Having Fun with Black Holes in dS

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Plan

* Motivation
* Shockwaves & information exchange
* SdS instantons
* Correlators & geodesics
* Summary

Motivation

QG in de Sitter?

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* $S_{dS} = \frac{3\pi}{G\Lambda}$?
* Information paradox / recovery ?

A bulk perspective

Inspired by AdS/CFT results (WHs) study $G \neq 0$ Non-Perturbative effects in de Sitter (EPI)

Euclidean Path Integral

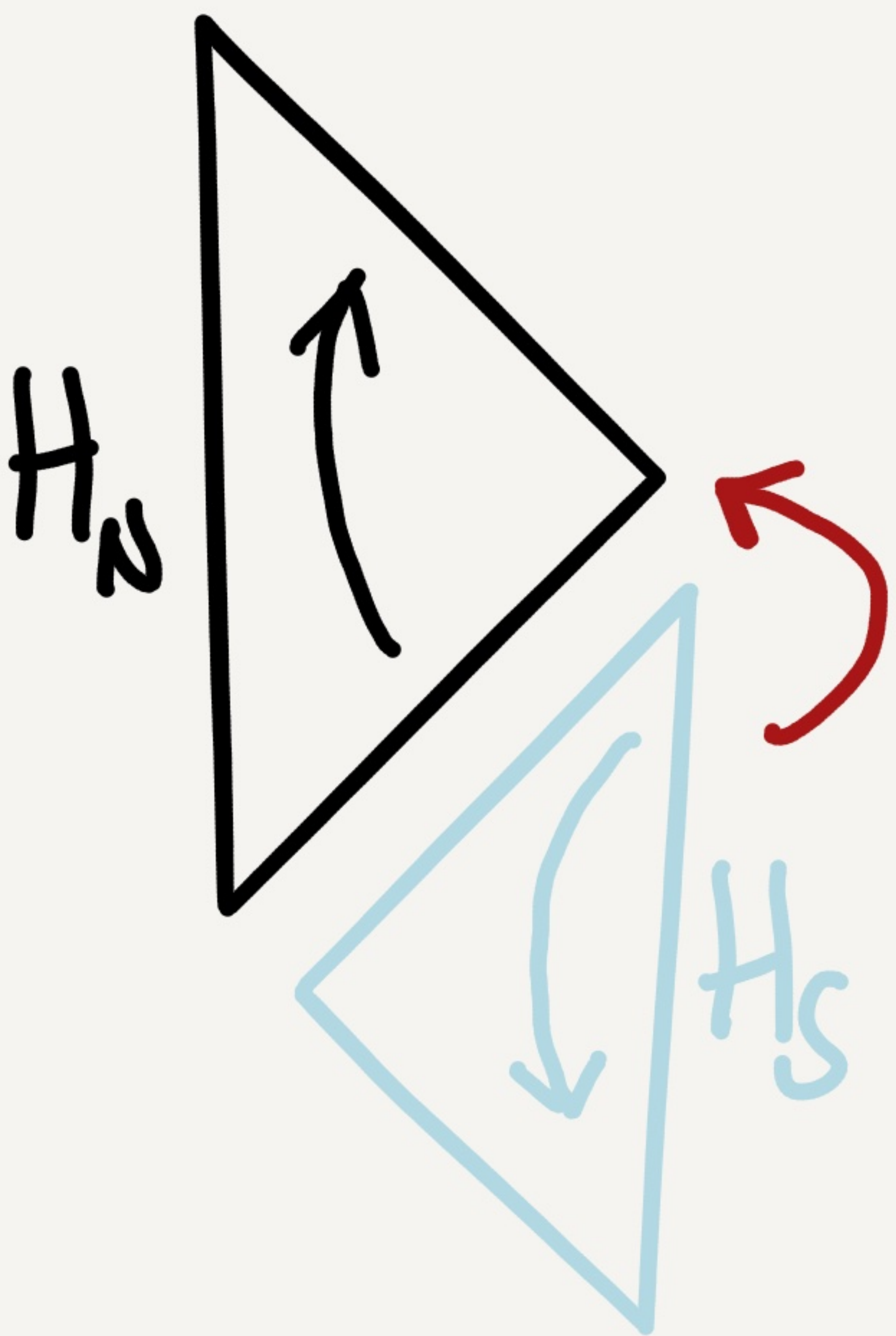
Black holes in AdS $\Rightarrow$ EPI & WHs

$$Z_{dS} = \int \mathcal{D}g \, e^{-S[g]}$$

(Annimos)

