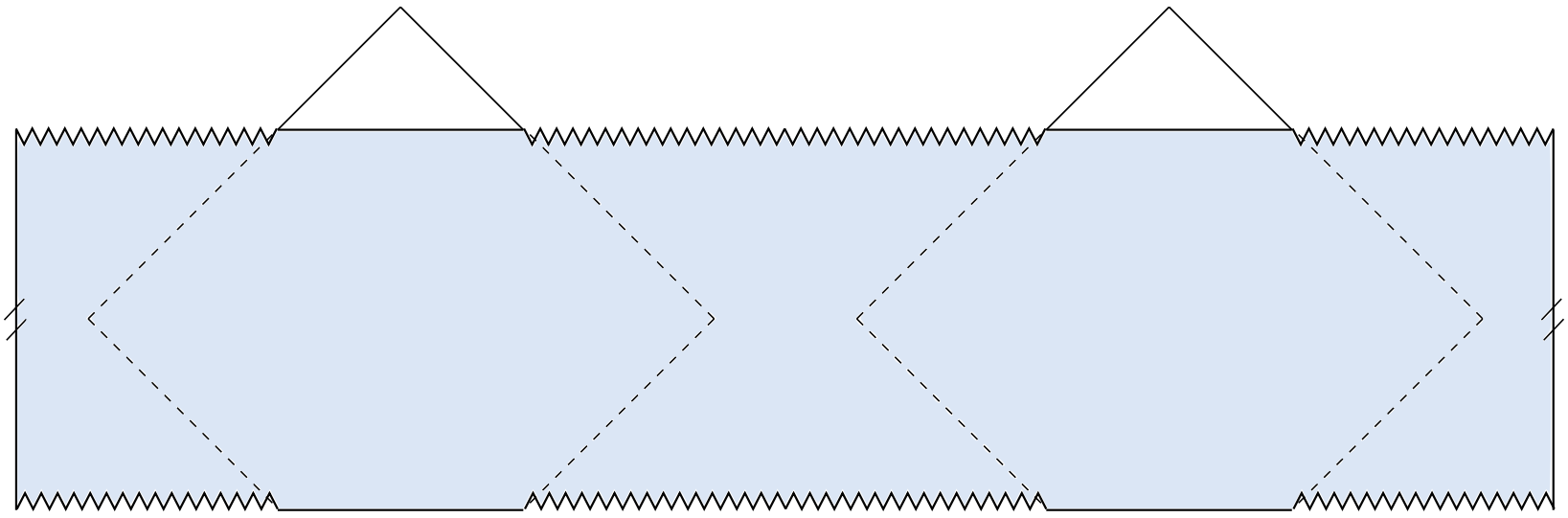

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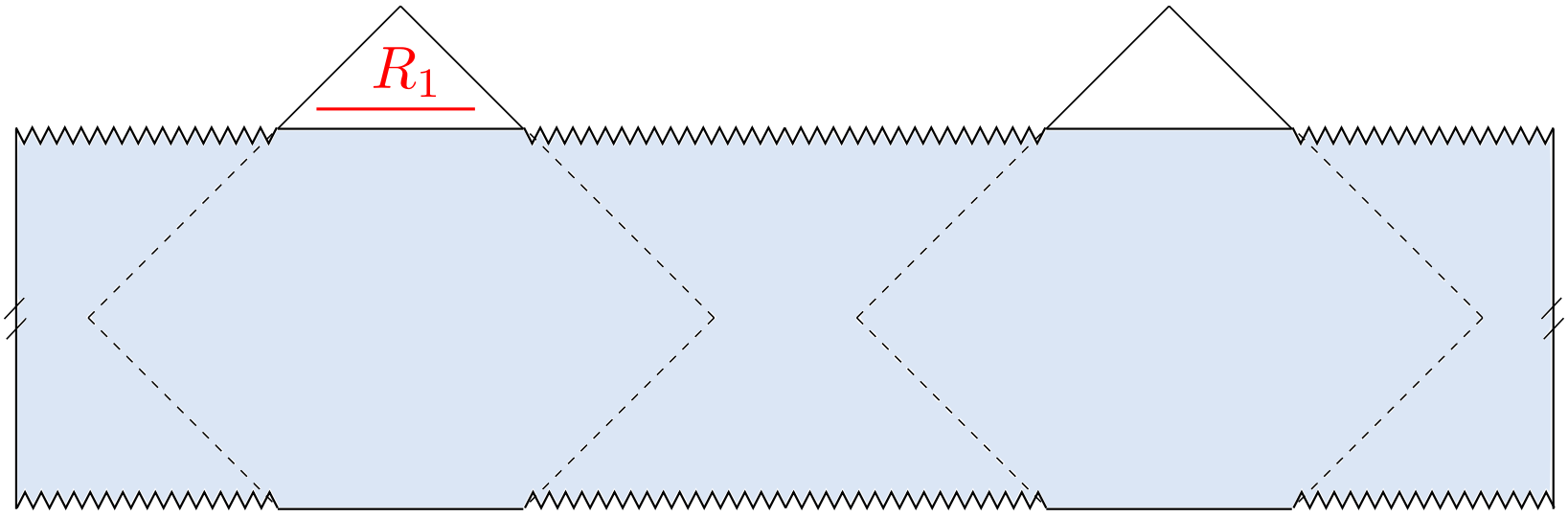

