Infalling observers and small black holes

arXiv:1601.05611 with Gilad Lifschytz

builds on a program of constructing local observables in AdS, pursued in collaboration with Lifschytz, Lowe, Hamilton, Roy, Sarkar & by other authors

Amherst workshop - 4/22/16

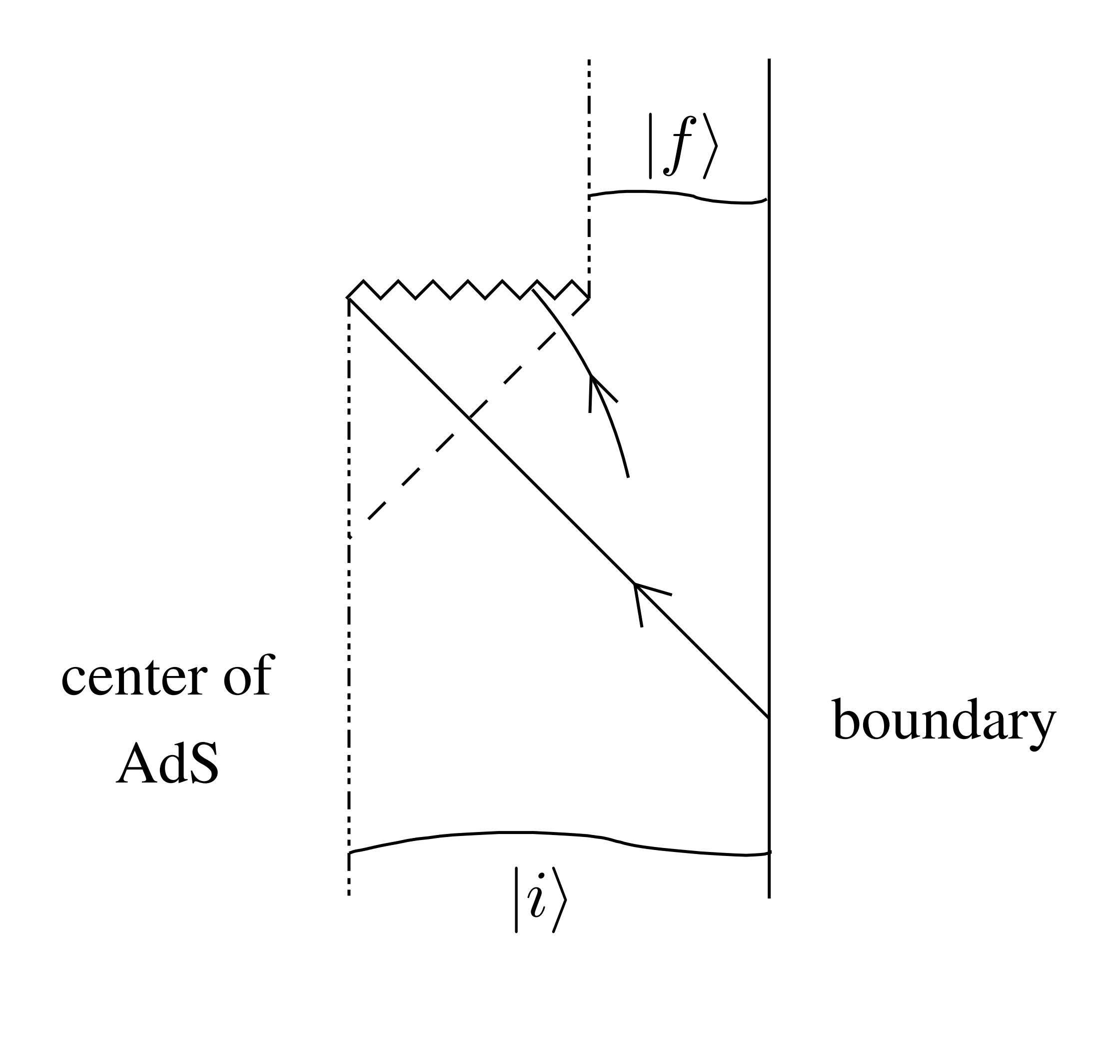
Outline

1. Black hole paradox
2. Ingoing and outgoing modes
3. Ingoing and outgoing fields
4. Black holes (eternal / stable / evaporating)

Black hole paradox

Conflict between two beloved ideas.