* Seems to know something about UV
* Study saddle-points (instantons)

States in the Static Patch



$H_N |0_S\rangle = 0 \Rightarrow$ singular

$$|TFD\rangle = \sum_i e^{-\beta/2 \, \varepsilon_i} |\varepsilon_i\rangle^N |\varepsilon_i\rangle^S$$

$$= |BD\rangle \Rightarrow \rho_N = \mathrm{Tr}_S |TFD\rangle \propto \underline{e^{-\beta H_N}}$$

$\Rightarrow$ smooth dS geometry

$(H_N - H_S)|TFD\rangle = 0$: boost isometry

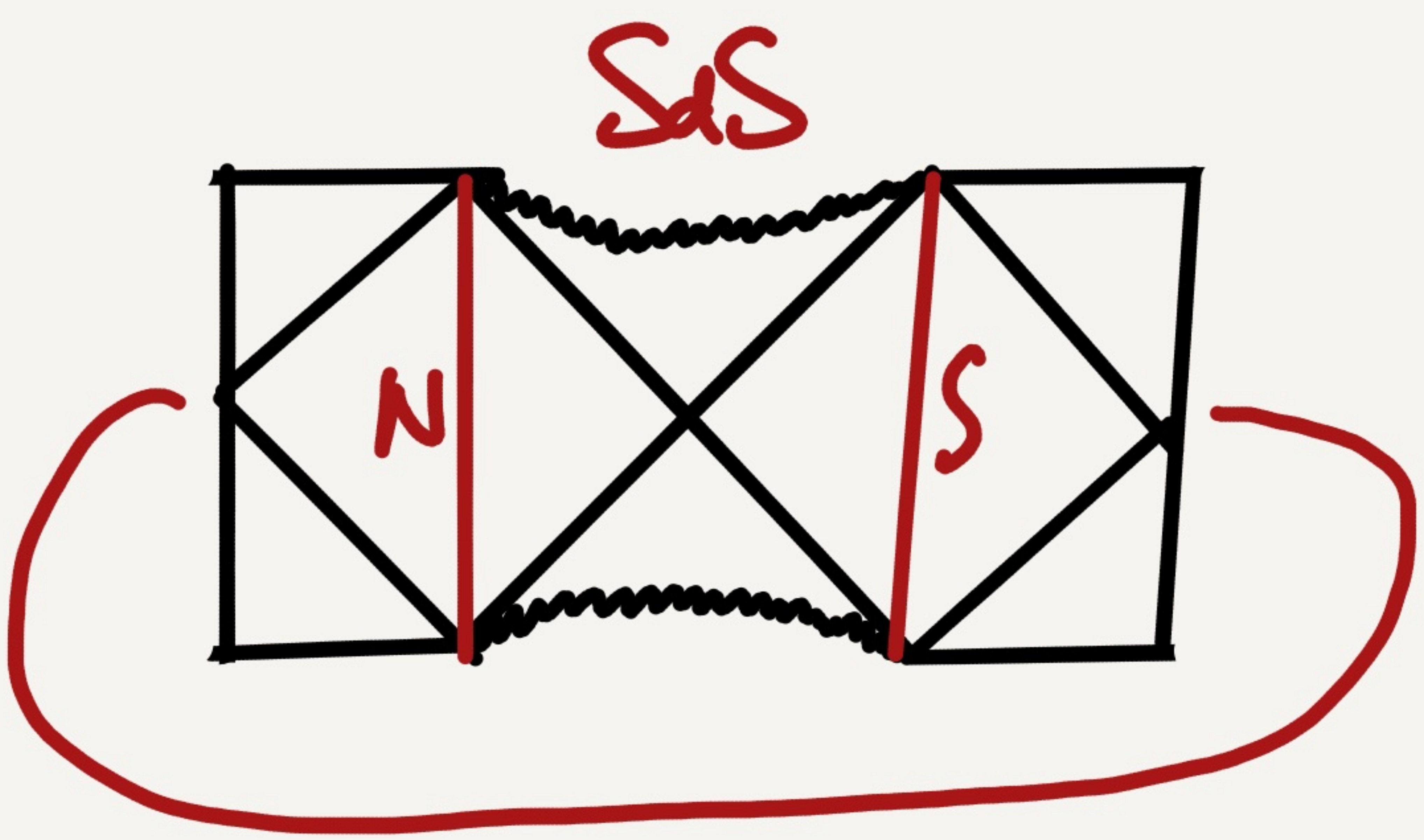
Excitations : $\frac{1}{2\pi \ell} \leq \varepsilon \leq \mathcal{O}(1) \frac{S_{dS}}{2\pi \ell}$

