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Quantum effects on local observers in JT gravity

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Based on work with Victor Franken and Thomas Mertens
[arXiv:2607.03344]

and with Thomas Mertens and Thomas Tappeiner
J. High Energy Phys. 2026, 145 (2026) [arXiv:2507.20983]

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Motivation

- Pervasive problem in quantum gravity: experience of local observers in highly quantum regime of the gravitational field
    - Theories of dynamical gravity must be diffeomorphism-invariant
    - Standard notion of locality is fundamentally modified
    - Definition of local observables, and therefore local observers, become part of the dynamical degrees of freedom of the system

Motivation

- Notion of locality is of central importance in quantum information:

    - Intimately tied to definition of subsystems
    - Imposes constraints on information-processing protocols
    - Often implicit in how we conceptualize measurements

- Useful to have explicit toy models of observers in fully quantum regimes of the gravitational field.

Goals of the talk

- Describe a preferred gravitational dressing of bulk observables in an exactly solvable model of quantum gravity

- Define a notion of local observers beyond the semiclassical regime

- Compute quantum-gravitational effects on the response of a particle detector falling into a black hole

- Study nonperturbative features of the thermal atmosphere as described by static observers in the exterior of a black hole

Intro: review of JT gravity

Basics of JT gravity

- Jackiw-Teitelboim (JT) gravity is defined by the action

$$S_{\mathrm{JT}}[g,\Phi] = \frac{1}{16\pi G_N}\int_M d^2x\sqrt{-g}\,\Phi(R+2) + \frac{1}{8\pi G_N}\int_{\partial M} dt\sqrt{-h}\,\Phi(K-1) + S_0\chi(M),$$

$$\begin{aligned} g &\to \text{two-dimensional metric}, \\ R &\to \text{Ricci scalar}, \\ \Phi &\to \text{dilaton field}, \\ K &\to \text{extrinsic curvature of } \partial M, \\ \chi(M) &\to \text{Euler characteristic of} M. \end{aligned}$$

- Obtained from dimensional reduction of 4D Einstein gravity around extremal black hole solutions

$$\Rightarrow S_0 \to \text{black hole entropy at extremality.}$$

- Last term essential in quantum gravity due to sum over topologies

Basics of JT gravity

Strengths of JT gravity:

- Describes the near-horizon physics of near-extremal black holes

- Encodes a universal, low-energy sector of the SYK model → concrete example of holography

- Analytically solvable both classically and quantum-mechanically → toy model for nonperturbative effects in quantum gravity

Dynamics of JT gravity

- The dilaton field appears in the bulk action a Lagrange multiplier → two-dimensional metric is locally AdS_2. In Poincaré coordinates,

$$ds^2 = \frac{-dT^2 + dZ^2}{Z^2} = -\frac{4dU\,dV}{(U-V)^2},$$
$$U = T + Z, \quad V = T - Z.$$

- Remaining dynamical degree of freedom encoded in the shape of the boundary curve, governed by the Schwarzian action

$$S_{\mathrm{Sch}}[F] = -C\int dt\,\{F,t\},$$
$$\{F,t\} = \frac{F'''}{F'} - \frac{3}{2}\left(\frac{F''}{F'}\right)^2$$

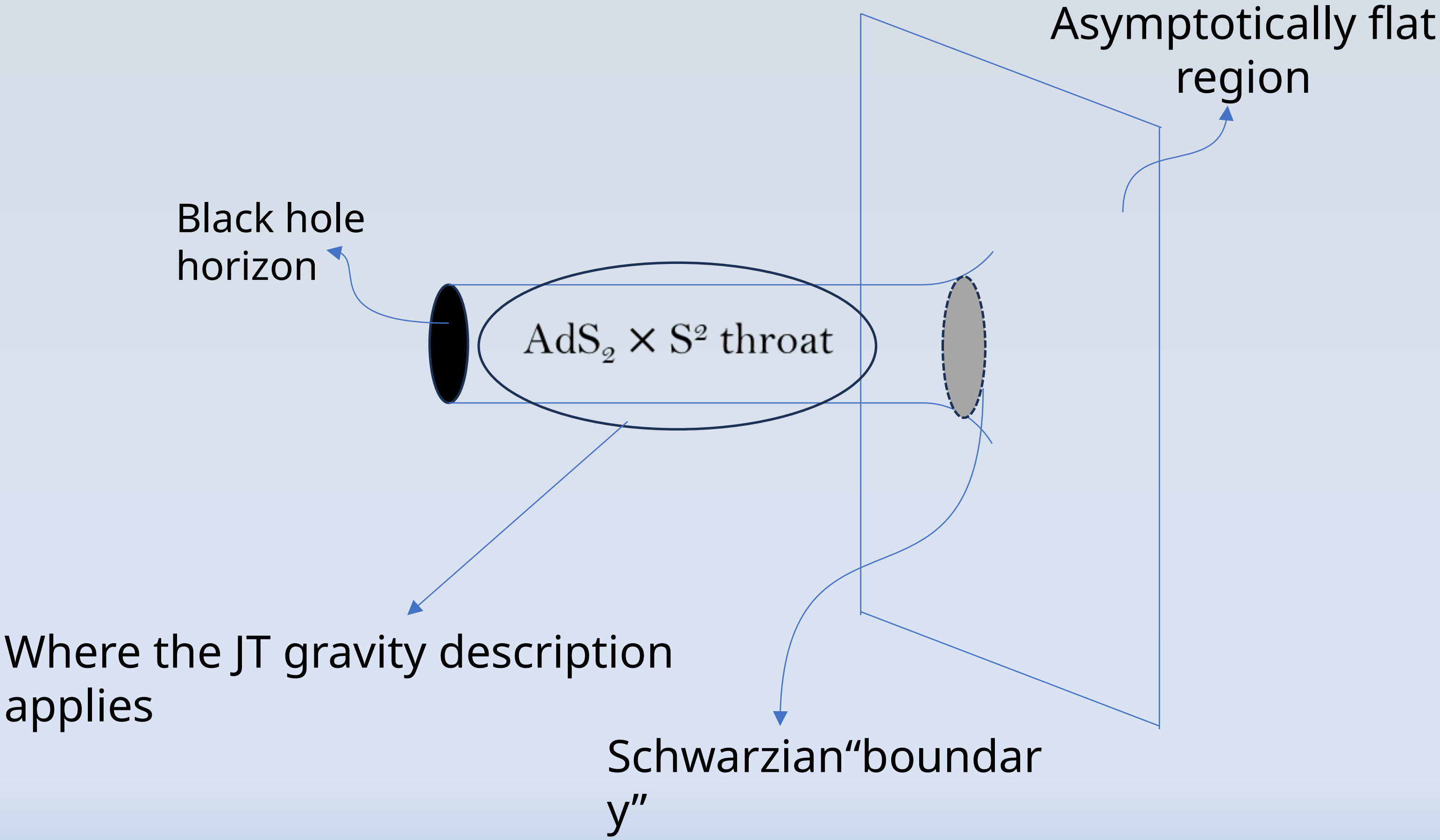
(Schwarzian derivative)

Dynamics of JT gravity

Two-dimensional picture:

Schwarzian $(T, Z) = (F(t), \epsilon F'(t))$

Higher-dimensional perspective:



Dynamics of JT gravity

Two-dimensional picture:

Schwarzian $(T, Z) = (F(t), \epsilon F'(t))$

For the remainder of this talk, we will focus on JT gravity as a standalone theory in its own right.

JT partition function and density of states

Examples of quantities of interest in JT gravity:

Thermal partition function:

$$Z(\beta) = e^{S_0} \int_{\mathrm{Diff}^+(S^1)/SL(2,\mathbb{R})} [\mathcal{D}f] e^{C \int_0^\beta d\tau \{\tan\left(\frac{\pi f(\tau)}{\beta}\right), \tau\}},$$

$$\tan\left(\frac{\pi f(\tau)}{\beta}\right) = F(\tau).$$

Partition function is one-loop exact[1]:

$$Z(\beta) = \frac{1}{4\pi^2}\left(\frac{2\pi C}{\beta}\right)^{3/2} e^{S_0 + \frac{2\pi^2 C}{\beta}}$$

Inverse Laplace transform then gives the density of states:

$$\rho(E) = e^{S_0}\rho_0(E), \quad \rho_0(E) = \sinh\left(2\pi\sqrt{2CE}\right)$$

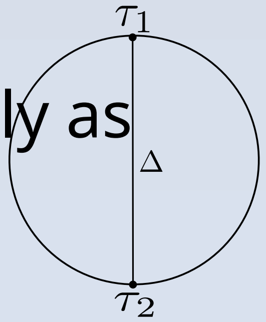
[1] D. Stanford, E. Witten, *JHEP* **2017**, 8 (2017)