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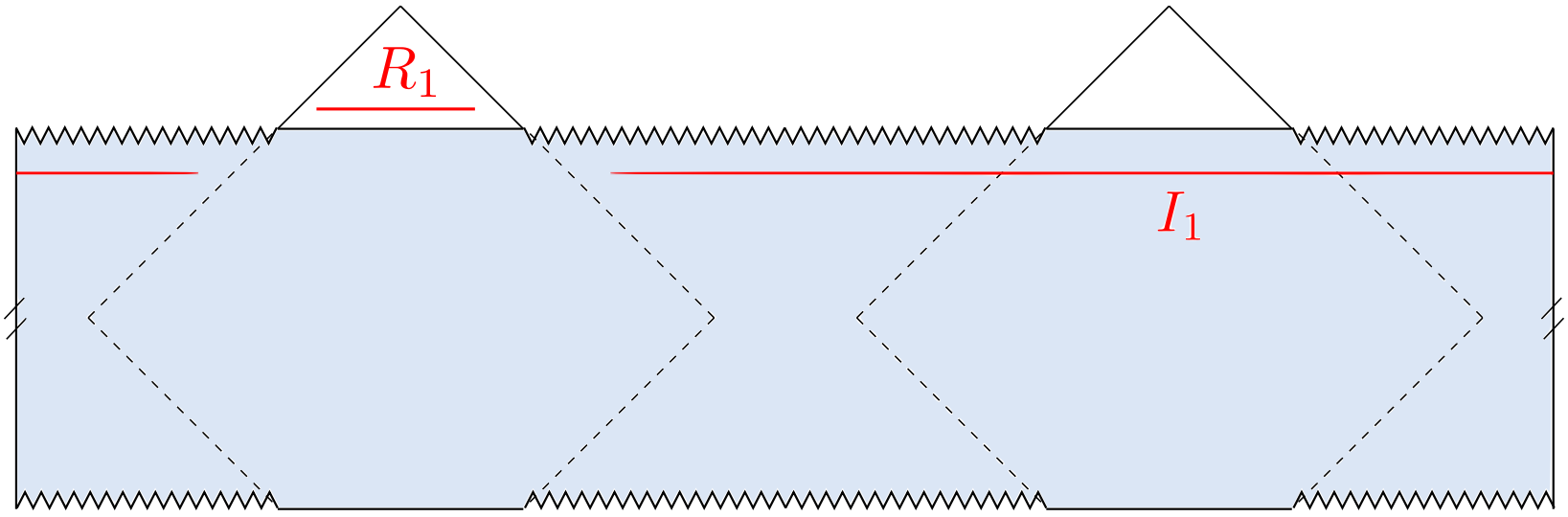

