# OPEN QUANTUM SYSTEMS AND HOLOGRAPHIC THERMAL BATHS


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Geometry from the Quantum

Jan 16, 2020


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# MOTIVATION: OPEN QUANTUM SYSTEMS

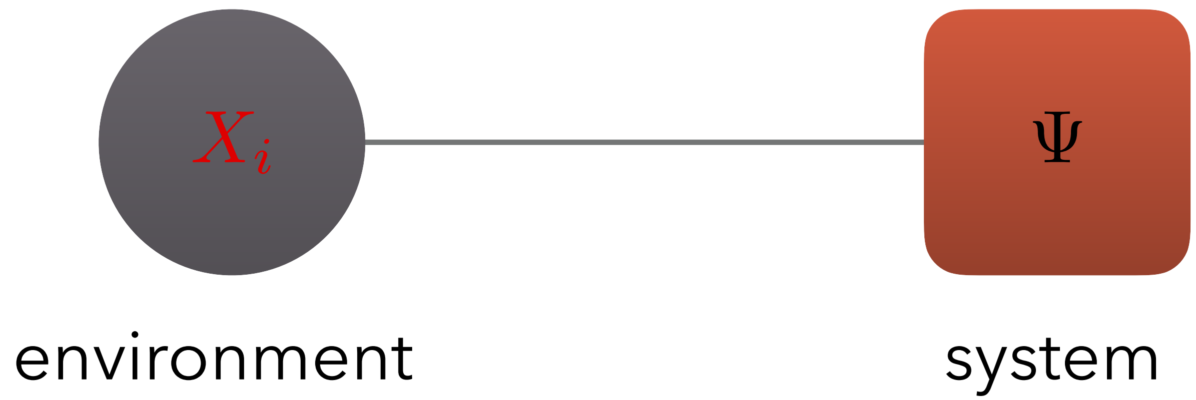
- Open quantum systems are ubiquitous: systems interacting with environment.
- Techniques to analyze effective dynamics while available in principle, have been challenging to implement in practice.
- Challenges: constraining influence functionals which need to encode of microscopic unitary evolution of system+environment.
- Identifying fluctuations associated with  the dissipation: non-linear fluctuation/dissipation relations.

# MOTIVATION: HORIZON DYNAMICS

- Horizons in general relativity behave effectively open: things fall in.
- Horizons induce thermal behaviour: dissipation well understood, fluctuations encoded in Hawking quanta generically suppressed.
- Scattering Hawking quanta off infalling matter?
- Implementing Schwinger-Keldysh in gravitational systems?

Use holographic systems to model and derive the general structure of open QFTs & obtain quantitative predictions for strongly coupled thermal baths.

# II. OPEN QFT PARADIGM




$$S_{\rm s}[\Psi] + S_{\rm e}[X_i] + S_{\text{s-e}}[\Psi, X_i]$$

$$\int [D\Psi] \int [DX_i] e^{i(S_{\rm s}[\Psi]+S_{\rm e}[X_i]+S_{\text{s-e}}[\Psi,X_i])} = \int [D\Psi_{\rm L}][D\Psi_{\rm R}] e^{i(S_{\rm s}[\Psi_{\rm R}]-S_{\rm s}[\Psi_{\rm L}]+S_{\rm IF}[\Psi_{\rm R},\Psi_{\rm L}])}$$

*influence functionals*

constrained by
microscopic unitarity

Feynman, Vernon; Caldeira Leggett

# HOLOGRAPHIC BATHS

- Story for Gaussian environment is well understood and leads in QM to effective Langevin dynamics.
- Fluctuation/dissipation relations follow from common microscopic origin – induced by the Gaussian environment.
- Non-Gaussian baths understood in QM cf., Chaudhuri, Chakrabarty, Loganayagam
- But challenging in QFT… Avinash, Jana, Loganayagam, Rudra