Consider an evaporating AdS black hole.



Semiclassical geometry => free fall across horizon, information lost

Unitarity => information escapes, semiclassical geometry misleading

Claim: AdS/CFT has both free fall and unitarity.

How?

In AdS/CFT unitarity is manifest (at least at the boundary), but the bulk geometry is not (must be recovered from the CFT).

Bulk geometry depends on who's asking!

- Infalling observers experience the semiclassical geometry. They follow bulk geodesics up to the singularity.
- Interior Hawking particles are more subtle. Up to the Page time they see the usual interior geometry, but past the Page time this geometry breaks down.

Ingoing and outgoing modes

A well-known property of Killing horizons.

(Boulware, 1975)

Static metric, tortoise coordinate r_*

$$ds^2 = f(r)(-dt^2 + dr_*^2) + r^2 ds_\perp^2$$

$$f(r) \to 0 \quad \text{at horizon}$$

Wave equation has an effective potential $V(r_*)$

$$V(r_*) \to 0 \quad \text{at horizon}$$

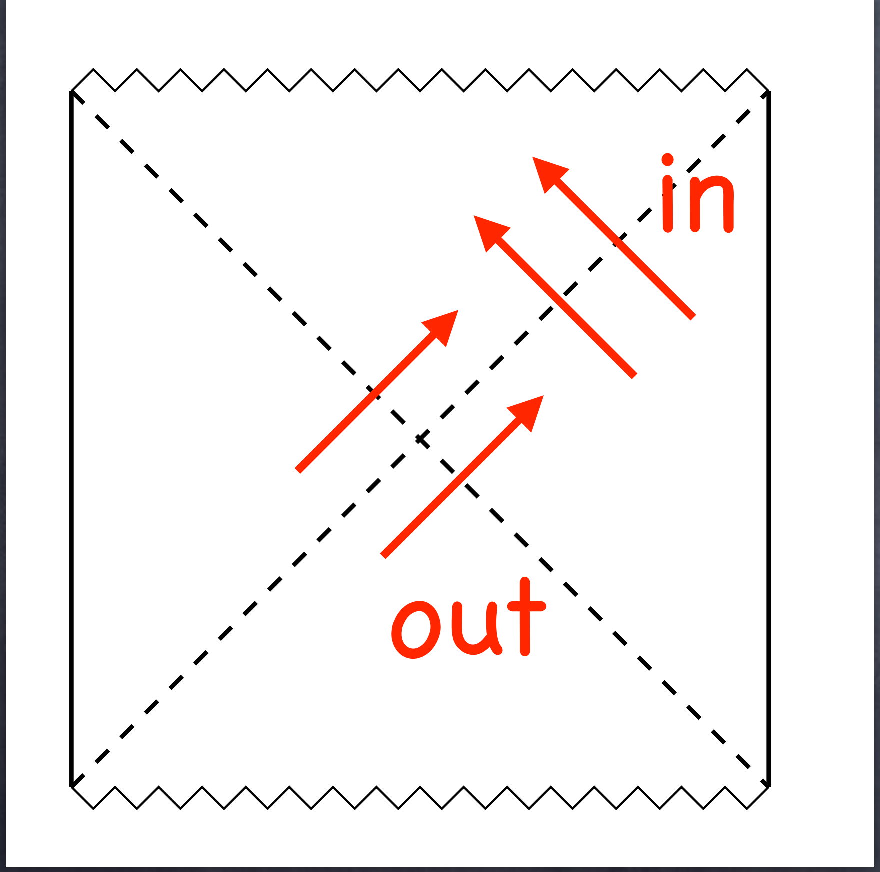
infinite gravitational redshift

Field modes have the near-horizon behavior

$$\text{ingoing:} \quad \phi \sim e^{-i\omega(t+r_*)}$$

$$\text{outgoing:} \quad \phi \sim e^{-i\omega(t-r_*)}$$

massless 2-D



Ingoing modes are smooth across the future horizon, singular on the past horizon.