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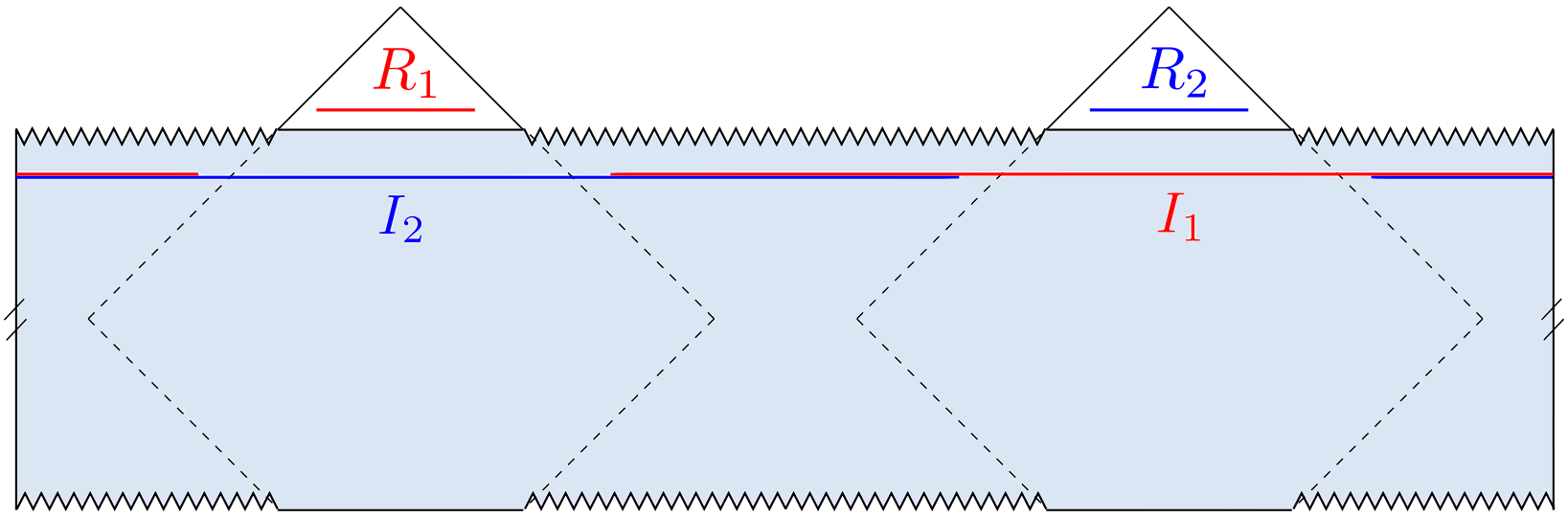