*Study open QFTs semi-holographically* Faulkner, Polchinkski

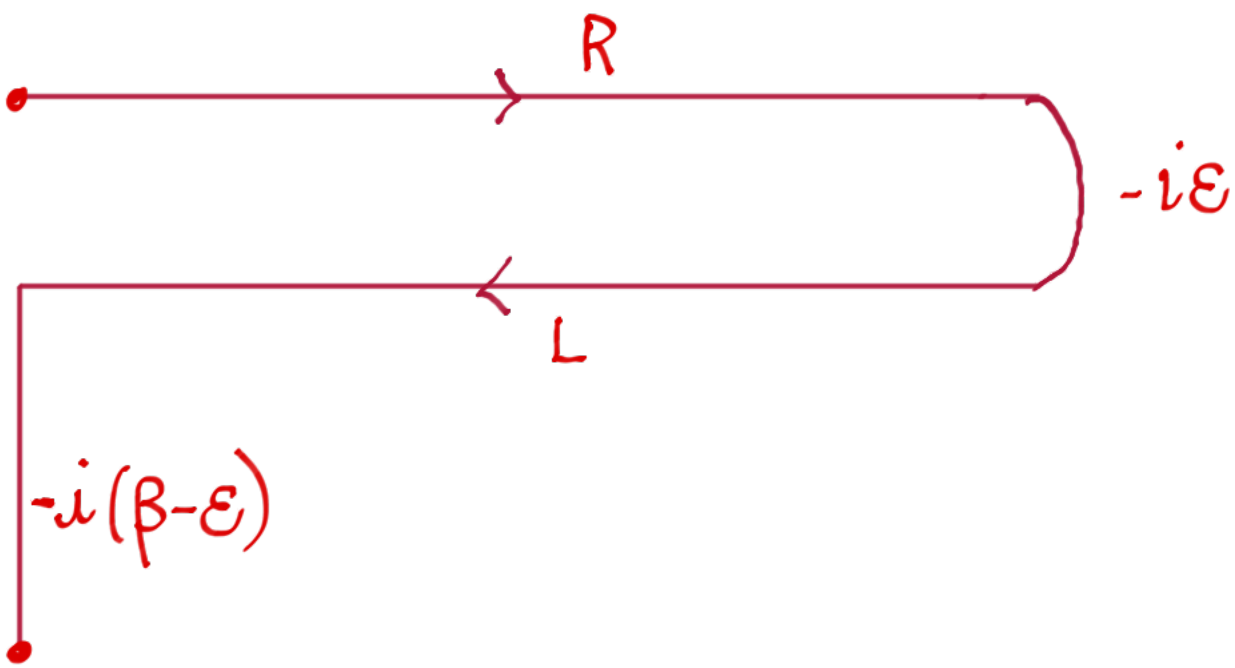
Influence functionals for a scalar EFT computed by holographic Schwinger-Keldysh observables.

$$S = \int d^d x \left( \mathcal{L}[\Psi] + \mathcal{L}[X] + \Psi(x)\, \mathcal{O}(x) \right)$$

probe quantum system

holographic bath

# III. SCHWINGER-KELDYSH OBSERVABLES




$$\mathcal{Z}_T[\mathcal{J}_{\rm R}, \mathcal{J}_{\rm L}] = {\rm Tr}\left(U[\mathcal{J}_{\rm R}]\, \hat{\rho}_T\, (U[\mathcal{J}_{\rm L}])^\dagger\right)$$

$$\mathcal{O}_a = \frac{1}{2}\left(\mathcal{O}_{\rm R} + \mathcal{O}_{\rm L}\right) , \qquad \mathcal{O}_d = \mathcal{O}_{\rm R} - \mathcal{O}_{\rm L}$$

$$J_a = \frac{1}{2}\left(J_{\rm R} + J_{\rm L}\right) , \qquad J_d = J_{\rm R} - J_{\rm L}$$

