Information Loss Paradox and Asymptotic Black Holes

Pei-Ming Ho

賀培銘

Physics Department
National Taiwan University

Kawai et al: [arXiv: 1302.4733]
[arXiv: 1409.5784]
[arXiv: 1509.08472]

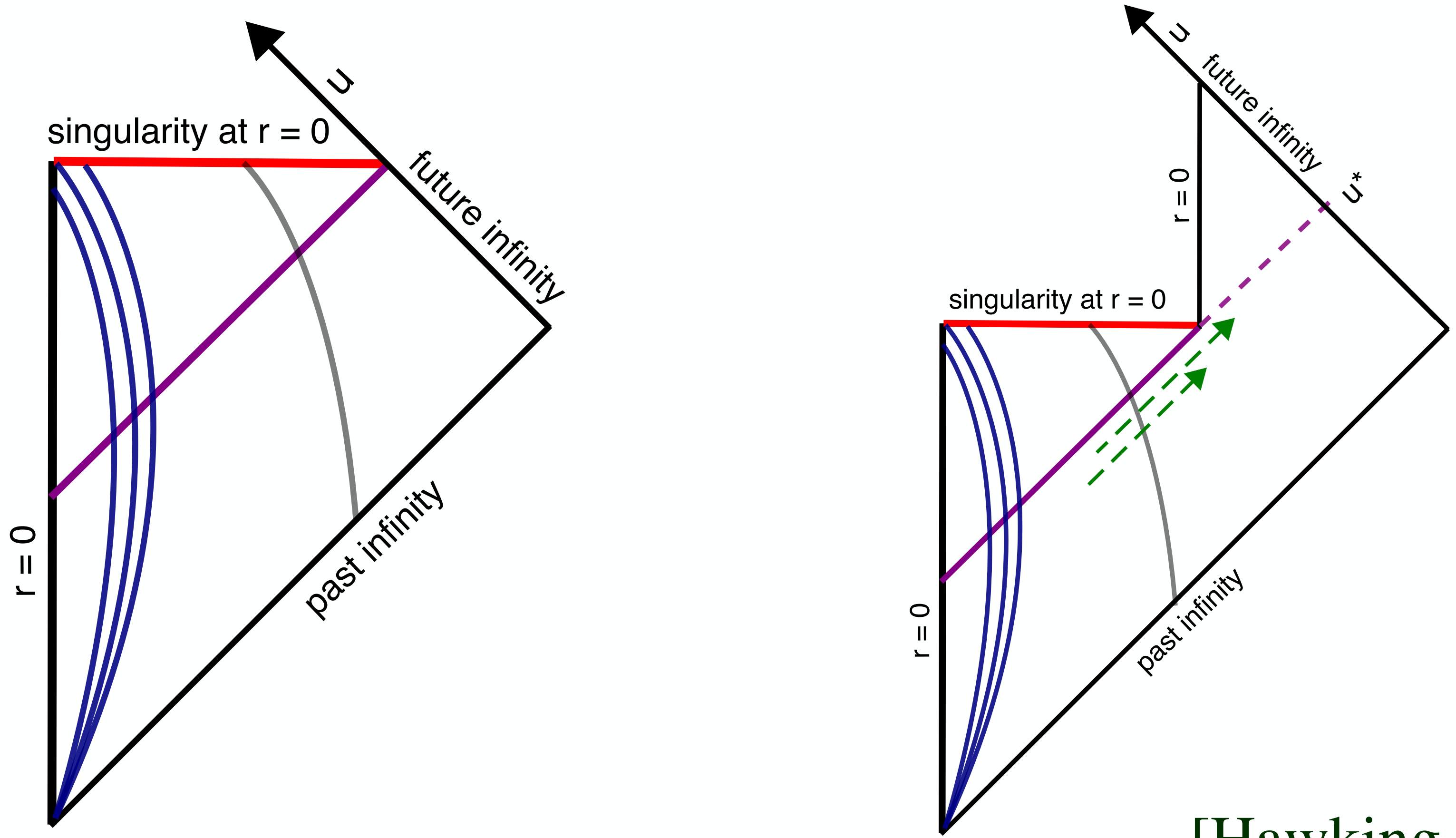
Ho: [arXiv: 1505.02468]
[arXiv: 1510.07157]
[arXiv: 160*.*****]

In the conventional model of BH:

Infalling observer: finite proper time to cross the horizon.