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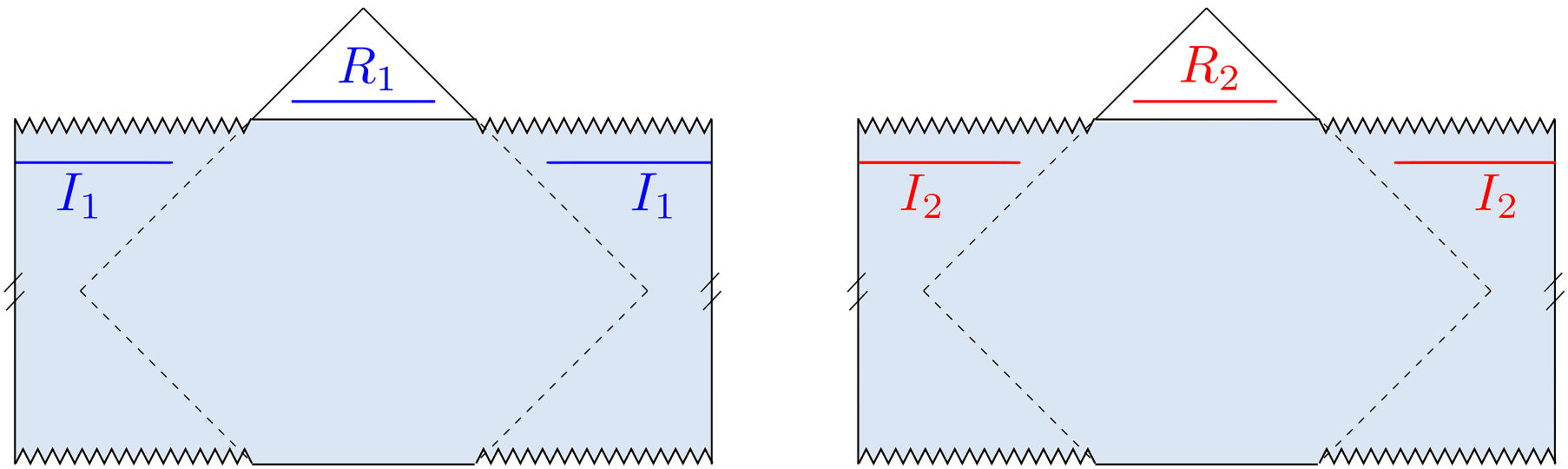

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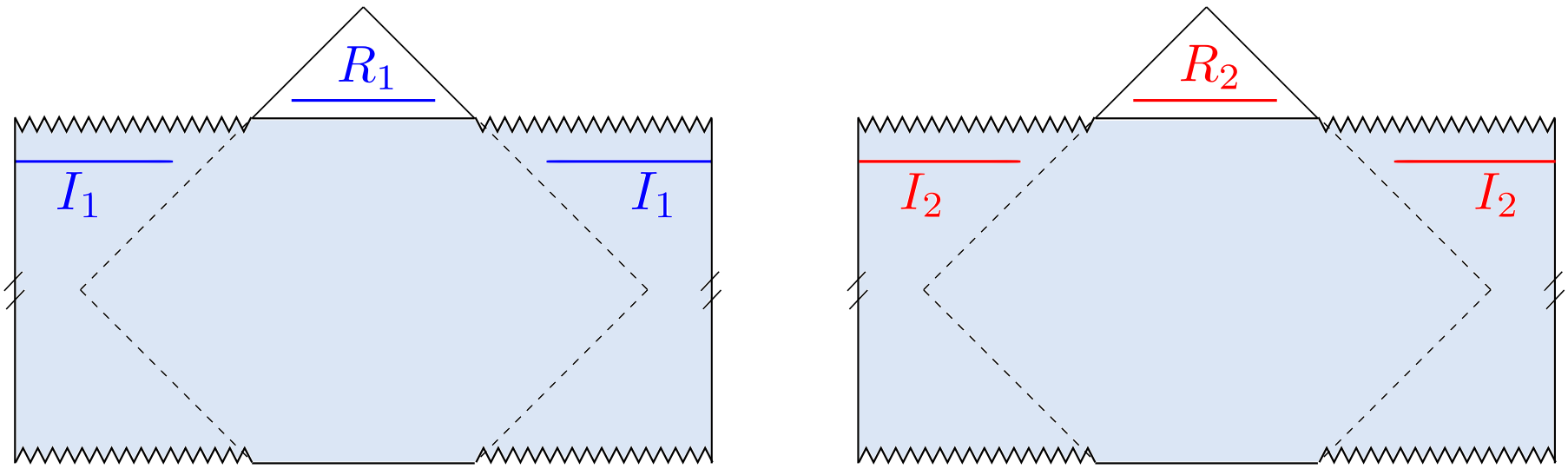

Maybe a semiclassical avatar of coarse-graining beyond the horizon

[Hartle, Hawking, Hertog]