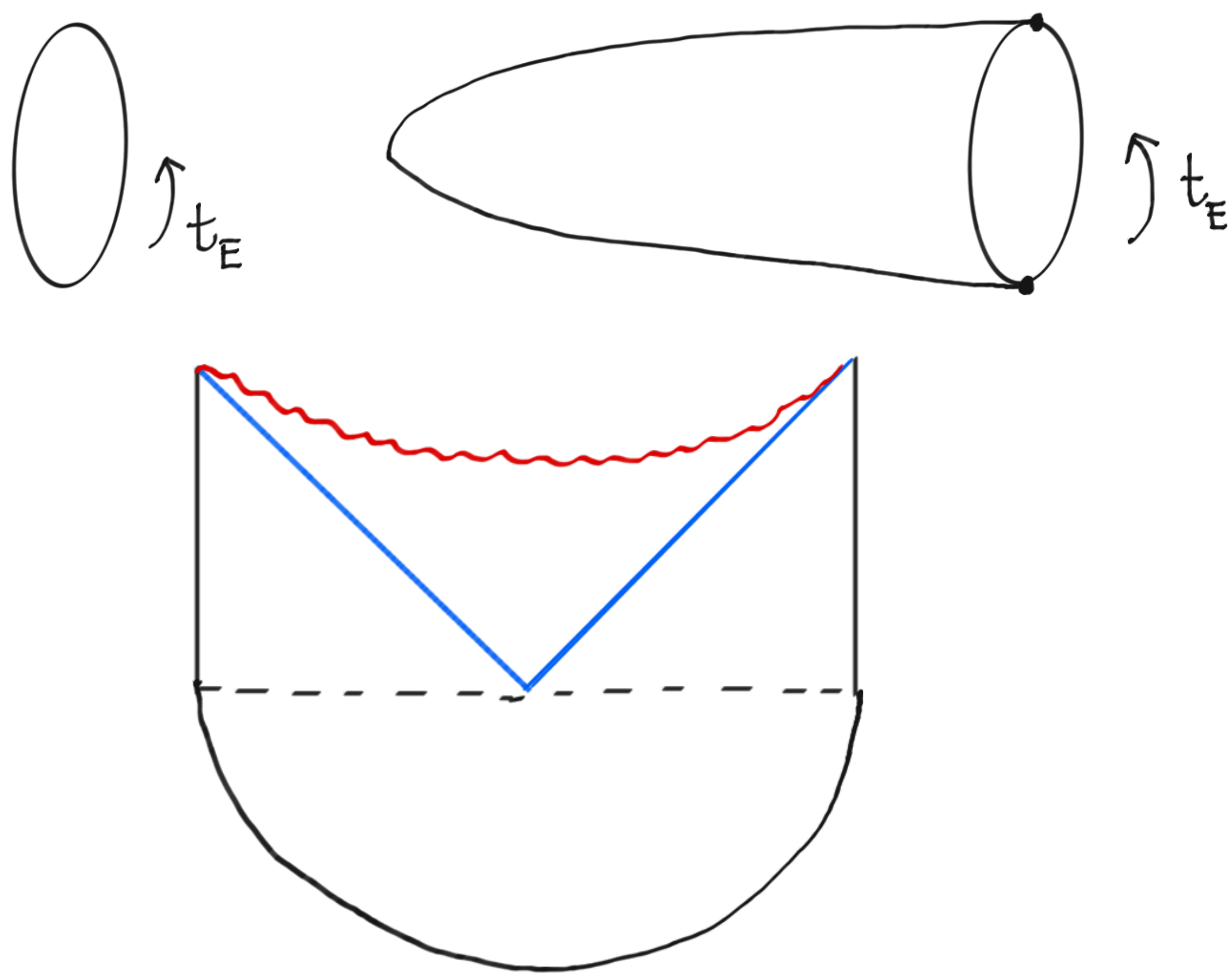
$$S_{IF}[J_a, J_d] = 0\,(J_a)^k + \mathfrak{I}_{aa\cdots d}\,(J_a)^{k-1}\, J_d + \cdots + \mathfrak{I}_{d\cdots d}\,(J_d)^k$$

$$\langle \mathcal{T}_{SK}\, \mathcal{A}_a \mathcal{B}_a \rangle = \langle \{\mathcal{A}, \mathcal{B}\} \rangle$$