Schwarzian bilocal

Another observable of relevance is the Schwarzian bilocal, the boundary limit of the bulk two-point function of a free scalar field:

$$\mathcal{O}_\Delta(\tau_1,\tau_2) = \left(\frac{F'(\tau_1)F'(\tau_2)}{(F(\tau_1)-F(\tau_2))^2}\right)^\Delta = \left(\frac{f'(\tau_1)f'(\tau_2)}{\frac{\beta^2}{\pi^2}\sin^2\left[\frac{\pi}{\beta}(f(\tau_1)-f(\tau_2))\right]}\right)^\Delta$$

It can be represented diagrammatically as



Its thermal expectation value in the Schwarzian theory is also known exactly[2]:

$$\langle \mathcal{O}_\Delta(\tau_1,\tau_2)\rangle_\beta = \frac{1}{Z(\beta)}\int_0^\infty \prod_{i=1,2}\left(dk_i^2\,\sinh(2\pi k_i)\right)e^{-\tau\frac{k_1^2}{2C}-(\beta-\tau)\frac{k_2^2}{2C}}\frac{\Gamma(\Delta\pm ik_1\pm ik_2)}{8\pi^4(2C)^{2\Delta}\Gamma(2\Delta)},$$

$$\tau = |\tau_1-\tau_2|.$$

[2] T. G. Mertens, G. J. Turiaci, H. L. Verlinde, *JHEP* **2017**, 136 (2017)

Towards bulk observables in JT gravity

Recipe to solve problems in JT gravity:

- Map the dynamical degrees of freedom of relevance in the problem to the Schwarzian;
- Express the physical observable of interest in terms of the Schwarzian bilocal or related quantities.

This is precisely the strategy that we will employ in the following.

Gravitational dressing in JT gravity

Gravitational dressing in JT gravity

- Diffeomorphism invariance naturally motivates a relational definition of local observables
- Physical observables defined in relation to other dynamical degrees of freedom of the problem, which also transform under diffeomorphisms
- Achieved through gravitational dressing, where gravitational field serves as reference

Gravitational dressing in JT gravity

In JT gravity, the only gravitational degree of freedom is the Schwarzian mode. The question then becomes:

- How to dress bulk points in AdS_2 to the Schwarzian degree of freedom describing the boundary trajectory?

Gravitational dressing in JT gravity

We will establish a concrete form of dressing of bulk points in JT gravity.

The proposal will define a family of local observers in the exterior region of AdS_2 black holes, and is based on three requirements:

- Observer worldlines foliate the exterior of the classical black hole;
- The worldlines asymptote to the Schwarzian curve as we approach the AdS_2 boundary;
- The flowlines of static observers are integral curves of conformal Killing vector fields of AdS_2.

Gravitational dressing in JT gravity

- Observer worldlines foliate the exterior of the classical black hole;

- The worldlines asymptote to the Schwarzian curve as we approach the AdS_2 boundary;

- The flowlines are integral curves of conformal Killing vector fields of AdS_2.

These requirements univocally lead to a mapping from bulk points in AdS_2 to the Schwarzian mode.

Gravitational dressing in JT gravity

Final result: bulk point in the Poincare patch with lightcone coordinates (U, V) defined in terms of two boundary times (u, v) simply via

$$U = F(u), \quad V = F(v)$$

with $F(t)$ the Schwarzian reparametrization function. "Boundary-intrinsic" time and radial coordinates can then simply be given by

$$t = \frac{u+v}{2}, \quad z = \frac{u-v}{2}$$

analogously to Einstein's radar definition of bulk coordinates.

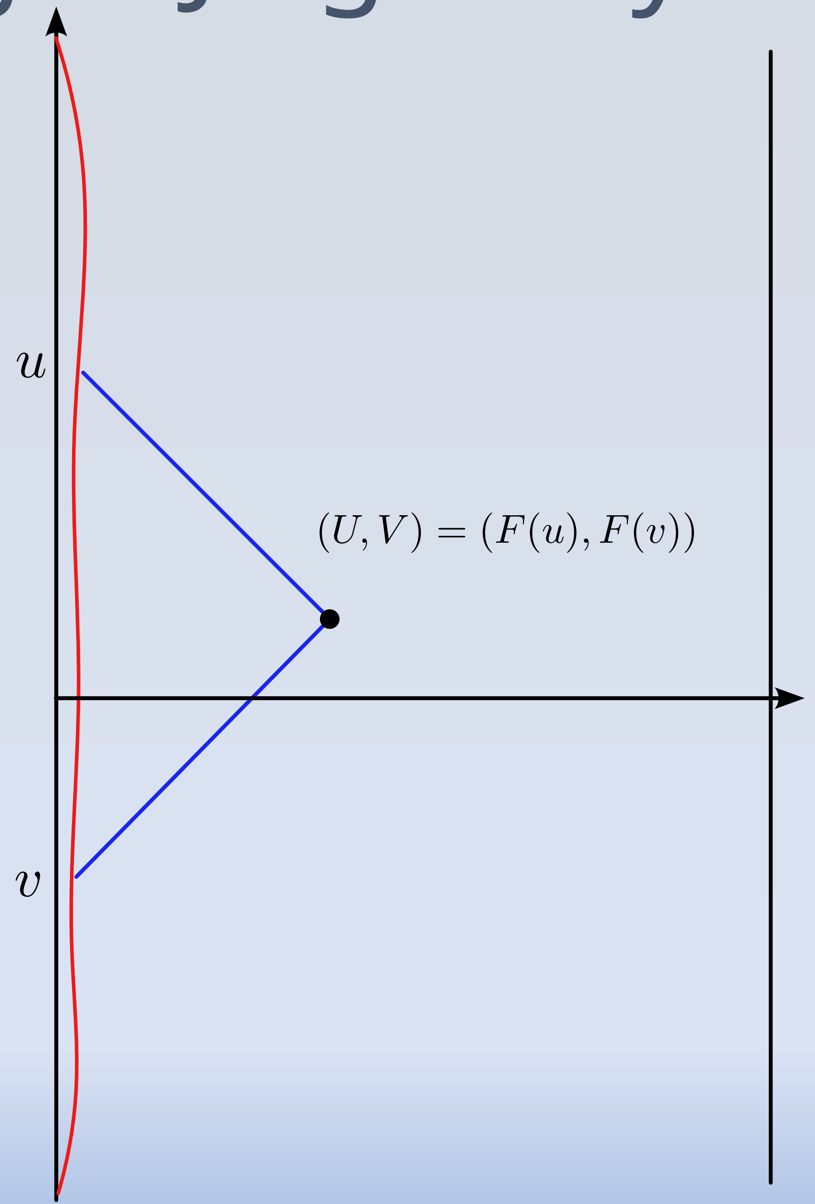
Gravitational dressing in JT gravity

Geometric interpretation:

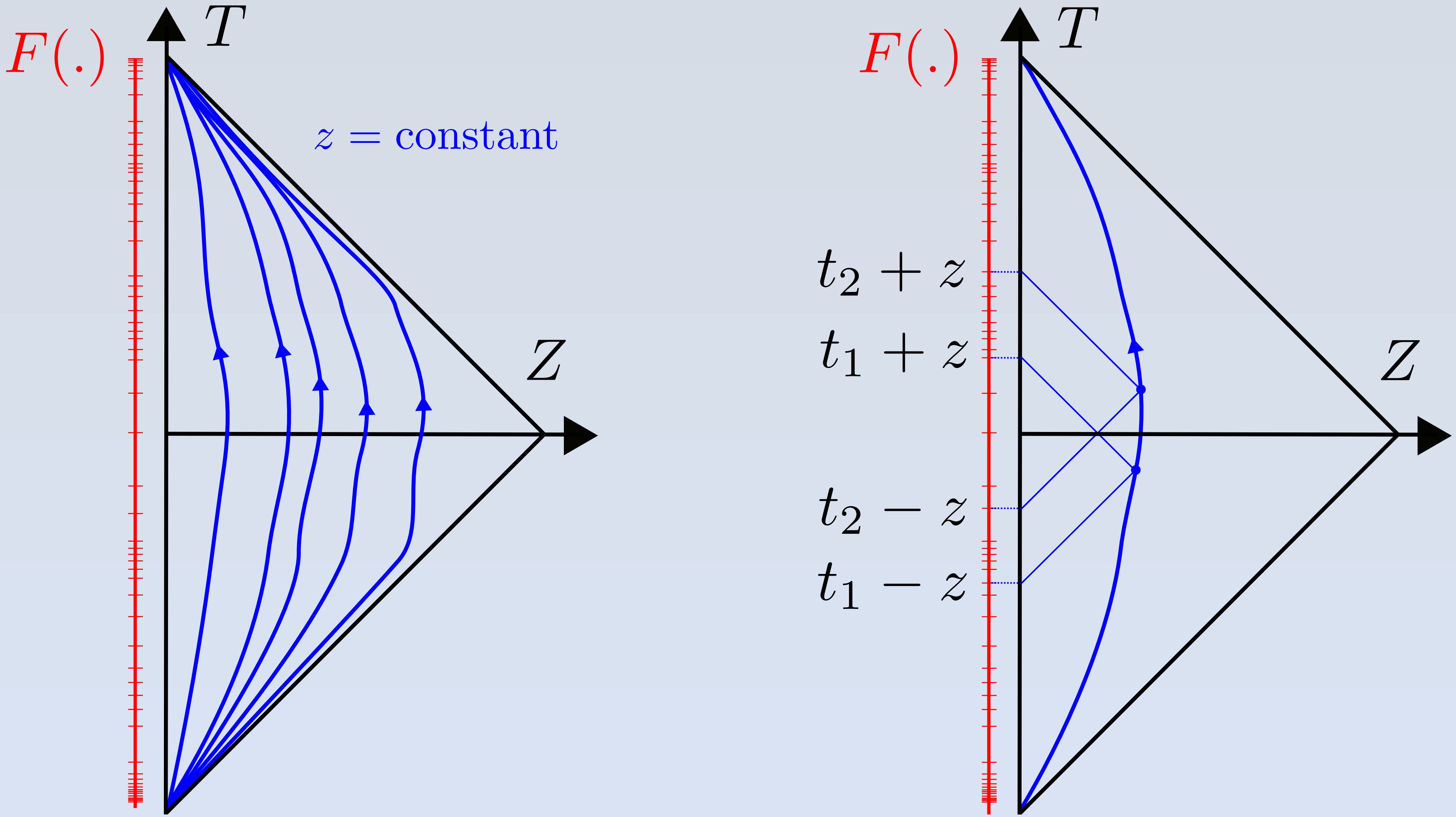
- Schwarzian boundary emits a lightray at boundary time v and receives another lightray at proper time u.