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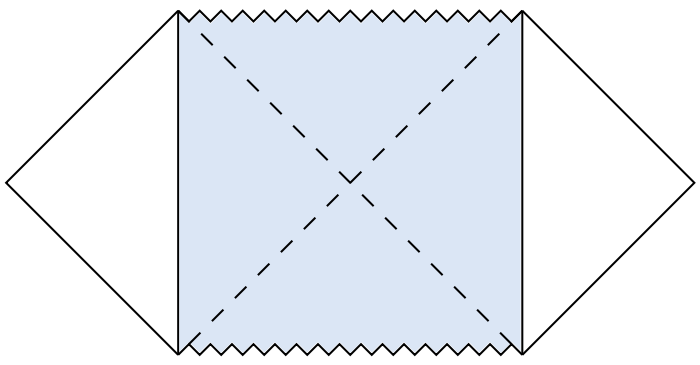
How to keep both hats in same spacetime? Revisit wings:



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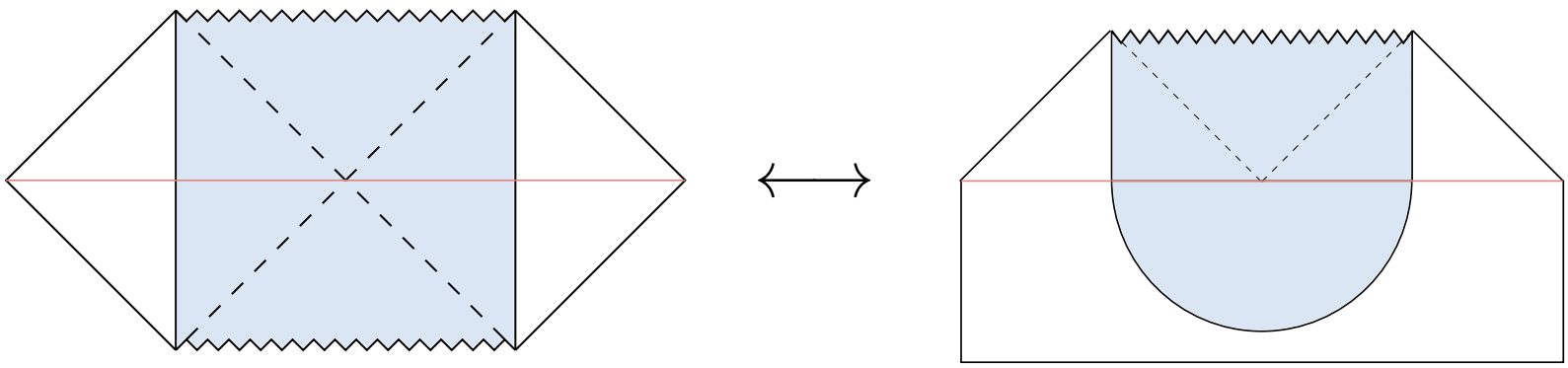

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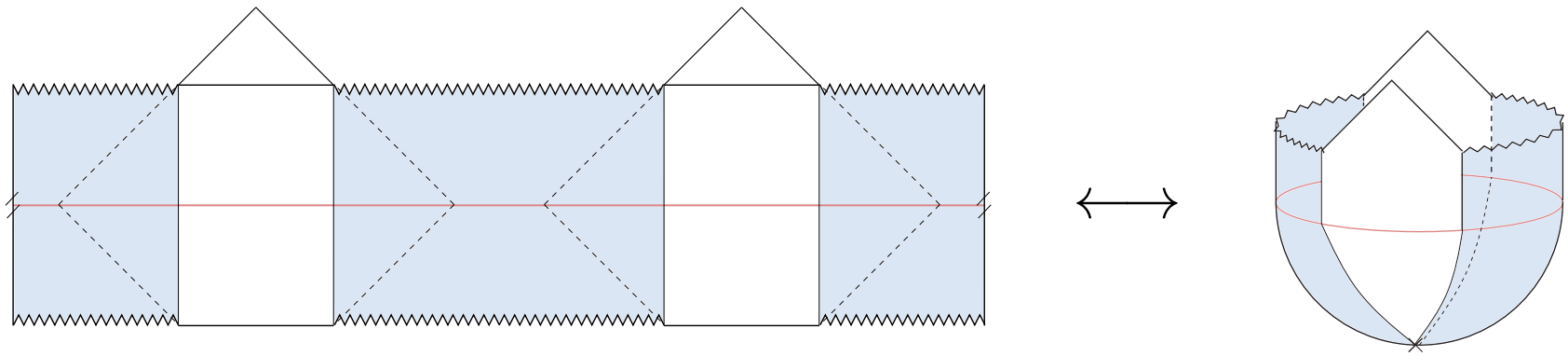