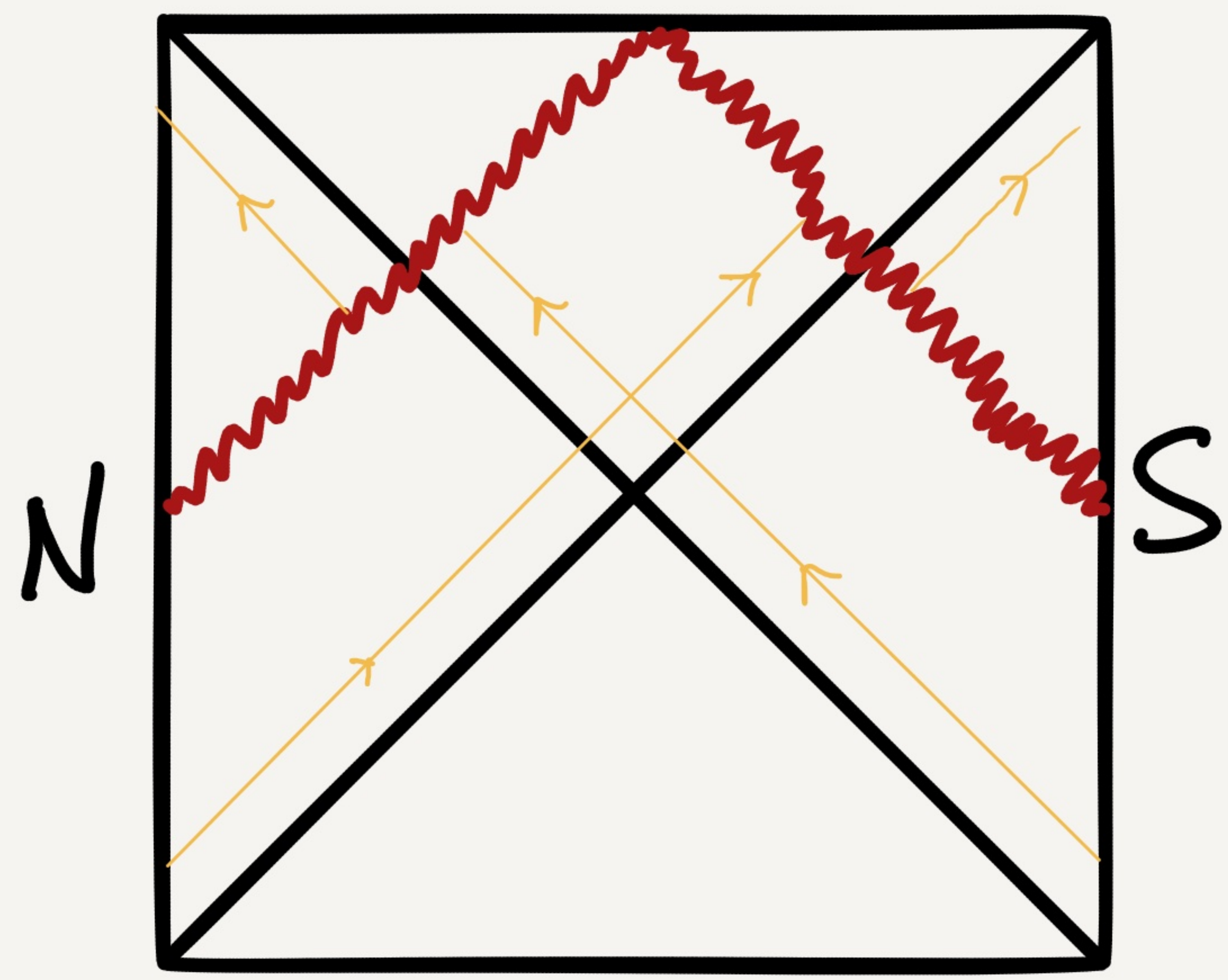
$\left(H_{tot} = H_N + H_S \rightarrow \text{nontrivial dynamics} \right)$ $\overline{\text{IR \& UV}}$ $\underline{\text{cut-off}}$.