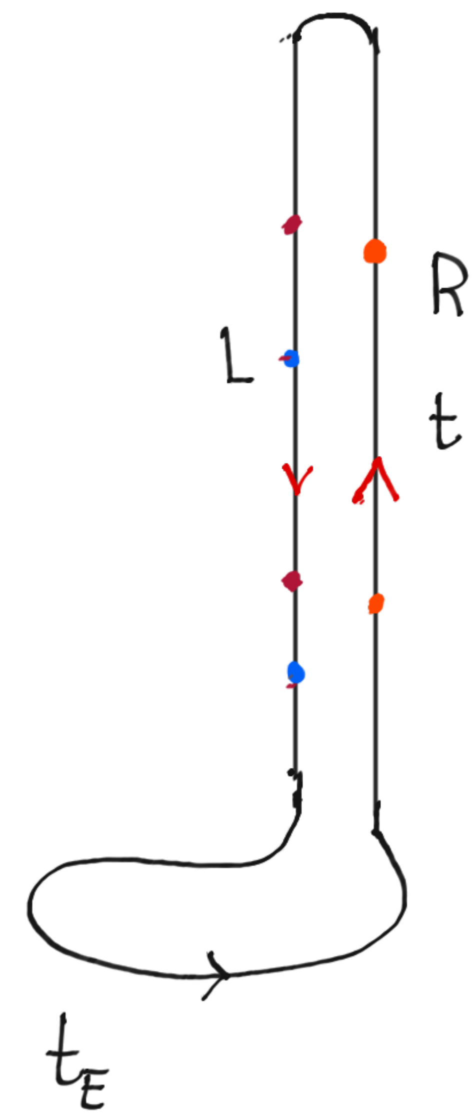
$$\langle \{\mathcal{A}, \mathcal{B}\} \rangle = \coth\left(\frac{\beta \omega_{\mathcal{A}}}{2}\right)\, \langle [\mathcal{A}, \mathcal{B}] \rangle$$