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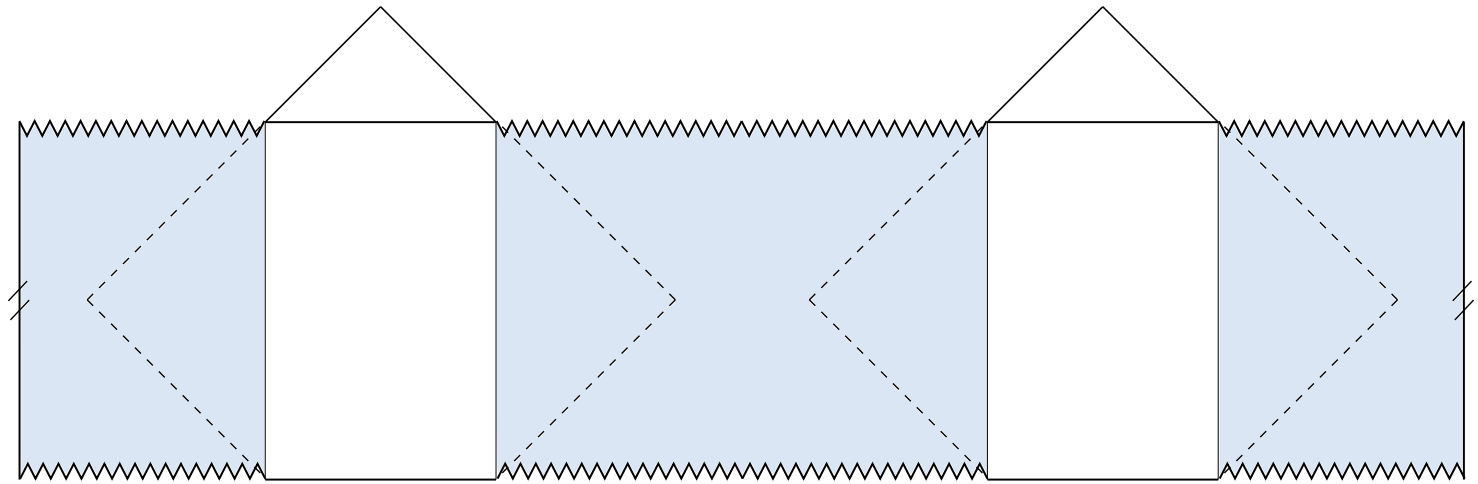