- Intersection of two lightrays defines the bulk point in AdS, for each configuration of the Schwarzian mode.

- Effective "radial position" of a dressed observer given by the displacement $z = (u - v)/2$. Fiducial observer can be thus defined, for any profile of the Schwarzian.



Gravitational dressing in JT gravity



Why conformal Killing vectors?

This dressing has been proposed in earlier constructions of bulk frames in JT gravity[3].

We have landed on this proposal via the requirement that boundary time translations be extended into the bulk as conformal Killing vectors.

- Why is this a good requirement?

  Because of the special connection between conformal isometries and geometric modular flow.

[3] A. Blommaert, T. G. Mertens, and H. Verschelde, *JHEP* **2019**, 60 (2019)

Gravitational dressing and geometric modular flow

- Recent breakthroughs in quantum gravity from connection between algebra of local observables and the modular crossed product[4, 5]
- Modular crossed product algebra interpreted as an algebra of diffeomorphism-invariant observables as long as modular flow is geometric
- A necessary condition for modular flow to be geometric is that the associated diffeomorphism be a conformal isometry of the background geometry[6]
- Only way to achieve this via the Schwarzian is through the dressing we have proposed.

[4] V. Chandrasekaran, R. Longo, G. Penington, E. Witten, *JHEP* **2023**, 82 (2023)
[5] J. De Vuyst, S. Eccles, P. A. Hoehn, J. Kirklin, *JHEP* **2025**, 63 (2025)
[6] J. Sorce, *JHEP* **2024**, 40 (2024)

Response of gravitationally dressed infalling detector

Setup: QFT in AdS_2

Concrete example: massless scalar in AdS_2

$$S[\phi] = -\frac{1}{2}\int d^2x\sqrt{-g}\,\nabla_a\phi\nabla^a\phi$$

Vacuum two-point function known in closed form: in the “black hole patch” of AdS_2,

$$W(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\log\left(\frac{\sinh\left(\frac{\pi}{\beta}(u-u')\right)\sinh\left(\frac{\pi}{\beta}(v-v')\right)}{\sinh\left(\frac{\pi}{\beta}(u-v')\right)\sinh\left(\frac{\pi}{\beta}(v-u')\right)}\right),$$

$$ds^2 = -\frac{4\pi^2}{\beta^2}\frac{du\,dv}{\sinh^2\left[\frac{\pi}{\beta}(u-v)\right)}.$$

Setup: QFT in AdS_2

Two-point function can also be written in the Poincare patch as

$$W(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\log\left(\frac{(U-U')(V-V')}{(U-V')(V-U')}\right),$$

$$ds^2 = \frac{-4dU\,dV}{(U-V)^2}.$$

Black hole patch obtainable from Poincare patch via

$$U = \frac{\beta}{\pi}\tanh\left(\frac{\pi}{\beta}u\right),$$
$$V = \frac{\beta}{\pi}\tanh\left(\frac{\pi}{\beta}v\right).$$

Gravitationally dressed bulk observables

Now we include our proposed gravitational dressing,

$$U = F(u), \quad V = F(v)$$

And rewrite the two-point function via

$$-\frac{1}{4\pi}\log\left(\frac{(F(u)-F(u'))(F(v)-F(v'))}{(F(u)-F(v'))(F(v)-F(u'))}\right) = -\frac{1}{4\pi}\int_v^u dt \int_{v'}^{u'} dt' \frac{\dot{F}(t)\dot{F}(t')}{(F(t)-F(t'))^2}.$$

We can then restrict to the black hole patch with a dynamical Schwarzian boundary by rewriting

$$F(t) = \tanh\left(\frac{\pi}{\beta}f_L(t)\right)$$

Gravitationally dressed bulk observables

With the Schwarzian dressing, the two-point function becomes

$$W(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\log\left(\frac{\sinh\left(\frac{\pi}{\beta}(f_L(u)-f_L(u'))\right)\sinh\left(\frac{\pi}{\beta}(f_L(v)-f_L(v'))\right)}{\sinh\left(\frac{\pi}{\beta}(f_L(u)-f_L(v'))\right)\sinh\left(\frac{\pi}{\beta}(f_L(v)-f_L(u'))\right)}\right)$$

$$= -\frac{\pi}{4\beta^2}\int_v^u dt\int_{v'}^{u'} dt'\,\frac{\dot f_L(t)\dot f_L(t')}{\sinh^2\left(\frac{\pi}{\beta}(f_L(t)-f_L(t'))\right)}$$

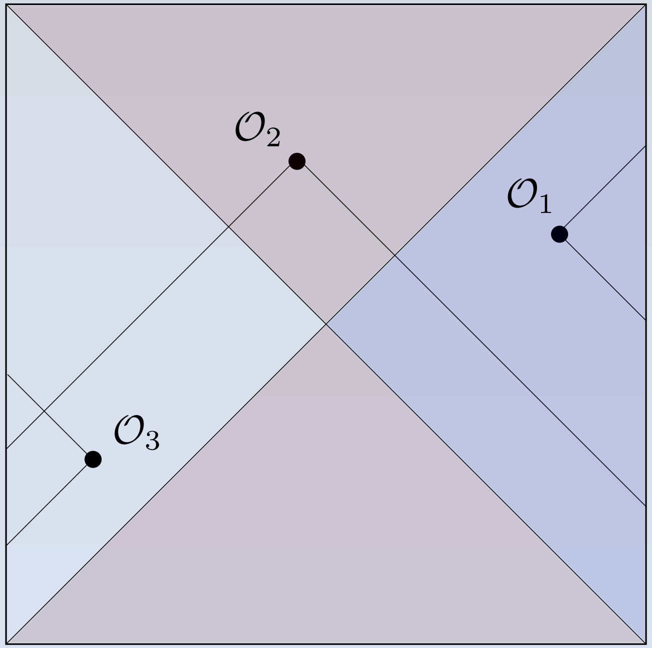
Which, if treated now as an operator in the Schwarzian theory, has expectation value

$$W(\mathsf{x},\mathsf{x}') = \frac{1}{4\pi}\int_v^u dt\int_{v'}^{u'} dt'\,\left\langle \mathcal{O}_1(it,it')\right\rangle_\beta\,,$$

$$\left\langle \mathcal{O}_1(z,z')\right\rangle_\beta = \left\langle \frac{\pi^2}{\beta^2}\frac{f'(z)f'(z')}{\sin^2\left[\frac{\pi}{\beta}(f(z)-f(z'))\right]}\right\rangle_\beta$$