Fluctuation/
dissipation

# IV. INTERLUDE: TFD VS SK HOLOGRAMS



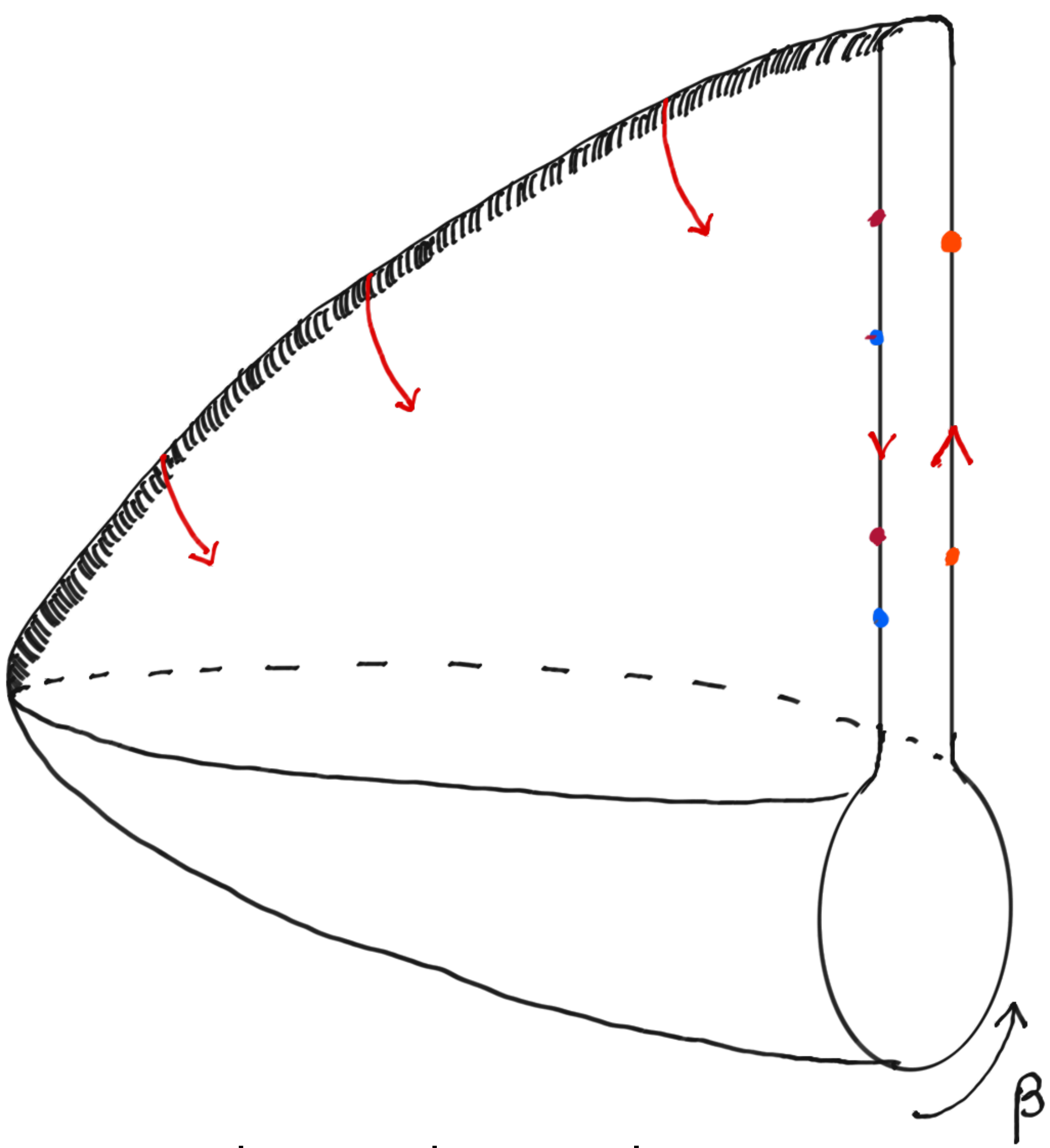

TFD construction from the Euclidean QG path integral

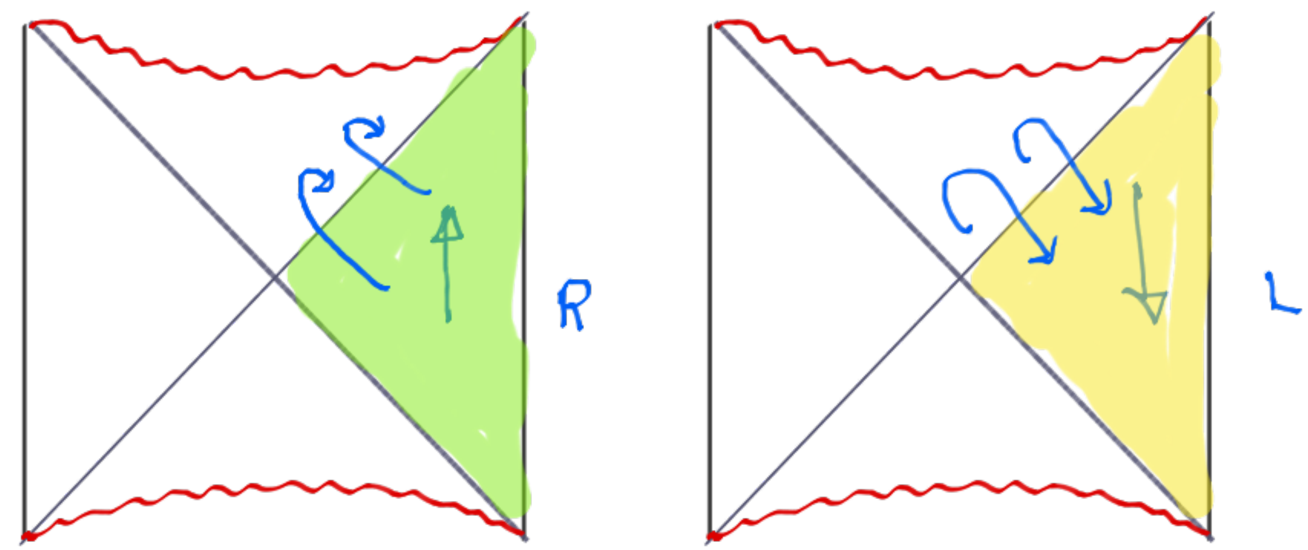



Holographic SK geometry: to be obtained by filling in the boundary SK contour

# IV. SCHWINGER-KELDYSH HOLOGRAMS

Glorioso, Crossley, Liu




Skenderis, van Rees

Two sheeted complex geometry
glued across future horizon

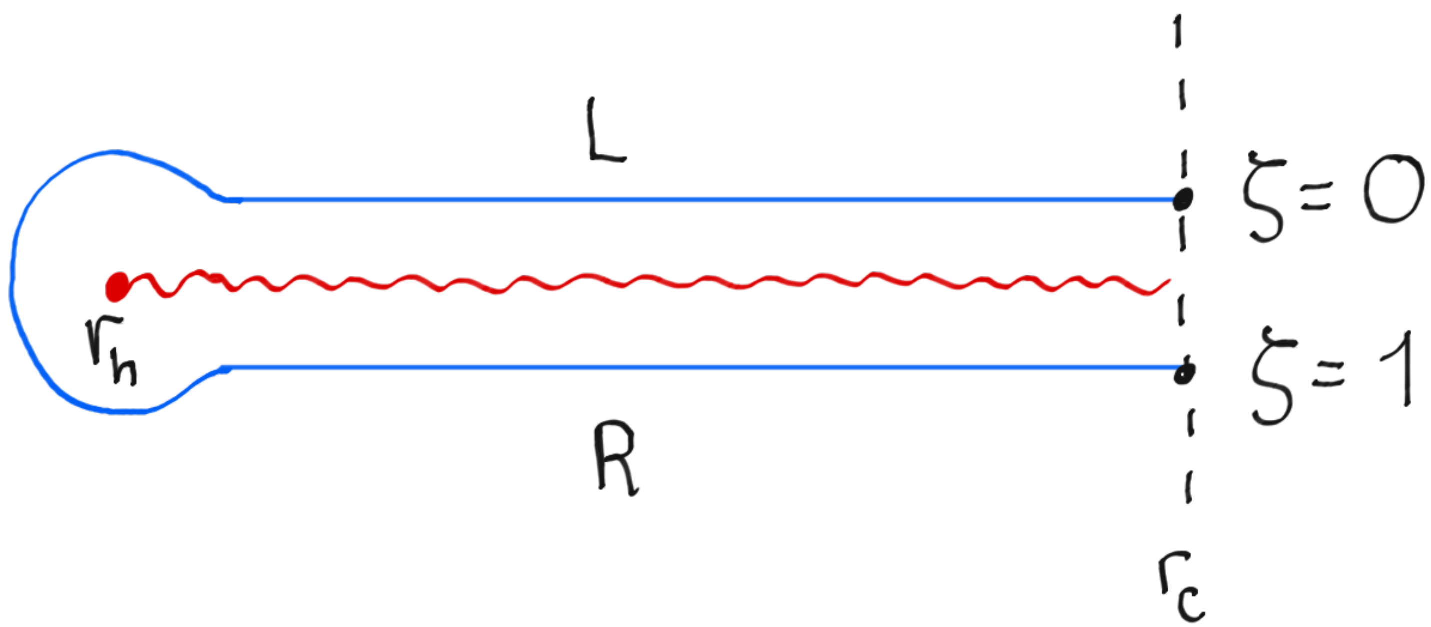
Son, Starinets    Herzog, Son

de Boer, Heller, Pinzani-Fokeeva

# IV. SCHWINGER-KELDYSH HOLOGRAMS

ingoing EF coordinates $ds^2 = -r^2\, f(r)\, dv^2 + 2\, dv\, dr + r^2\, d\mathbf{x}^2\,, \qquad f(r) = 1 - \frac{r_h^d}{r^d}\,.$

$$\frac{dr}{d\zeta} = \frac{i\,\beta}{2}\, r^2\, f(r) \qquad \zeta(r_c + i\,\varepsilon) = 0\,, \qquad \zeta(r_c - i\,\varepsilon) = 1\,.$$