dS Shockwaves & Information Exchange

Maldacena, Stanford, Yang 1704.05333
Verheijden

* $|BD\rangle = |TFD\rangle$
* Positive energy $\Rightarrow$ reservoir SdS
* $N \propto \log S_{dS}$





Aalsma, Cole, Morvan, Shiu, JPvdS 2105.12737

SdS solutions

$$ds^2 = -f(r)\,dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega_{d-2}^2$$

$$f(r) = \left(1 - \frac{r^2}{\ell^2} - \frac{\mu}{r}\right)$$; r_b, r_c : zeroes of $f(r)$

$\mu \leq \mu_{\text{Nariai}}$

$$I_E = -\frac{1}{16\pi G}\int d^d x \sqrt{g}\,(R - 2\Lambda)$$

* Strictly speaking : not saddle points
* Natural expectation : $I_E = -\left(\frac{A_b}{4G} + \frac{A_c}{4G}\right)$
* Lowest action, max entropy state : $\mu = 0$.

Non-equilibrium

* $T_b > T_c$: decay to max entropy dS
* Euclidean solution: conical singularity
* Except for $\mu = 0$, $\mu = \mu_{Nariai}$
* Nariai limit : $dS_2 \otimes S^2$
  True instanton saddlepoint (negative mode)

$$T_{b,c} = \frac{\kappa_{b,c}}{2\pi} \; ; \; \xi^\mu \nabla_\mu \xi^\nu = \kappa \xi^\nu$$

$$\xi = \gamma \partial_t \; ; \; \gamma = \frac{1}{\sqrt{f(r_0)}} \Rightarrow T_N = \frac{1}{2\pi \ell_2}$$

$$T_b \delta S_b + T_c \delta S_c = 0$$

Draper, Farkas
2203.02426

Morvan, Visser, JPvdS
2203.06155

Conical Singularities & the Euclidean Action

Smarr : $\boxed{T_b S_b + T_c S_c - \frac{\Theta \Lambda}{8\pi G} = 0}$; $\Theta = \int_\Sigma \xi \, dV$

SdS Euclidean action : $I_E = I_E^{bulk} + I_E^{con}$

$$I_E^{bulk} = -\frac{\beta \Theta \Lambda}{8\pi G}$$

$$I_E^{con} = -\frac{1}{8\pi G}\left(A_b \varepsilon_b + A_c \varepsilon_c\right) = -\frac{A_b}{4G} - \frac{A_c}{4G} + \frac{A_b n_b}{4G} + \frac{A_c n_c}{4G}$$

$$\varepsilon_{b,c} = 2\pi(1 - n_{b,c}) \; ; \; \beta \kappa_{b,c} = 2\pi n_{b,c} \quad \left(T_{b,c} = \frac{\kappa_{b,c}}{2\pi}\right)$$

Works in general dimensions

$$I_E = \beta \underbrace{\left[\frac{A_b \kappa_b}{8\pi G} + \frac{A_c \kappa_c}{8\pi G} - \frac{\Theta \Lambda}{8\pi G}\right]}_{=0} \boxed{- \frac{A_b}{4G} - \frac{A_c}{4G}} \quad ✓$$

Conical Singularities & the Euclidean Action

$$I_E = I_E^{bulk} + I_E^{con}$$

$\oplus$ Smarr relation

$$\Longrightarrow \boxed{I_E = -(S_b + S_c)}$$

Gregory, Moss, Withers 1401.0017

* Fluctuation probabilities governed by entropy difference $P_{SdS} \propto e^{-\Delta S}$

$$\Delta S = S_{dS} - (S_b + S_c)$$

Constrained Instantons

EPI : sum over geometries with conical sing.