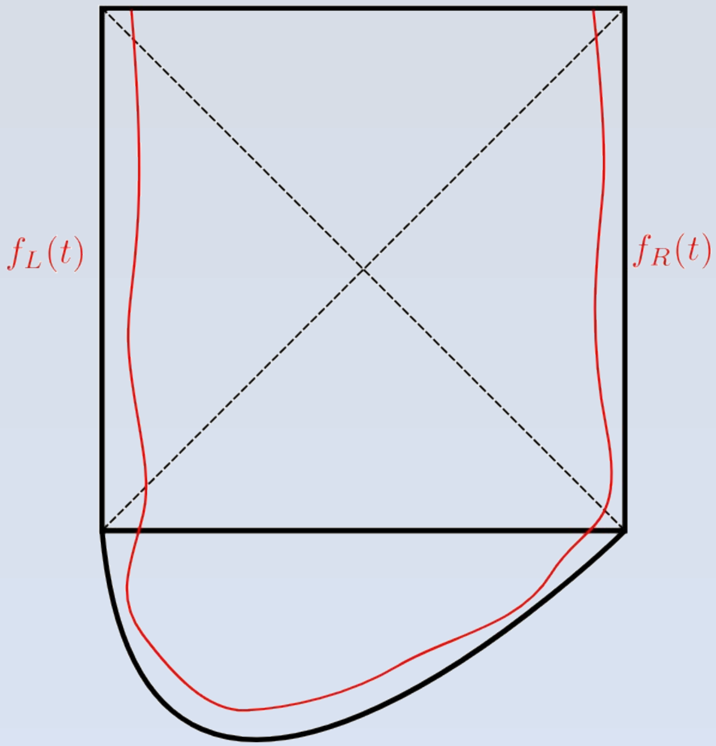
Dressing beyond the black hole horizon

This recipe can also be adapted to describe the black hole interior if we now dress points to two boundaries:



$$f_L(t) = -if(it),$$

$$f_R(t') = if(-it' - \beta/2) + i\frac{\beta}{2}$$



$f(z) =$ Schwarzian mode in Euclidean signature

Correlation functions on opposite sides of the horizon can now be computed. Correlators inside the horizon are obtained by analytic continuations of correlators on the exterior.

Infalling detector crossing the horizon

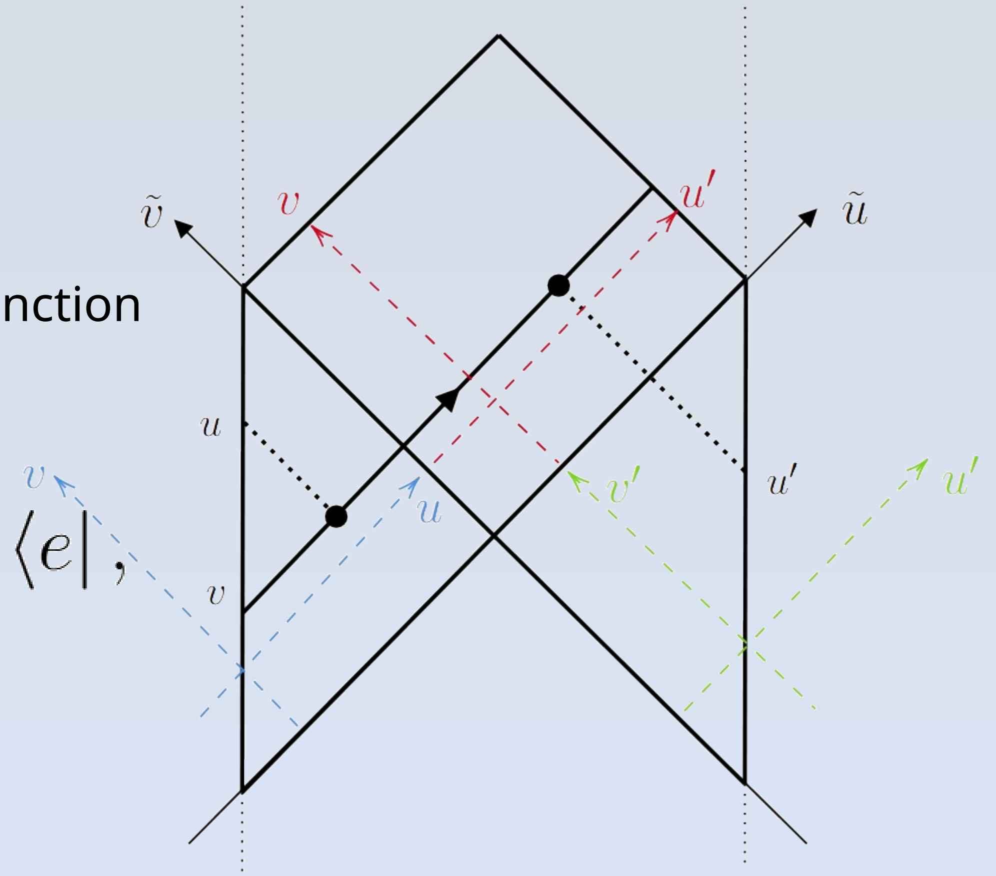
To directly probe the effect of the Schwarzian dressing, we throw a probe (UDW detector) into the black hole, following an approximately null trajectory:

$$S_I = q \int d\lambda \, \mu(\lambda) \chi(\lambda) \, k^a \nabla_a \phi,$$

Coupling constant

Affine time

Switching function



Monopole moment: $\mu(\lambda) = e^{i\omega\lambda} \left|e\right\rangle \left\langle g\right| + e^{-i\omega\lambda} \left|g\right\rangle \left\langle e\right|,$

Tangent vector: $k^a \nabla_a = \dfrac{\partial}{\partial \lambda}$

Infalling detector crossing the horizon

Simplest observable we can compute is the detector's excitation probability:

Detector starting in the ground state transitions to excited state with probability

$$P_{\text{exc}} = q^2 \int d\lambda \, d\lambda' \chi(\lambda)\chi(\lambda')e^{-i\omega(\lambda-\lambda')}\partial_\lambda \partial'_\lambda W(\lambda, \lambda').$$

For concreteness, we pick a Gaussian switching function:

$$\chi(\lambda) = e^{-(\lambda-\lambda_0)^2/2\sigma^2}.$$

Infalling detector crossing the horizon

To find affine time as a function of the original coordinates, note

$$ds^2 = -\frac{4f'(u)f'(v)du\,dv}{\frac{\beta^2}{\pi^2}\sinh^2\left[\frac{\pi}{\beta}(f(u)-f(v))\right]} = \mathcal{O}_1(u,v)\,d\tilde{s}^2,$$

$$d\tilde{s}^2 = -4du\,dv.$$

Relation between affine time λ and boundary time along an infalling null trajectory then fixed by

$$\frac{d\lambda}{du} = \mathcal{O}_1(u,v),$$

Whose expectation value in the Schwarzian theory can be computed explicitly

Infalling detector crossing the horizon - semiclassical

The prediction from usual QFT in curved spacetimes comes from thermal saddlepoint:

$$\frac{d\lambda}{du} = \frac{\pi^2}{\beta^2}\frac{1}{\sinh^2\left[\frac{\pi}{\beta}(u-v)\right]} \Rightarrow \lambda(u) = -\frac{2\pi}{\beta}\frac{e^{-\frac{2\pi}{\beta}(u-v)}}{\left(1-e^{-\frac{2\pi}{\beta}(u-v)}\right)},$$

$$\partial_\lambda \partial_{\lambda'} W(\lambda, \lambda') = -\frac{1}{4\pi(\lambda-\lambda')^2}$$

$$P_{\text{exc}} = \frac{g^2}{4}\left(e^{-\sigma^2\omega^2} - \sqrt{\pi}\sigma\omega\,\text{erfc}(\sigma\omega)\right).$$

Excitation probability explicitly independent of λ_0 (due to translational invariance) and β (global state always the same, despite choice of patch being apparently distinct)

- Both of these will change substantially when we include the gravitational dressing.

Infalling detector crossing the horizon - Schwarzian

Thermal expectation value of Schwarzian simplifies dramatically at very late times: just before the probe crosses the horizon,

$$u - v \gg C \Rightarrow \quad \lambda(u) \sim -\frac{A}{(u-v)^2},$$

$$A = \frac{C}{8\pi Z_0(\beta)}.$$

Direct consequence of the fact that

$$\frac{d\lambda}{du} = \langle \mathcal{O}_1(u,v) \rangle \propto \frac{1}{(u-v)^3} \text{ for } \; u - v \gg C$$