*mock tortoise coordinate*

$$ds^2 = -r^2\, f(r)\, dv^2 + i\,\beta\, r^2\, f(r)\, dv\, d\zeta + r^2\, d\mathbf{x}^2$$

# IV. BOUNDARY-BULK PROPAGATORS

future ingoing/retarded
regular on future horizon

$$G^+(\omega, k, \zeta)$$

$$G^+\big|_{r_c} = 1\,, \qquad \frac{dG^+}{d\zeta}\bigg|_{r_h} = 0$$

outgoing/advanced

$$G^-(\omega, k, \zeta)$$

$$v \to i\,\beta\,\zeta - v\,, \qquad \omega \to -\omega$$

solutions related by time reversal implemented by an involution on the geometry

$$G^-(\omega, k, \zeta) = G^+(-\omega, k, \zeta)e^{-\beta\omega\,\zeta}$$

# V. OPEN SCALAR DYNAMICS

Scalar operator: dual scalar dynamics in the holographic SK geometry

$$S_\Phi = -\oint d\zeta \int d^d x\, \sqrt{-g}\, \left[\frac{1}{2}\, g^{AB}\, \partial_A \Phi \partial_B \Phi + \frac{1}{2}\, m^2\, \Phi^2 + \frac{\lambda}{4!}\, \Phi^4\right]$$