Distant observer: infinite time if no radiation.

Hawking radiation ⇒ Horizon shrinks, but finite time!



[Hawking 1976]

Misconception #1

For a classical black hole, an infalling object crosses the horizon in finite proper time. This is also true for a very small deformation of the classical black hole, e.g. due to the back-reaction of a very weak radiation.

Outgoing Vaidya metric

$$ds^2 = -\left(1 - \frac{a(u)}{r}\right) du^2 - 2du dr + r^2 d\Omega^2$$

$$a(u) = 2M(u) \qquad T_{uu} = \frac{G_{uu}}{8\pi G} = -\frac{1}{8\pi G}\frac{\dot{a}(u)}{r^2}$$

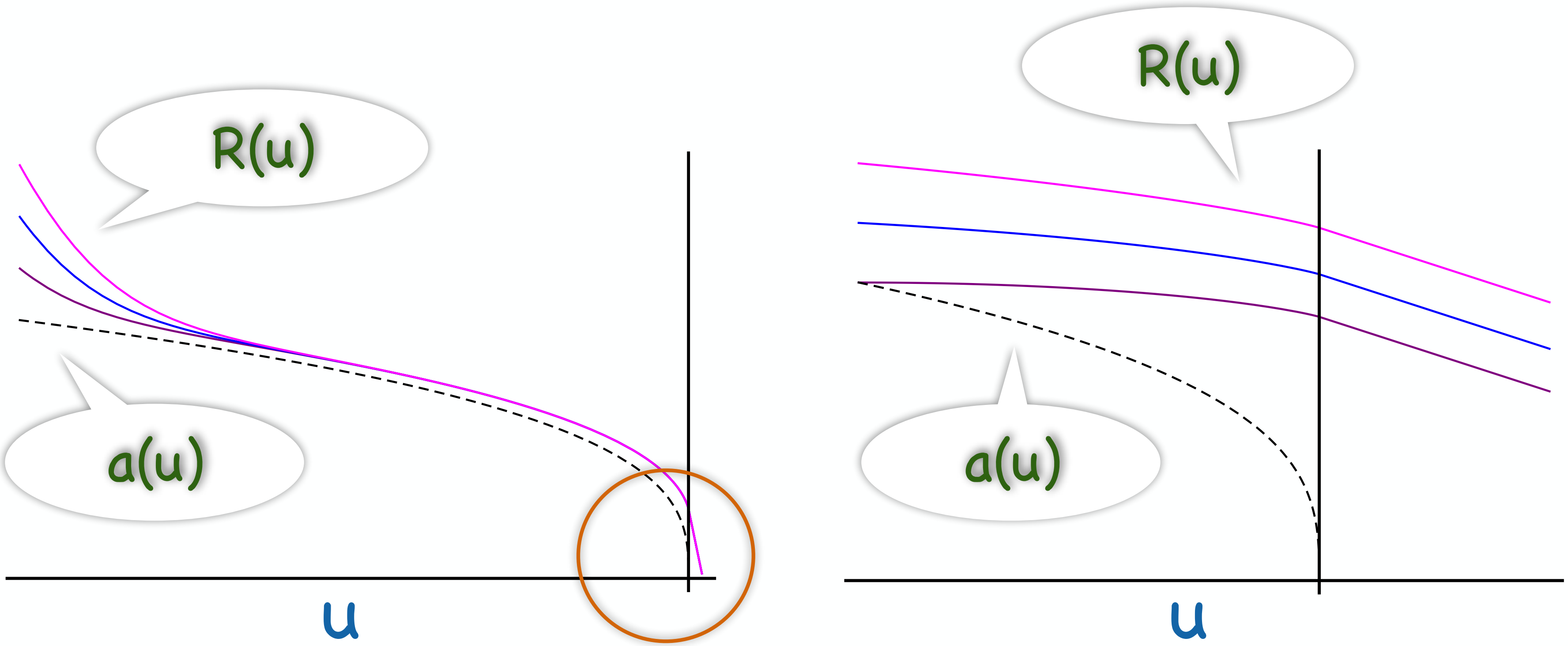
Light-like geodesics:

$$du = 0 \qquad \left(1 - \frac{a(u)}{r}\right) du + 2dr = 0$$

Outgoing

Ingoing for $r > a$

R(u) vs a(u)



All infalling null trajectories are geodesically complete without crossing horizon. [KMY2013][Ho2015]

Proof of no black-hole apparent horizon

[Ho2015]

Schwarzschild radius is space-like:

$$r = a(u)$$

$$ds^2 = 0du^2 - 2da(u)du = -2\dot{a}(u)du^2 > 0$$

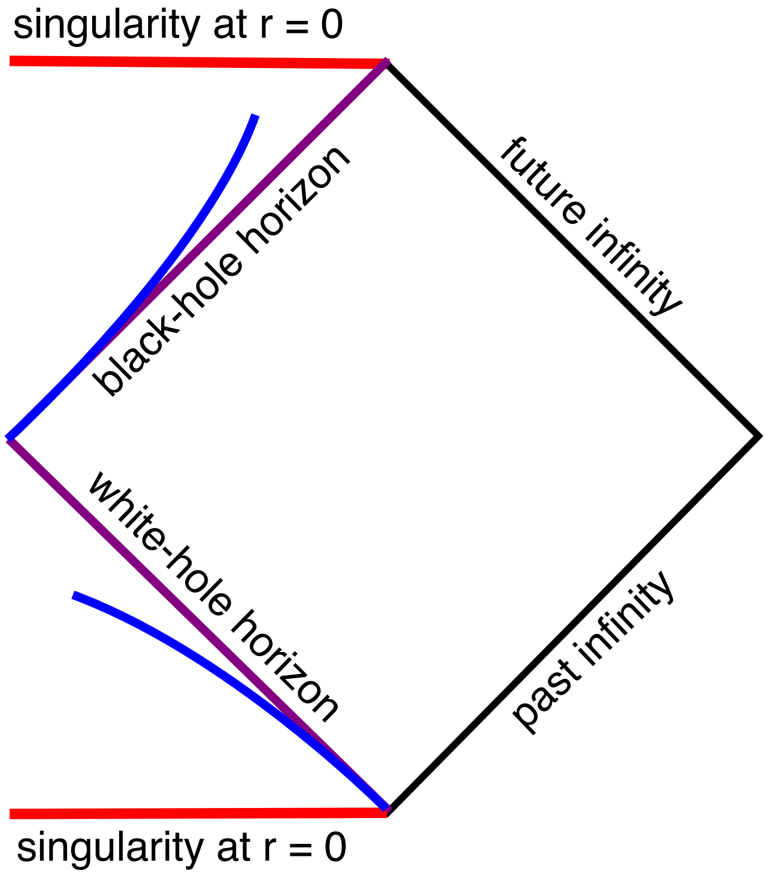
Schwarzschild radius shrinks faster than light!

Complete evaporation ($a(\mathrm{u}) = 0$ for $\mathrm{u} > \mathrm{u}^*$)

$\longrightarrow$ infalling trajectories are geodesically complete

$\Rightarrow$ No black-hole apparent horizon.

Outgoing radiation can be arbitrarily weak.