Infalling detector crossing the horizon - Schwarzian

Similarly, right after crossing the horizon, the relation between the detector's affine time and the boundary time u' of the right boundary is

$$\lambda(u') \sim \frac{A}{(u'+v)^2}\,.$$

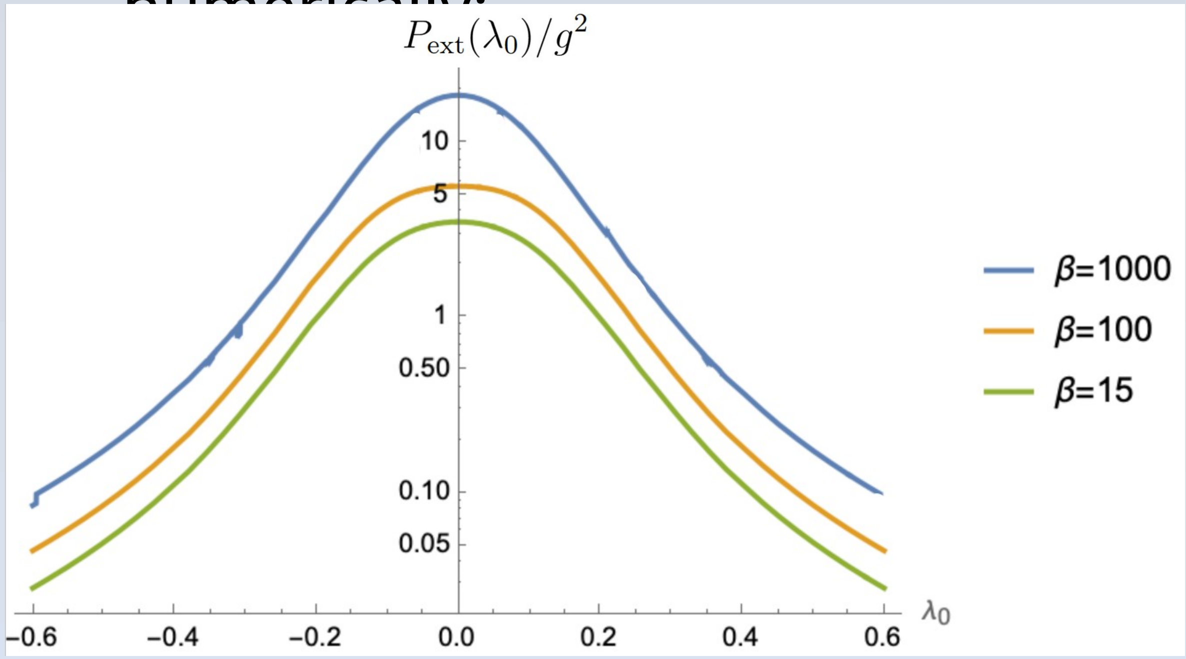
Gravitationally dressed two-point function then takes the form

$$\partial_\lambda \partial_{\lambda'} W \sim \frac{A}{4Z_0(\beta)} \frac{\mathrm{sgn}(\lambda\lambda')}{|\lambda\lambda'|^{3/2}} \int_0^\infty dM\,\rho(M) e^{-\beta M} \int_0^\infty dE\,\rho(E) \left|\mathcal{O}^1_{ME}\right|^2 \times \exp\left\{-(E-M)\left[\frac{\beta}{4}\left(1-\mathrm{sgn}(\lambda\lambda')\right) + i\sqrt{A}\left(\frac{1}{\sqrt{|\lambda|}} - \frac{1}{\sqrt{|\lambda'|}}\right)\right]\right\}$$

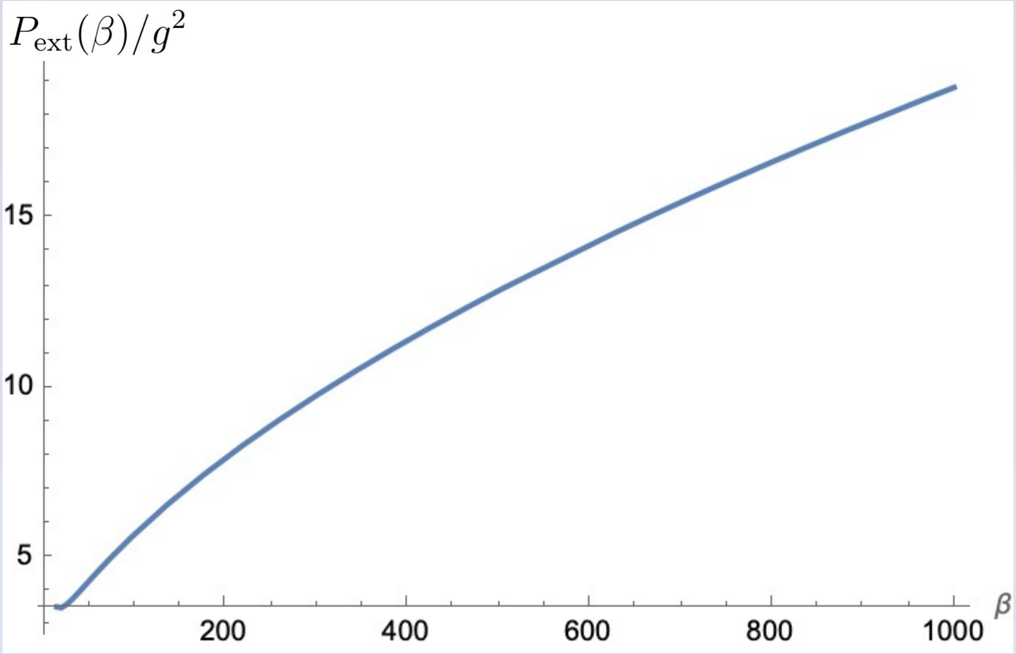
which can be integrated against the switching functions to extract the detector's excitation probability.

Detector’s excitation probability - Schwarzian

With all of these ingredients, excitation probability can be computed numerically:



Excitation probability as a function of peak of switching function, for various temperatures

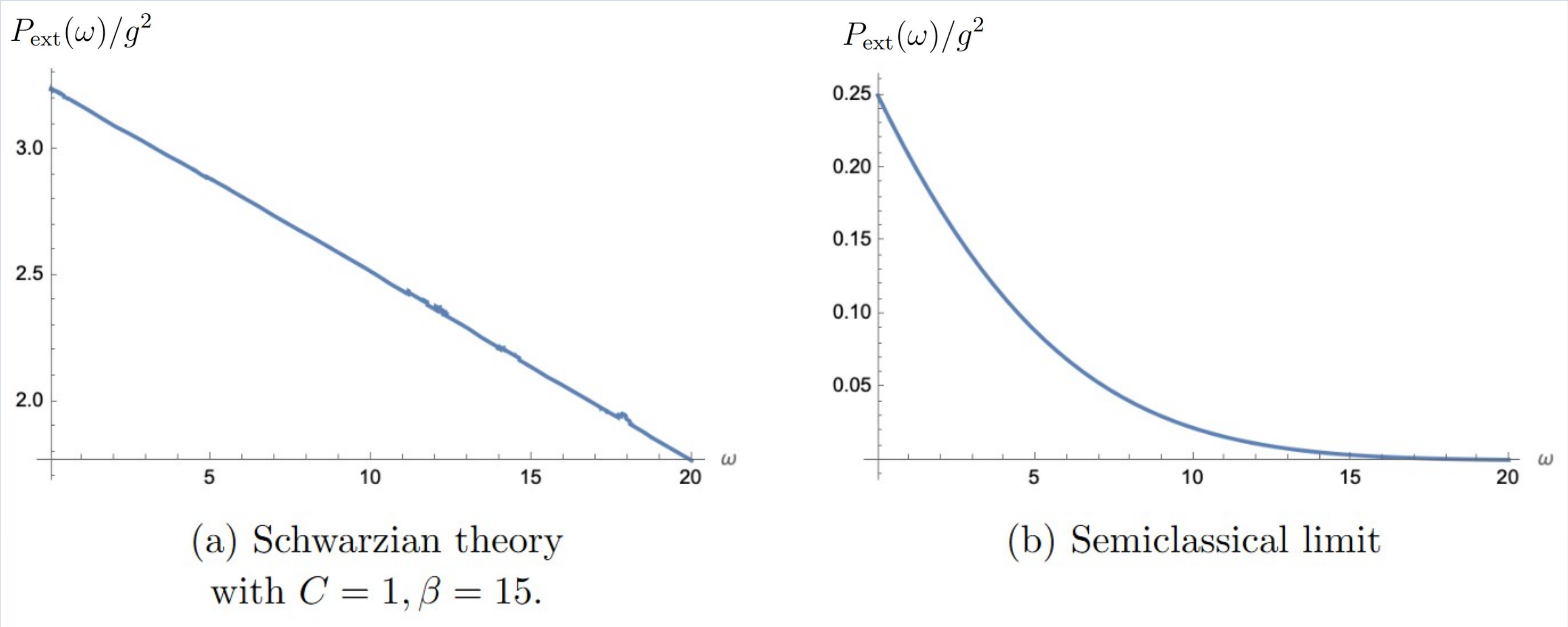


Excitation probability as a function of inverse temperature, for switching peaked at the horizon

Upshot: gravitational dressing is such that detector is able to locally detect location of the horizon and infer the temperature of the black hole.

Detector's excitation probability - Schwarzian

Comparing this to the semiclassical result:



Excitation probabilities for $\lambda_0 = 0, \sigma = 0.1.$

For fixed coupling constant, excitation probability with coupling to Schwarzian is substantially higher than semiclassical expectation

- ➢ More fluctuations, more noise

Thermal atmosphere in quantum JT gravity

Thermal atmosphere in quantum JT gravity

Another interesting application of this framework is the calculation of the entropy of quantum fields in the exterior of the black hole.

For concreteness, consider a two-dimensional CFT minimally coupled to gravity.