Standard Dirichlet boundary conditions asymptotically. General solution on the holographic SK geometry given by Green's functions:

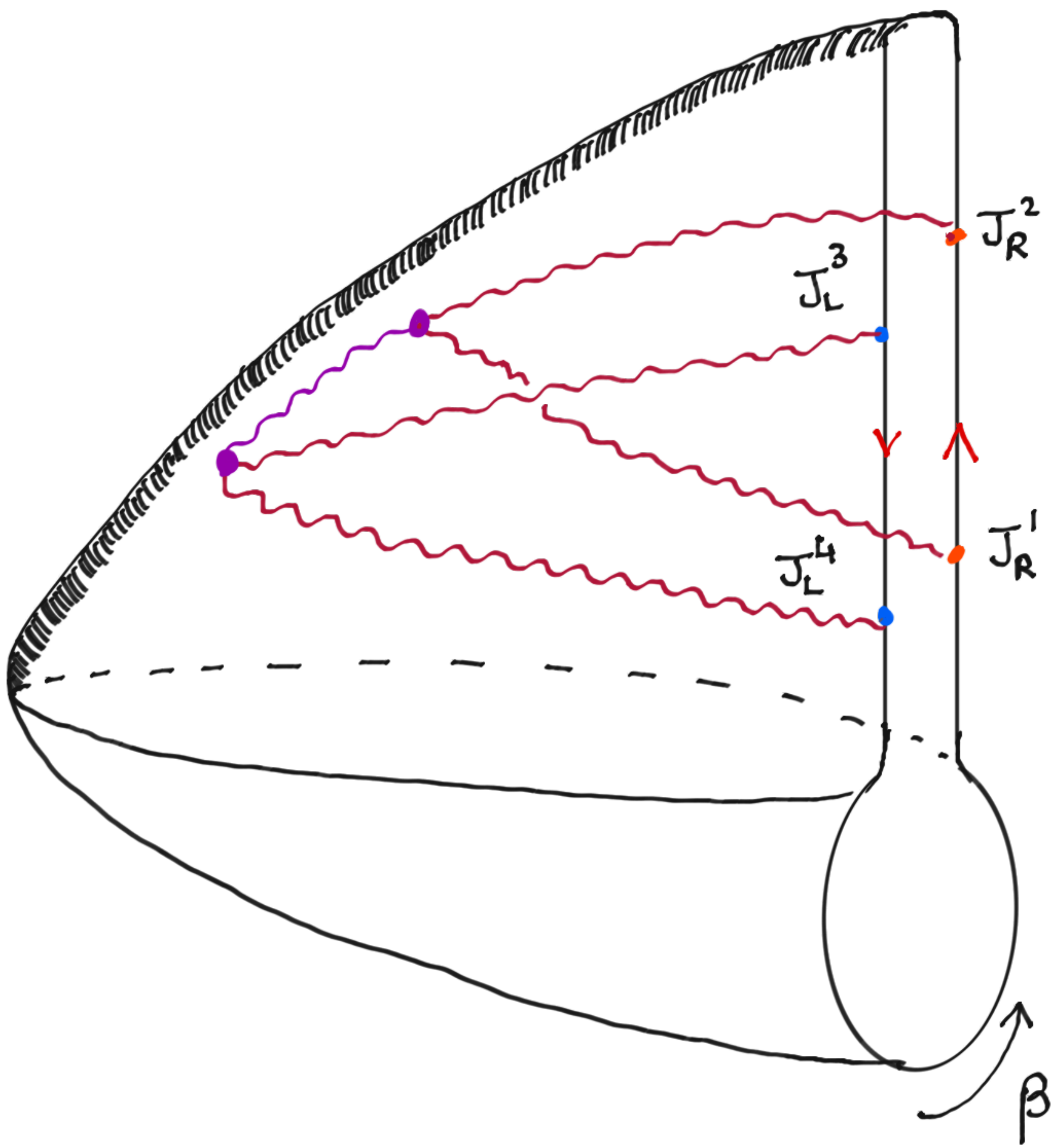
$$\begin{aligned}\Phi(\omega, k, \zeta) &= G^+(\omega, k, \zeta)\left(J_a(\omega, k) + \left(n_\omega + \frac{1}{2}\right) J_d(\omega, k)\right) - n_\omega\, e^{\beta\omega(1-\zeta)}\, G^-(\omega, k, \zeta)\, J_d(\omega, k) \\ &= G^+\, J_a + \frac{1}{2}\, G^H\, J_d\end{aligned}$$

$$n_\omega \equiv \frac{1}{e^{\beta\omega} - 1}$$

Hawking Green's function

Thermal structure built in (transported into the bulk via the mock tortoise coordinate).