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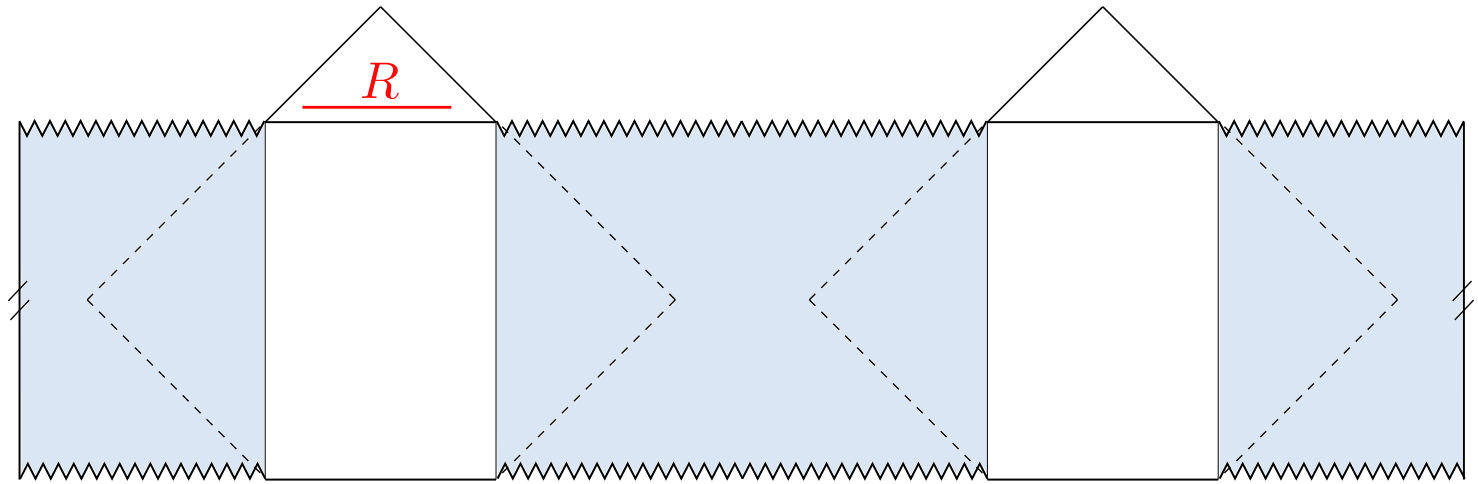

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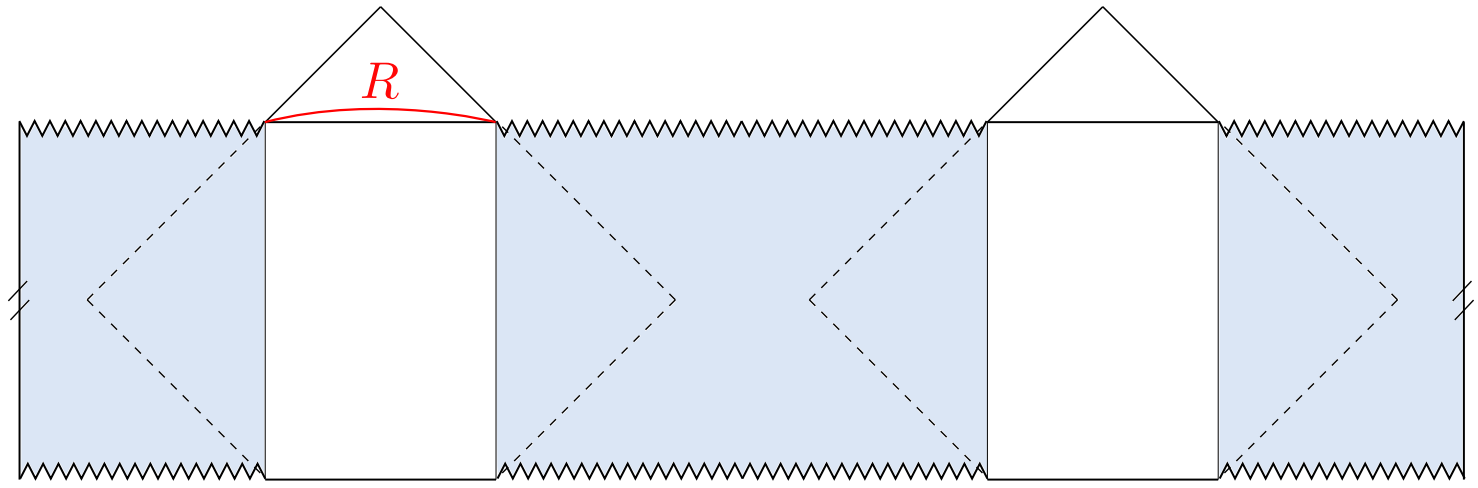