How? Not saddle-points!

$$\Rightarrow \quad Z = \int Dg\, e^{-I_E[g]} \propto e^{-I_0[g_0]}$$

$$= \int Dg \int d\mu\, \delta(C[g]-\mu)\, e^{-I_E[g]}$$

$$= \int Dg \int d\mu \int_{-i\infty}^{+i\infty} d\lambda\, e^{-I_E[g]+\lambda(C[g]-\mu)}$$

$$-\delta I_E + \lambda\, \delta C = 0$$
$$C[g] = \mu$$

Cotler Jensen
2104.00601

Black Hole Fluctuations

$$\Gamma_{\text{dS}} \propto \int d\mu \, \langle BD|SdS\rangle\langle SdS|BD\rangle$$

$$= \int_0^1 d\mu \; e^{-\Delta S(\mu)} \; ; \; \Delta S \approx (S_{dS}-S_N)\mu$$

$$\simeq \frac{\mu_N}{S_{dS}-S_N}\left(1-e^{-(S_{dS}-S_N)}\right) \simeq T_{dS}\left(1-e^{-(S_{dS}-S_N)}\right)$$

Susskind

- T_{dS} part : Gibbons-Hawking rate
- $\exp(-S_{dS}-S_0)$: Nariai instanton 'contribution'

$\Longrightarrow$ charged generalization (Morvan)

Morvan, Visser, JPvdS 2212.12713

Late-time correlators @ finite G

$$\langle BD | O_N O_S | BD \rangle_{G\neq 0} \simeq \langle BD | O_N O_S | BD \rangle_{G=0}$$

$$+ \int d\mu \, \langle BD | O_N | S_{dS} \rangle \langle S_{dS} | O_S | BD \rangle$$

$$+ \ \ldots$$

breaking dS isometries except boosts

Susskind

$$\langle BD | O_N(t) O_S(-t) | BD \rangle_{G=0} \propto e^{-\lambda t}$$

$$\underline{G \neq 0} \Rightarrow S_{dS} = \frac{A}{4G} \Rightarrow$$ quasi-periodic correlators $O(e^{-S_{dS}})$

AdS/CFT: non-perturbative contributions $\longleftrightarrow$ de Sitter ?

Beyond the Exponential

Constraint functional $C[g] \to$ fixing the conical singularity

* Compute 1-loop det
  $\Rightarrow$ zero-mode volume (boost isometry)

Observation: zero-mode volume of AdS WH's generates ramping behavior of the spectral form factor.

$$\Omega(\beta_1, \beta_2) \propto \frac{\sqrt{\beta_1 \beta_2}}{\beta_1 + \beta_2} \sim \frac{T}{\beta}$$

Work in progress:
Chris Ventura, Manus Visser

Saad, Shenker, Stanford 1806.06840
Saad 1910.10311
Cotler, Jensen, 2104.00601

Correlators & Geodesics

* Heavy mass & late-time
  ⇒ geodesic approximation
* dS geodesics & late-time exponential decay.