# IV. SCHWINGER-KELDYSH HOLOGRAMS




Witten diagrams on the holographic SK geometry

# V. OPEN SCALAR DYNAMICS: RESULTS

1. Quadratic terms in the influence function: d=2 CFTs

Gubser

retarded Green's function with the quasinormal spectrum

Son, Starinets

$$\mathfrak{I}_{ad}(\omega, k) = -\frac{4}{\pi\beta}\frac{1}{\Gamma(\Delta-1)^2}\left|\Gamma\left(\Delta-\mathfrak{p}_-\right)\Gamma\left(\mathfrak{p}_+\right)\right|^2 \sin\left(\pi\left(\Delta-\mathfrak{p}_+\right)\right)\sin\left(\pi\left(\Delta-\mathfrak{p}_-\right)\right)$$

Birmingham, Sachs, Solodukhin

fluctuation counterpart related by fluctuation/dissipation:

$$\mathfrak{I}_{dd}(\omega, k) = \frac{i\pi}{2}\frac{\cosh\left(\mathfrak{w}\right)\sin\left(\pi\Delta\right)}{\cosh\left(\mathfrak{q}\right)-\cosh\left(\mathfrak{w}-i\,\pi\,\Delta\right)}\mathfrak{I}_{ad}(\omega, k)$$

$$\mathfrak{w} = \frac{\beta\omega}{2}\,, \qquad \mathfrak{q} = \frac{\beta k}{2} \qquad\qquad \mathfrak{p}_+ = i\,\frac{\mathfrak{q}-\mathfrak{w}}{2\pi}+\frac{\Delta}{2}\,, \qquad \mathfrak{p}_- = -i\,\frac{\mathfrak{q}+\mathfrak{w}}{2\pi}+\frac{\Delta}{2}$$

2. Quadratic terms in the influence function: general d CFTs (dimension d scalar)

$$\mathfrak{I}_{ad}(\omega, \mathbf{k}) = i\, r_h^{d-1}\,\omega\,, \qquad \mathfrak{I}_{dd}(\omega, \mathbf{k}) = \frac{i}{\beta}\, r_h^{d-1}$$

# V. OPEN SCALAR DYNAMICS: RESULTS

Quartic terms in the influence function (gradient expansion):
general d marginal scalar operator

$$\mathfrak{I}_{aaaa} = 0$$

$$\mathfrak{I}_{aaad} = \frac{i\,\lambda_+}{3!}\delta(k)$$

$$\mathfrak{I}_{aadd} = -\frac{i\,\lambda_+}{4}\,\frac{\beta\omega_4}{4}\,\delta(k)$$

$$\mathfrak{I}_{addd} = \frac{i\,\lambda_+}{3!}\left[\frac{1}{2} + \frac{3i\,\zeta(3)}{2\pi^3}\,\beta\omega_4\right]\delta(k)$$

$$\mathfrak{I}_{dddd} = \frac{i\,\lambda_+}{4!}\,\frac{3i\zeta(3)}{\pi^3}\,\delta(k)$$

$$\beta = \frac{4\pi}{d\,r_h}$$

$$\lambda_+ = \frac{\lambda\,r_h^d}{d}$$

$$\delta(k) = (2\pi)^d\,\delta(\sum_{i=1}^{4} k_i)$$

cf., Barnes, Vaman, Wu, Arnold

# VI. OUTLOOK

- Black holes are great environments for getting intuition about strongly coupled thermal baths.
- Existence proof for sensible non-Gaussian effective open QFTs.
- Many potential generalizations/issues to ponder:
  - deriving horizon dynamics using fluid/gravity in real-time
  - imprints of out-of-time-order observables
  - beyond geometry…