For any given off-shell profile for the Schwarzian, the line element can be written as

$$ds^2 = \frac{F'(t+z)F'(t-z)}{(F(t+z)-F(t-z))^2}(-dt^2+dz^2) = \frac{F'(u)F'(v)}{(F(u)-F(v))^2}du\,dv,$$

$$u = t+z, \quad v = t-z.$$

Then, the entropy of the Poincare vacuum restricted to the region between the asymptotic boundary and a point in the bulk labeled by null coordinates $(u,\ v)$ is given by

$$S_{\text{ent}} = \frac{c}{12}\log\left(\frac{(F(u)-F(v))^2}{F'(u)F'(v)}\right) = -\frac{c}{12}\partial_\Delta\left(\frac{F'(u)F'(v)}{(F(u)-F(v))^2}\right)^\Delta\Bigg|_{\Delta=0}.$$

Thermal atmosphere in quantum JT gravity

$$S_{\text{ent}} = \frac{c}{12}\log\left(\frac{(F(u)-F(v))^2}{F'(u)F'(v)}\right) = -\frac{c}{12}\partial_\Delta\left(\frac{F'(u)F'(v)}{(F(u)-F(v))^2}\right)^\Delta\Bigg|_{\Delta=0}.$$

This is just the derivative of the Schwarzian bilocal with respect to the conformal weight Δ.

We can thus compute quantum-gravitational effects in the entanglement entropy by treating the expression above as an operator insertion in the Schwarzian path integral:

$$S_{\text{ent}} \propto \partial_\Delta\left[\int[\mathcal{D}f]e^{-S_{\text{Sch}}[f]}\mathcal{O}_\Delta(u,v)\right]_{\Delta=0}.$$

This admits a closed-form expression, thanks to exact solutions in JT gravity.

Thermal atmosphere – Schwarzian theory

By plugging in the known thermal expectation values of the Schwarzian bilocal, we get

$$S_{\mathrm{ent}} \propto \int d\mu(k_1)\, d\mu(k_2) e^{2iz\frac{k_1^2}{2C}} e^{-(\beta+2iz)\frac{k_2^2}{2C}} \partial_\Delta \left[\frac{\Gamma(\Delta \pm ik_1 \pm ik_2)}{(2C)^{2\Delta}\Gamma(2\Delta)}\right]\Bigg|_{\Delta=0},$$

$$d\mu(k_i) = dk_i^2 \, \sinh(2\pi k_i).$$

In the limit $\beta \ll C \ll z$ (high temperatures, bifurcation surface approaching the horizon), this reduces to

$$S_{\mathrm{ent}} \sim \frac{c\pi}{3\beta} z$$

which is just the volume law for the thermal entropy of a CFT with 1 spatial dimension.

Thermal atmosphere – higher topology

- The Schwarzian path integral therefore does not change the semiclassical answer for the entropy of the thermal atmosphere.

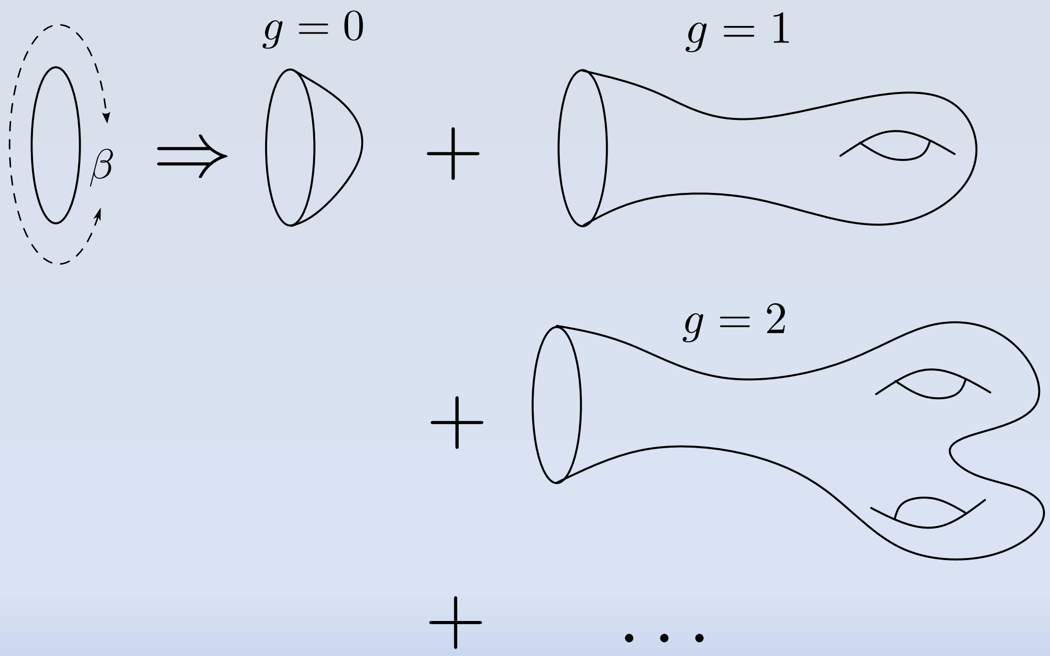
- But JT gravity is not just the Schwarzian: there are also higher-genus contributions to the gravitational path integral.

- This will qualitatively change the nature of the black hole horizon.

Small detour: JT gravity as a matrix integral[6]

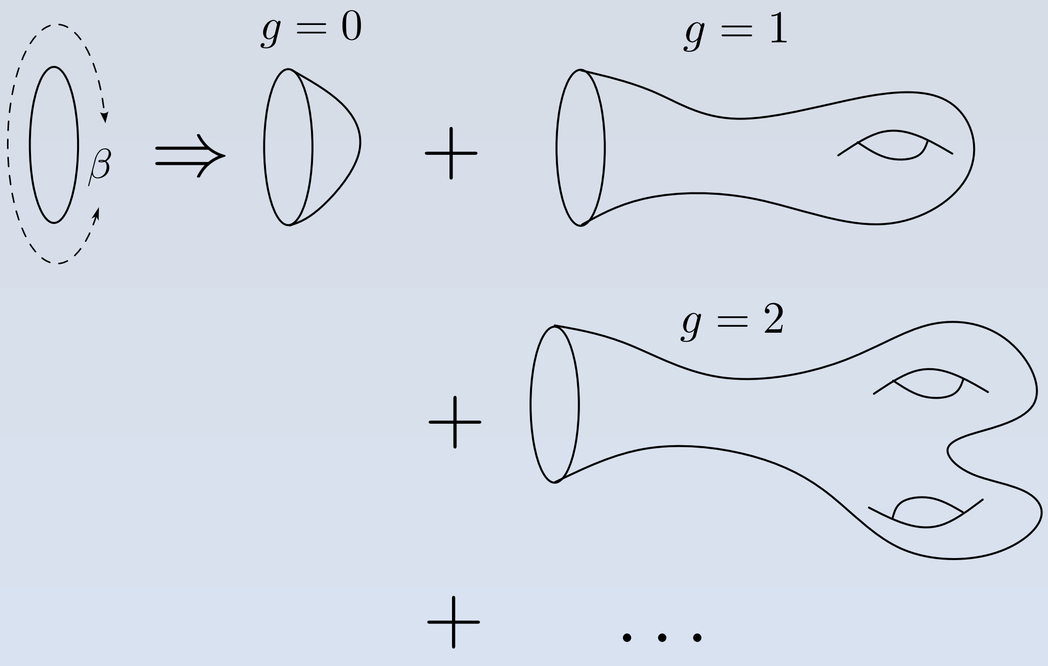
Higher topologies can be systematically included in our model via the formulation of JT gravity as a matrix integral.

As an illustration, consider the partition function:



[7] P. Saad, S.H. Shenker, D. Stanford, arXiv:1903.11115 [hep-th]

Small detour: JT gravity as a matrix integral



$$\chi(M) = 2 - 2g - n \Rightarrow$$

$$Z(\beta) = e^{S_0}\left(\sum_{g=0}^{\infty} e^{-2gS_0}\, Z_{\mathrm{Sch}}^{(g)}(\beta)\right),$$

$Z_{\mathrm{Sch}}^{(g)}(\beta) =$ (Schwarzian partition function on hyperbolic surface of genus g)

The full partition function (including all topologies) can thus be organized in a series expansion on the parameter e^{-2S_0}.

Small detour: JT gravity as a matrix integral

Now compare this to a different problem, dealing with ensembles of Hermitian $L \times L$ matrices H sampled according to some probability measure

$$d\mu(H) = [dH]\, e^{-\underbrace{L\,\mathrm{Tr}(V(H))}_{\text{Matrix potential}}}$$

We can compute compute the expectation value of the partition function as an observable in this ensemble:

$$\langle Z(\beta) \rangle = \int d\mu(H)\, \mathrm{Tr}\left(e^{-\beta H}\right)$$

Small detour: JT gravity as a matrix integral

$$\langle Z(\beta)\rangle = \int d\mu(H)\,\mathrm{Tr}\left(e^{-\beta H}\right)$$

In the limit $L \to \infty$, this integral also admits an expansion of the form

$$\langle Z(\beta)\rangle = L\sum_{g=0}^{\infty}\frac{Z^{(g)}(\beta)}{L^{2g}},$$

where now g corresponds to the genus of the matrix diagrams (in 't Hooft's double line notation) that contribute to a given term in the sum.