For outgoing modes the behavior is reversed.

Only a particular combination of in and out is normalizeable near the boundary.

Ingoing and outgoing fields

A normalizeable bulk field can be decomposed

$$\phi = \phi_{\rm in} + \phi_{\rm out}$$

It's easy to express $\phi_{\rm in}$ and $\phi_{\rm out}$ as operators in the CFT, at least outside the horizon.

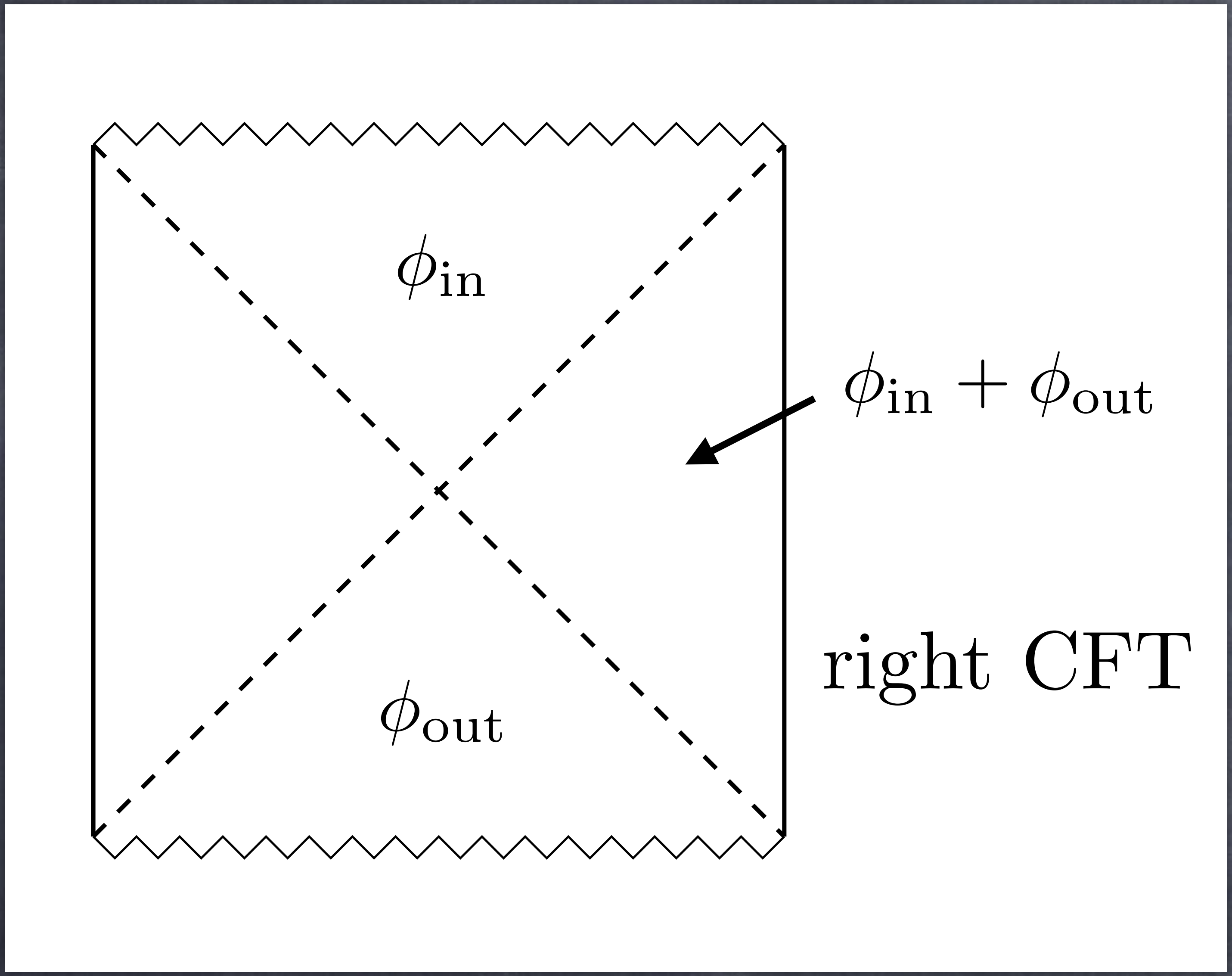
Example: free massless field in AdS_2

$$\phi_{\rm in}(t, r_*) = \frac{1}{2}\int_{t+r_*}^{\infty} dt' \, \mathcal{O}(t')$$