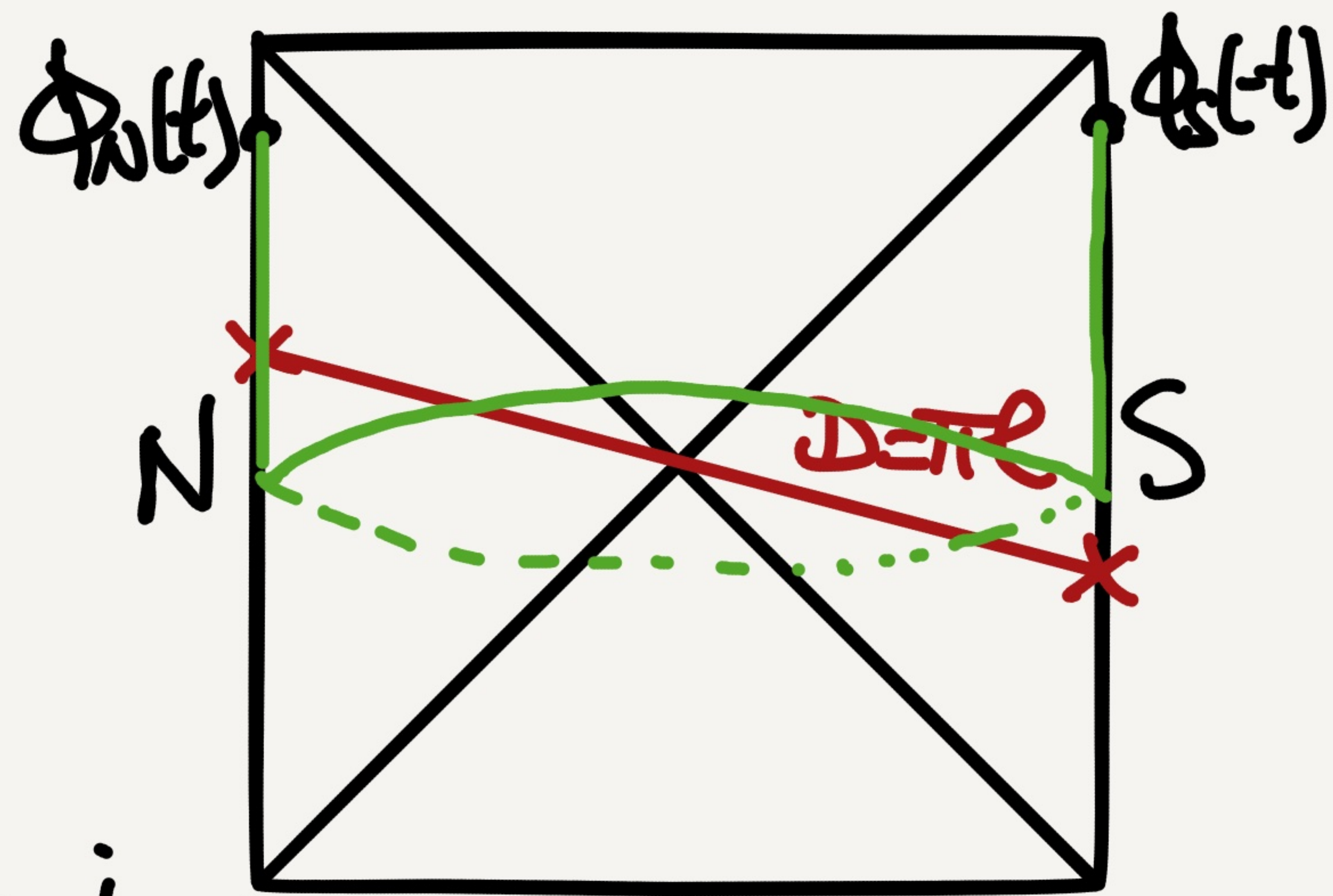
⇒ Sum over (complex) geodesics in heat kernel approximation

Chapman, Galante, Harris, Sheorey, Vegh 2212.01398

Aalsma, Mehedi Faruk, de Witte, Visser, JPvdS 2212.01394

Conjugate Correlator

$$\langle BD|\,\phi_N(t)\,\phi_S(-t)\,|BD\rangle$$



$$Z(x,y) = \frac{1}{e^2}\,\eta_{AB}\,X^A(x)\,X^B(y)$$
$$= \cos\left(\frac{D(x,y)}{e}\right)$$

$$G(x,y) = i\int_0^\infty ds\; K(x,y;s)$$

$$K(x,y;s) = -i\left(\frac{1}{4\pi i s}\right)^2 e^{-im^2 s + \frac{i}{2s}\sigma(x,y)}\,\Delta(x,y)^{1/2}\,(1+\dots)$$

$$\Rightarrow\; T_c = -i\pi e + T \quad ; \quad W(x,y) = i\,G_s(T_c) - i\,(G_s(T_c))^*$$
$$\propto e^{-Me\pi}\,\underline{\underline{e^{-\frac{3}{2}\frac{T}{e}}}}\,\cos\left(\frac{3\pi}{4} - MT\right)$$

Late time decay

$$W(x,y) \propto e^{-\frac{3}{2}T/\ell}\, e^{-n\pi\ell} \quad ; \; T_c = -i\pi\ell + T$$

* Exponential decay $\rightarrow$ <u>timelike part</u>
* Proof of principle $\rightarrow$ SdS heat kernel
* NP corrections $\rightarrow$ corrections due to new geodesics.

Summary

- SdS corrections (1-loop det + correlators)
- Correlators & geodesics → SdS
- Information recovery protocol?
- Other NP corrections? Higher order?

Thanks!