Small detour: JT gravity as a matrix integral

Gravitational path integral in JT gravity

$$Z(\beta) = e^{S_0} \sum_{g=0}^{\infty} \frac{Z^{(g)}_{\mathrm{Sch}}(\beta)}{e^{2gS_0}}$$

Matrix integral

$$\langle Z(\beta) \rangle = L \sum_{g=0}^{\infty} \frac{Z^{(g)}(\beta)}{L^{2g}}$$

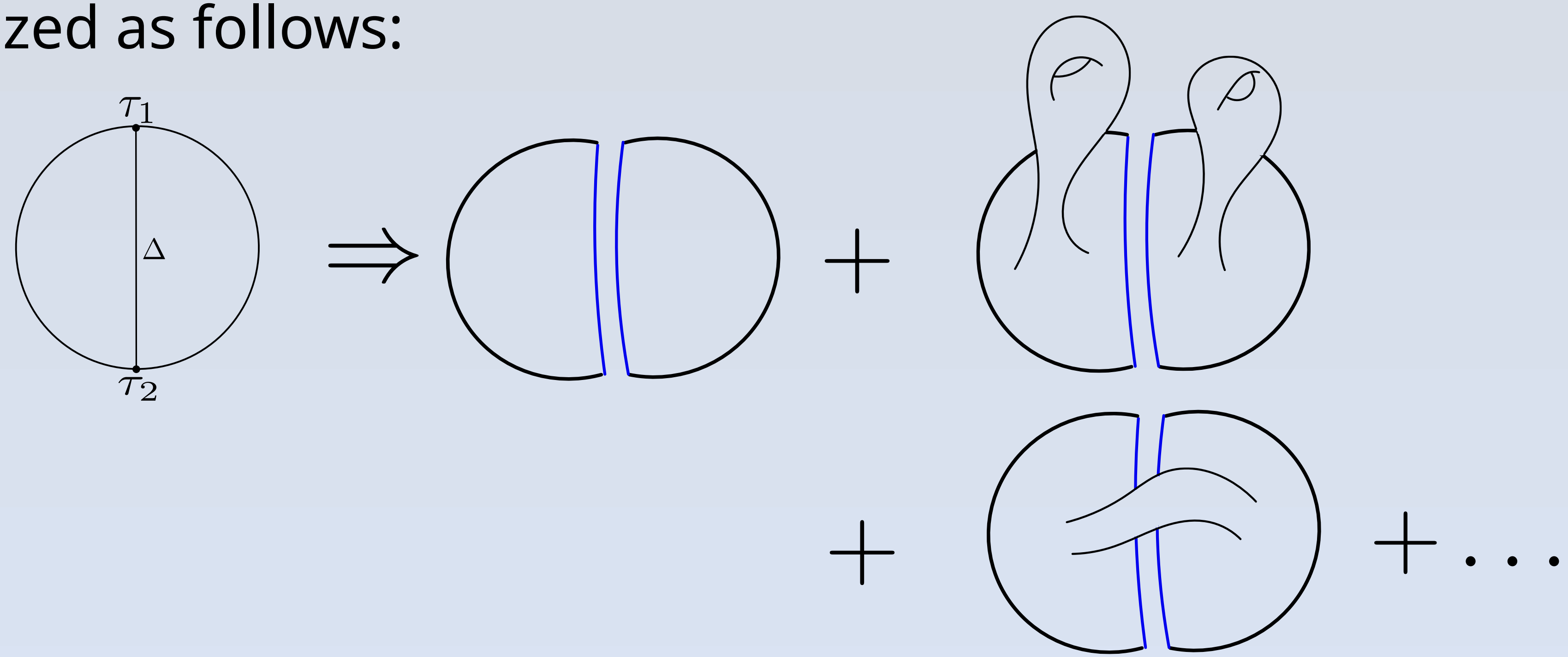
It can be shown that:

- Coefficients in both series satisfy the same recursion relations (Mirzakhani's recursion relation $\Leftrightarrow$ Eynard-Orantin topological recursion for matrix integrals)
- One can match the zeroth-order term by tuning the matrix potential $V(H)$

➢ Conclusion: JT gravity (including higher topologies) = a matrix integral

Higher-topology effects in JT gravity

The effect of higher topologies e.g. on the Schwarzian bilocal can thus be visualized as follows:



- Wormholes geometrize the effect of coupling a matter theory (in our case, the two-dimensional CFT) to a quantum-chaotic system described by random matrix statistics (i.e., the black hole).

Back to the thermal atmosphere

At a pragmatic level, the effect of higher topologies on the Schwarzian bilocal is obtained by simply replacing

$$\rho(E_1)\rho(E_2) \to \langle \rho(E_1, E_2) \rangle_{\text{RMT}}$$

$$\text{pair density correlator:} \;\; \int d\mu(H) \text{Tr}\Big(\delta(H - E_1)\Big) \text{Tr}\Big(\delta(H - E_2)\Big)$$

In other words, the Schwarzian bilocal now becomes

$$\langle \mathcal{O}_\Delta(\tau_1, \tau_2) \rangle \propto \int dE_1 \, dE_2 \langle \rho(E_1, E_2) \rangle_{\text{RMT}} \, e^{-\tau E_1} e^{-(\beta-\tau)E_2} \Gamma(\Delta \pm i\sqrt{2CE_1} \pm i\sqrt{2CE_2}).$$

Back to the thermal atmosphere

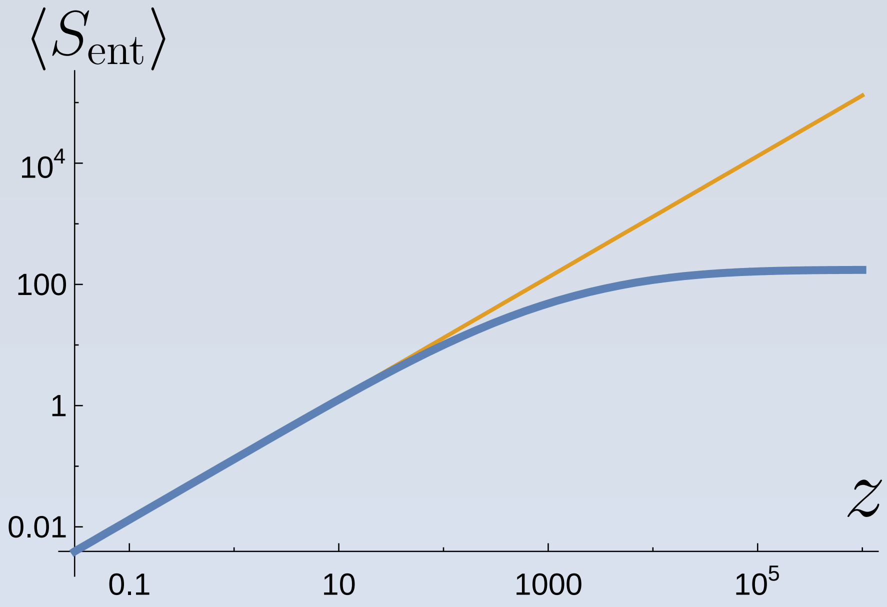
For small energy separations, the pair density correlator is also known explicitly:

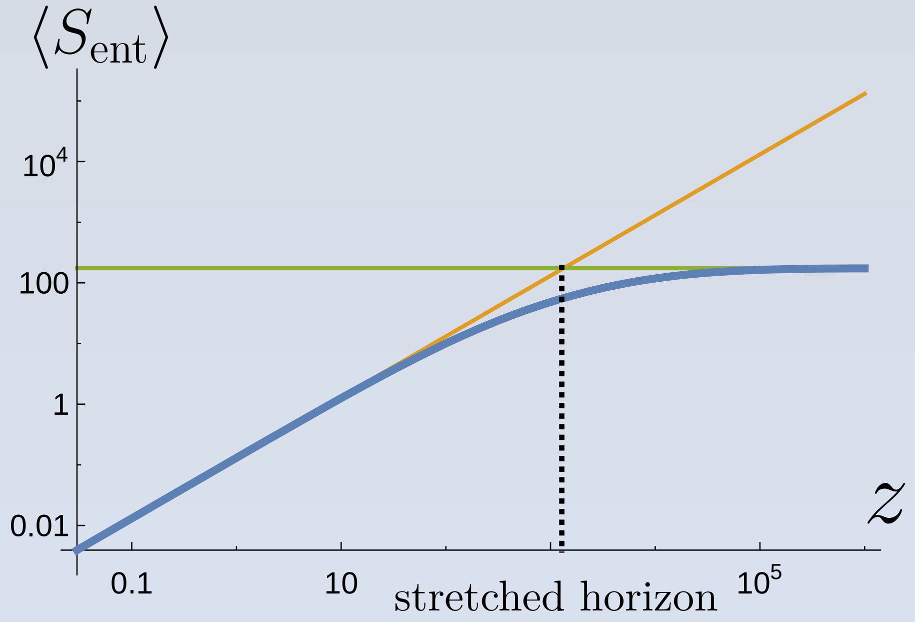
$$\langle \rho(E_1, E_2) \rangle = \rho(E_1)\rho(E_2) - \frac{\sin^2\left[\pi\rho(E_2)(E_1 - E_2)\right]}{\pi^2(E1 - E_2)^2} - \rho(E_1)\delta(E_1 - E_2).$$

Leading-order density of states, determined from the partition function on lowest topology

The resulting Schwarzian path integral can subsequently be evaluated, once again, in the limit $\beta \ll C \ll z$.