$$\phi_{\rm out}(t, r_*) = -\frac{1}{2}\int_{t-r_*}^{\infty} dt' \, \mathcal{O}(t')$$

operator in right CFT

Not surprisingly ϕ_{in} extends to the future interior as a CFT operator, and ϕ_{out} extends to the past.



Outside the horizon we can recover the full field from the right CFT. Inside the past or future horizon we get partial information about the field.

The ingoing part of the field lets us describe infalling wavepackets in the CFT.

$$\phi = \int d\omega \, a_\omega \, e^{-i\omega t} \, \phi_\omega^{in}(r)$$

a_ω sharply peaked about $\omega = \omega_0$

In a stationary-phase approximation, the peak of the wavepacket tracks an infalling geodesic.

This description becomes exact in the geometric optics limit $\omega_0 \to \infty, \, m \to \infty, \, \frac{\omega_0}{m}$ fixed.

Recovers infalling geodesics from the CFT!

Black hole interior

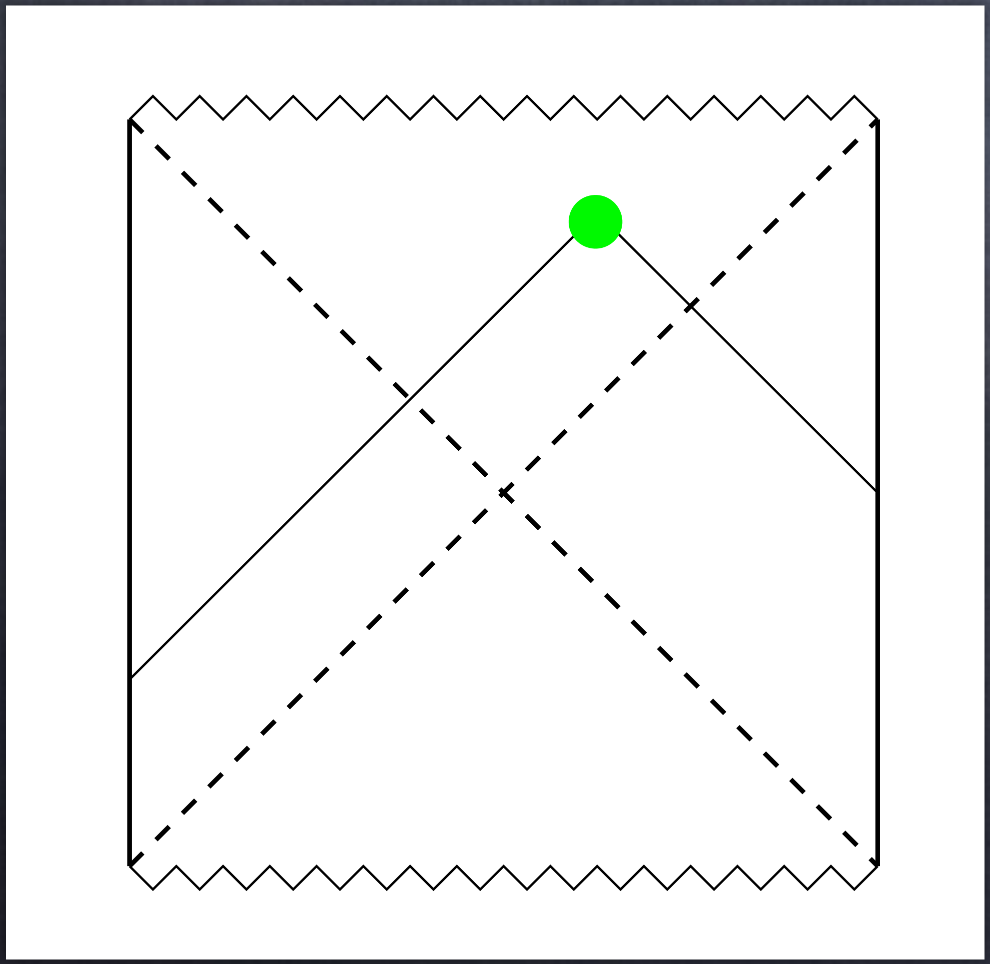
There are three different cases to consider, with very different outcomes.

