Geometry of the infalling causal patch

Based on arXiv:1406.6043 with Freivogel, Kabir, Yang

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The information paradox

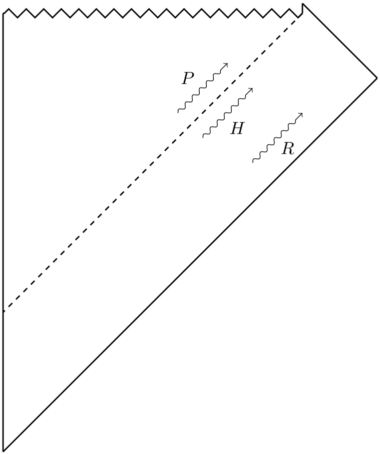

Figure : Penrose diagram depicting the near-horizon Hawking mode H, its behind-the-horizon partner P, and the early radiation R.

Black hole complementarity

Postulates of BHC:

- Unitarity evolution
- Validity of effective field theory (EFT)
- Equivalence principle ("no drama")

Exterior observer has access to H and R, confirms unitarity. Interior observer has access to H and P, confirms equivalence.

AMPS[1] innovation: consider an infalling observer whose causal patch contains H, R, and $P \implies$ *firewall*.

Question: can an infalling observer see enough of the horizon sphere to successfully measure the interior mode P?

[1] arXiv:1207.3123

Singing in the rainframe

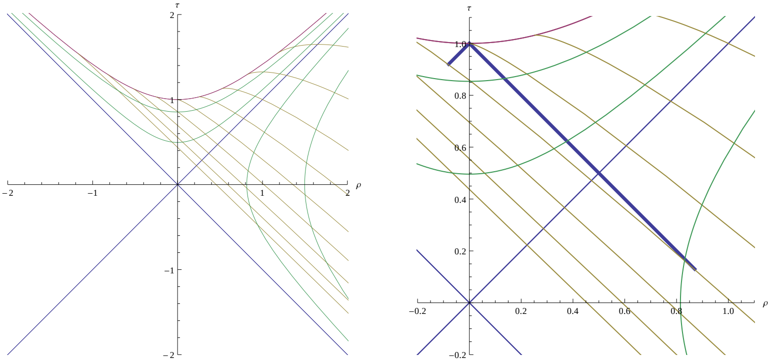

Figure : Schwarzschild black hole in Gullstrand-Painlevé coordinates, with singularity at $r = 0$ (red), showing constant r slices (green), and constant T slices (yellow). The intersection of the past light-cone (bold blue) of an observer hovering just above the singularity with a given T-slice demarcates the radial extremes of the causal patch.

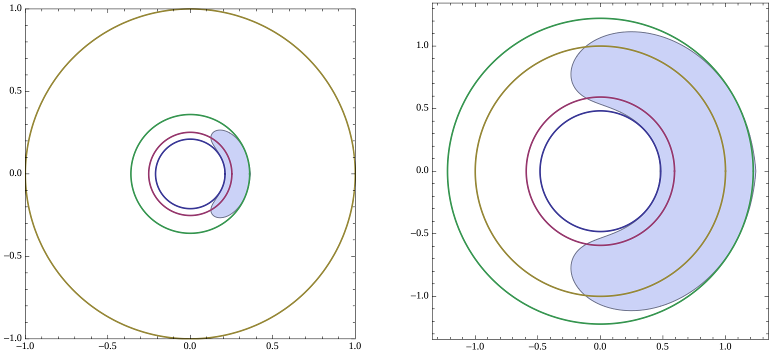

Figure : The shaded region depicts the portion of the spacelike T-slice visible to the observer. The concentric rings show the horizon $r_s = 1$ (yellow), and maximum (green) and minimum (blue) radial extent for the given slice.