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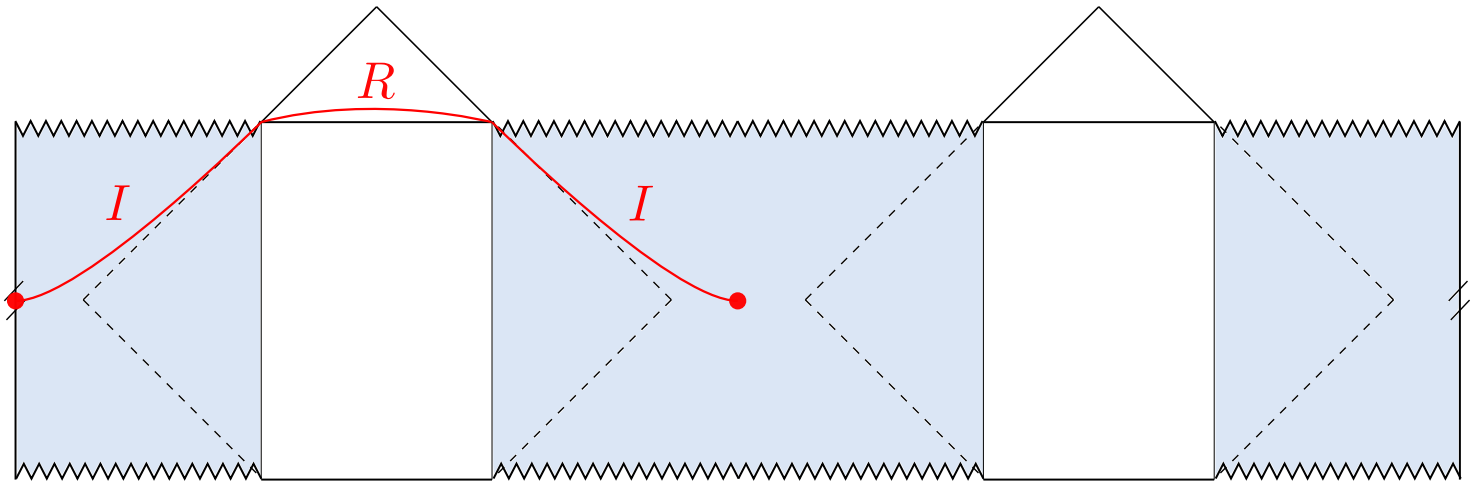

Decay of 2-point function

Two-point function in black hole background decays to zero, whereas for finite system we expect much richer structure. [Maldacena]

Wormholes on top of black hole background modify this conclusion. [Saad]

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Spectral form factor $\langle Z(iT)Z(-iT)\rangle$ is simpler observable which captures same issue. "Double cone" proposed to capture part of rich structure, the linear-in-T ramp for times $T \ll e^S$:

$$ds^2 = -\left(1 - \frac{\mu}{r^{d-2}} + r^2/\ell^2\right) dt^2 + \frac{dr^2}{1 - \frac{\mu}{r^{d-2}} + r^2/\ell^2} + r^2 d\Omega^2$$

$$t \sim t + T$$

Compact zero mode related to twist before identification of two sides gives a factor of T (rigorous in JT gravity).

dSouble cone

We would like to do the same thing in de Sitter [WIP w Banihashemi]:

$$ds^2 = -\left(1 - r^2\right) dt^2 + \frac{dr^2}{1 - r^2} + r^2 d\Omega^2$$

$$t \sim t + 2\pi i + T$$

Makes no sense to twist then glue the two disks together. Need to introduce a feature at pode and antipode (e.g. an observer/Dirichlet wall [Banihashemi, Jacobson]). Then can twist relative to this!

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General lesson: to mimic black hole features, we need to introduce a feature at static patch origin. [see e.g. Penington's talk]

Future

Gravity path integral may give clues to microscopic theory in dS.

Need somewhere to anchor ourselves: exit inflation, dress to observer, SOMETHING.

If you have a microscopic theory, please tell me.