- Eternal black holes
- Stable black holes formed in collapse
- Evaporating black holes

Eternal black hole

There is no difficulty describing the interior, if one uses both copies of the CFT.

Fields in the interior are a sum of ingoing from the left and ingoing from the right.



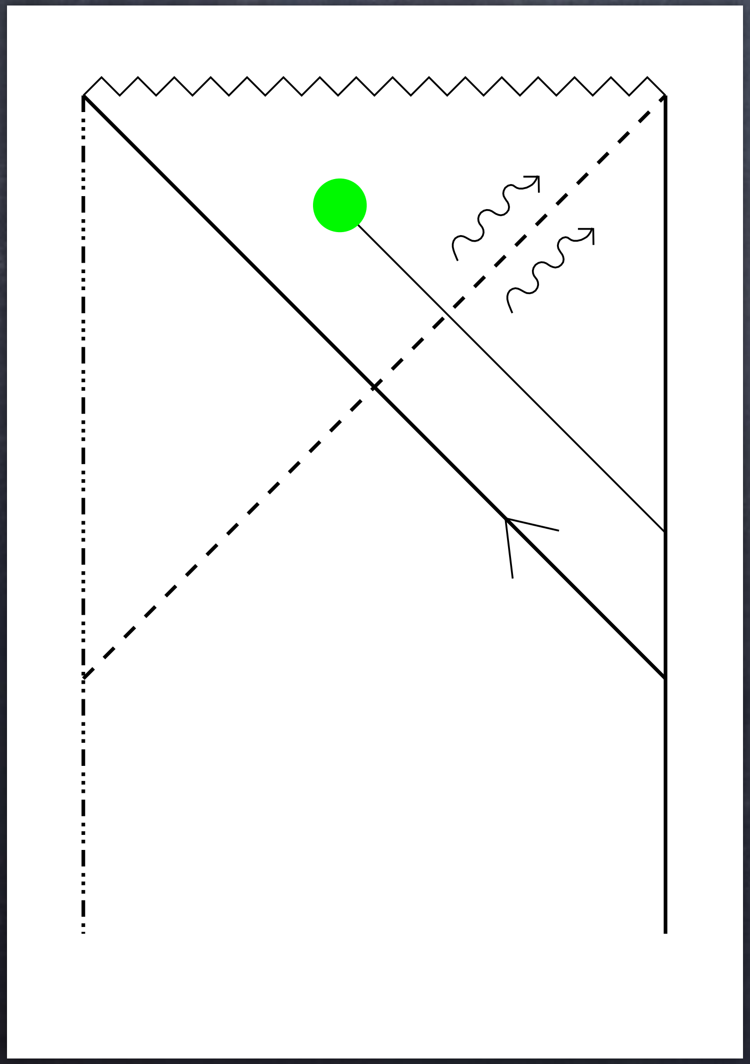
$$\phi = \phi_{\rm in}^{L} + \phi_{\rm in}^{R}$$

Conventional internal geometry, encoded in the CFT.

Stable black hole

Now there's only a single CFT to work with.

Ingoing part can be represented by an operator in the CFT, outgoing part can be represented using entanglement.



PR construction

Future horizon is an entangling surface for outgoing modes.

Defines a pairing between states inside and outside the horizon.