Quantum-corrected thermal atmosphere and stretched horizon





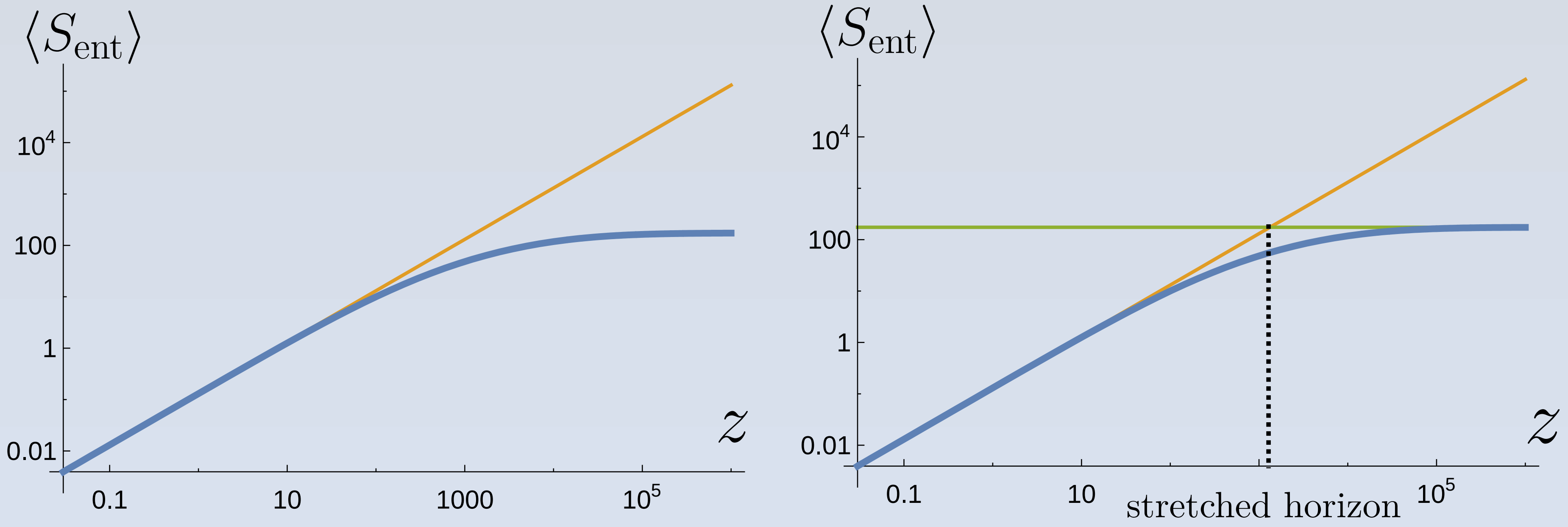
Orange: semiclassical prediction

Blue: wormhole corrections

"Stretched horizon": distance where semiclassical prediction breaks down:

$$\ell_{\rm sh} \approx \frac{\beta}{\pi} e^{-\frac{2\pi}{\beta} C e^{S_0} \frac{4\pi}{3} e^{\frac{6\pi^2}{\beta} C}},$$ doubly nonperturbative in G_N (or in $1/C,\ 1/S_0$).

Quantum-corrected thermal atmosphere and stretched horizon



Orange: semiclassical prediction

Blue: wormhole corrections

Conclusion: nonperturbative effects lead to plateau in entanglement entropy!

Conclusions

Conclusions

- We studied quantum-gravitational effects on the experience of local observers in Jackiw-Teitelboim gravity.
- Notion of “observer” defined in terms of the “gravitational” degree of freedom of the model; form of gravitational dressing.
- Semiclassically, the dressing results from demanding that stationary trajectories extend boundary time translations to bulk conformal isometries. Motivated by connection between conformal isometries and geometric modular flow.
- Dressing can be extended to include two asymptotic boundaries to describe the black hole interior.

Conclusions

- Infalling UDW detector with gravitational dressing is sensitive to Schwarzian fluctuations
    - ➢ Location of black hole horizon and its temperature become locally accessible

- Extending the semiclassical definition into the topological completion of JT gravity leads to nonperturbative modifications to the thermal entropy of the black hole atmosphere
    - ➢ Matrix model statistics lead to plateau in the matter entanglement entropy.

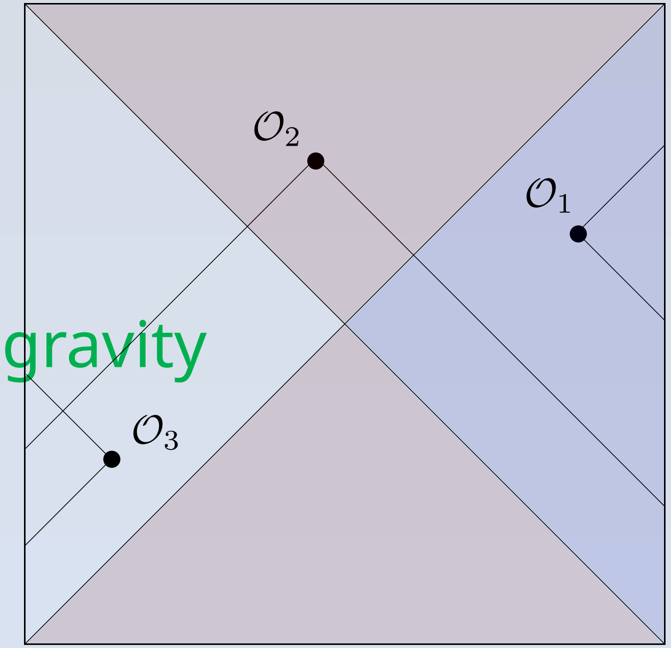
Future directions

Several interesting directions for future work:

- More relativistic quantum info protocols in JT gravity
  - Local measurements in quantum gravity?
  - Gravitationally dressed entanglement harvesting?

- Schwarzian dressing and geometric modular flow in JT gravity
  - How to make this connection more precise?

- Quantum reference frames in nonperturbative JT gravity
  - Fully explicit, solvable example of quantum reference frames far beyond semiclassical regime?



Falling through the horizon of a quantum black hole

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Abstract: We study quantum-gravitational effects on the response of an infalling detector as it crosses the horizon of a near-extremal black hole in the framework of quantum JT gravity. These effects are incorporated via the gravitational dressing needed to define both the infalling trajectory and the local observables probed by the detector in a diffeomorphism-invariant way. In the black hole exterior, a preferred choice of dressing to the Schwarzian mode of JT gravity can be motivated in connection to geometric modular flow. We show how to extend this dressing to the black hole interior, defining local observables that are gravitationally dressed to both boundaries in the thermofield double state. The gravitational dressing connects the near-horizon region to the IR sector of the Schwarzian theory, leading to measurable effects as the horizon is approached. We find that the infalling detector is able to locally determine the location of the horizon and its temperature, violating the equivalence principle, but without encountering a firewall.

Fiducial observers and the thermal atmosphere in the black hole quantum throat

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Abstract: We propose a construction of fiducial observers in the throat region of near-extremal black holes within the framework of JT quantum gravity, leading to a notion of local observers in a highly quantum regime of the gravitational field. The construction is based on an earlier proposal for light-ray anchoring to the asymptotic boundary and is uniquely fixed at the semiclassical level by demanding that the notion of time translations for an observer at the asymptotic boundary of JT gravity should be extended into the bulk as the flow of a conformal isometry. Since conformal isometries are a necessary condition for geometric modular flow, our construction is amenable as a candidate geometric gravitational dressing that may be interpreted via the modular crossed product, potentially connecting our choice of dressing with recent developments on the literature on local observables in quantum gravity. Taking this definition beyond the semiclassical regime, we compute quantum gravitational wormhole contributions to the black hole thermal atmosphere, directly producing a finite thermal entropy and leading to a quantum description of the stretched horizon in this model.

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Thomas Mertens

Thomas Tappeiner

Thank you!