Causal patch geometry

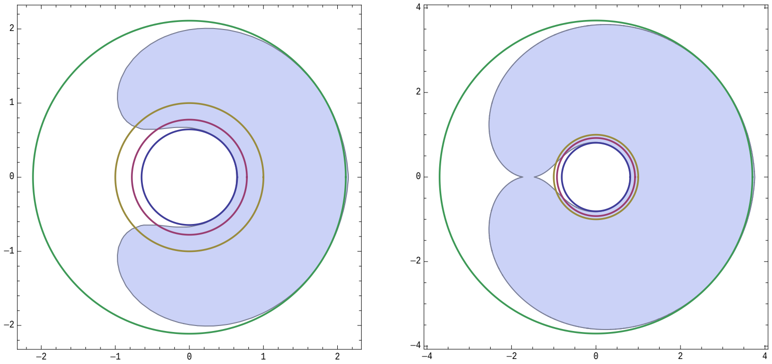

Figure : Increasing $|\Delta T|$ corresponds to selecting a T-slice closer to the past horizon. Note the trade-off between angular visibility and the energy scale of the measurable interior mode.

Rain in the rainframe

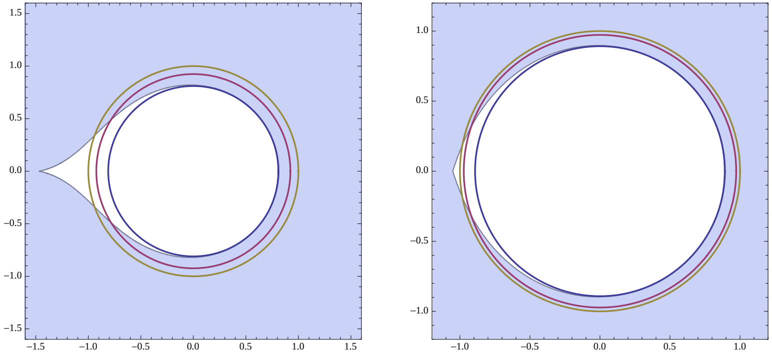

Figure : Close-up of exclusion regions for different $|\Delta T|$. The pointed end of the raindrop diminishes, and the droplet approaches a circular region with radius r_s, in the limit of large $|\Delta T|$.

Droplet analysis

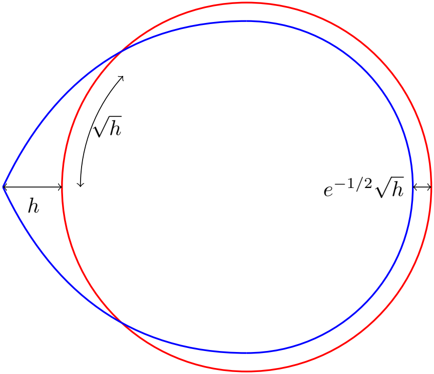

Figure : Sketch of a heavily distorted droplet (blue) against the horizon $r_s = 1$ (red) with parameters of interest labelled. Note that distances are not to scale, although the height is indeed less than the width for $h << 1$ ($|\Delta T|$ large).

Conclusions and open questions

- A physical observer will have difficulty identifying the quantum state necessary to recognize a paradox for all static, spherically symmetric $D \geq 4$ black holes.
- A single observer is always missing at least $\sqrt{N}$ out of N bits of information.
- Large angular visibility only for high energy modes.
- Reconstruction of s-wave probabilistic or via quantum secret sharing?
- Local formulation of the paradox? BHC enough?

Alright, alright, here's some math:

Metric: $\mathrm{d}s^2 = -f(r)\mathrm{d}t^2 + f(r)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\Omega_{D-2}^2$

Maximal angular null ray: $\Delta\theta = \int_0^{r_h} \frac{\mathrm{d}r}{\sqrt{-f(r)}} = \frac{\pi}{D-3}$

GP time: $T = t + r_h\left(2\sqrt{\frac{r}{r_h}} + \ln\left|\frac{\sqrt{\frac{r}{r_h}}-1}{\sqrt{\frac{r}{r_h}}+1}\right|\right)$

GP metric: $\mathrm{d}s^2 = -f\mathrm{d}T^2 + 2\sqrt{\frac{r_h}{r}}\mathrm{d}T\mathrm{d}r + \mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$

Null distances: $$\begin{cases} \Delta\theta = \int_0^{r'} \frac{\pm\mathrm{d}r}{\sqrt{\epsilon^2 r^4 + r^2 f}} \\ \Delta T = \int_0^{r'} \frac{\mathrm{d}r}{f}\left(\sqrt{\frac{r_h}{r}} \pm \frac{\epsilon r}{\sqrt{\epsilon^2 r^2 - f}}\right) \end{cases} \qquad \epsilon \equiv E/l$$