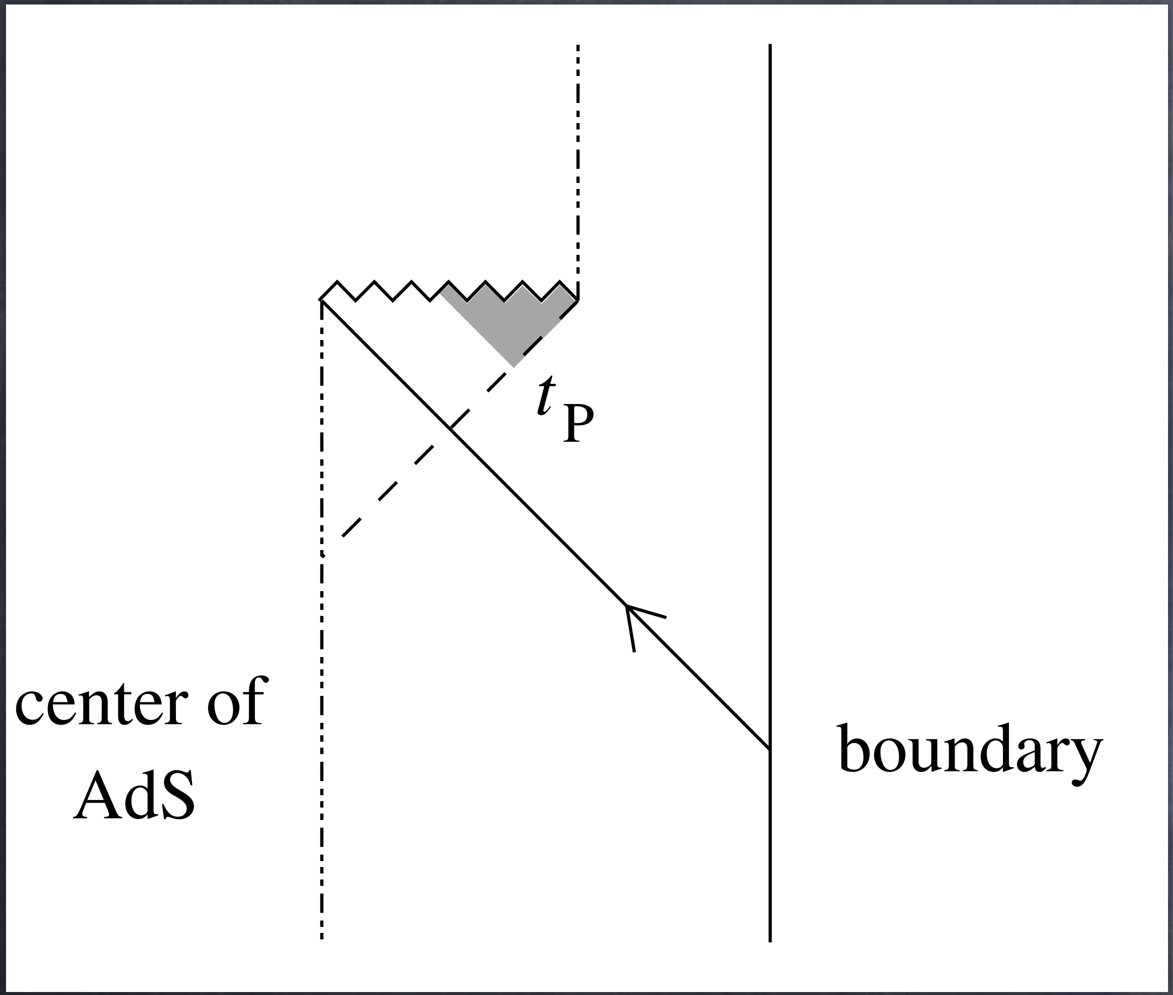
Lets us describe local operators in the interior.

Evaporating black holes

These behave like stable black holes up to the Page time. But around the Page time the entanglement changes. Late Hawking particles are entangled with distant early radiation, not with the interior.

Could still apply the PR construction,
but it won't give local fields in the interior.

So evaporating black holes have a conventional interior geometry up to the Page time.



But past the Page time the ingoing modes are geometric, the outgoing modes are not.

Reconciles semiclassical geometry for an infalling observer with the breakdown of geometry required by unitarity.