Black-hole apparent horizon vs white-hole apparent horizon

[KMY2013][Ho2015]

Schwarzschild solution is degenerate. [Ho2015]

Gravitational collapse ~ critical phenomenon

KMY Model

[Kawai-Matsuo-Yokokura 2013]
[Kawai-Yokokura 2014]
[Kawai-Yokokura 2015]

Assumptions:

- Spherical Symmetry
- Collapsing massless dust
- (pre-)HR of massless particles

The energy-momentum tensor is that of a light-like energy flux outside the surface of the collapsing sphere.

Outside the Collapsing Sphere

r > R(u) > *a*(u): the outgoing Vaidya metric [KMY2013]

$$ds^2 = -\left(1 - \frac{a(u)}{r}\right) du^2 - 2dudr + r^2 d\Omega^2$$

$$a(u) = 2M(u) \qquad T_{uu} = \frac{G_{uu}}{8\pi G} = -\frac{1}{8\pi G}\frac{\dot{a}(u)}{r^2}$$

Light-like geodesics:

$$du = 0 \qquad \left(1 - \frac{a(u)}{r}\right) du + 2dr = 0$$

Outgoing
e.g. HR

Ingoing for $r > a$

e.g. $r = \mathrm{R(u)}$

Information Loss Paradox

Apply the same arguments ⇒

If complete evaporation,

there is no horizon ⇒ No info loss

→ **Asymptotic Black Hole**

a *consistent* approach.

No paradox even if there is horizon.

Collapsing matter is never behind a horizon.

(pre-)HR created near the collapsing matter,
like peeling off an onion.

[KY2015]

* Burning through quantum tunnelling
at macroscopic scale
* Hard to distinguish from a black hole.

Misconception #2

The blue-shift factor approaches to infinity as the collapsing surface approaches to the Schwarzschild radius, and thus there would be a diverging energy flux near the collapsing surface, if Hawking radiation exists there.

Surface of the collapsing sphere:

$$\frac{dR(u)}{du} = -\frac{1}{2}\left(1 - \frac{a(u)}{R(u)}\right) \qquad \dot{a}(u) \simeq -\frac{\sigma}{a^2(u)}$$

$$R(u) \simeq a(u) + \frac{2\sigma}{a(u)} \qquad \sigma = \frac{NG\hbar}{48\pi}$$

The surface of a collapsing sphere stays above the Schwarzschild radius by the separation:

$$\Delta r = R - a \simeq \frac{2\sigma}{a}$$

energy flux at collapsing surface

The energy-momentum tensor near the outer surface of the shell is

$$T_{uu} = -\frac{1}{8\pi G}\frac{\dot{a}}{r^2} \qquad T_{ur} = T_{rr} = 0$$

$$\hat{n}^\mu = (\hat{n}^u, \hat{n}^r, 0, 0) \qquad \hat{n}^\mu \hat{n}_\mu = -1$$

$$\hat{n}^u = \frac{e^\zeta}{\sqrt{1 - a/r}} \qquad \hat{n}^r = -\sqrt{1 - a/r}\ \sinh\zeta$$

$$T_{\mu\nu}\hat{n}^\mu\hat{n}^\nu = -\frac{1}{8\pi G}\frac{\dot{a}}{r^2}\frac{e^{2\zeta}}{1 - a/r} \simeq \frac{1}{16\pi G}\frac{e^{2\zeta}}{a^2}$$

which is very weak for a large aBH. [Ho2015]

Hawking radiation in the absence of black-hole apparent horizon?

→ pre-Hawking radiation

Hawking radiation without horizon?

Bogoliubov transformation:

Exponential relation between u and U.

[Barcelo-Liberati-Sonego-Visser 1011.5911]

$R > a \Rightarrow$ no horizon

$R - a = \Delta r = \textit{extremely small}$

Hawking radiation of wavelengths $\lambda >> \Delta r$ are expected to appear.

Hawking radiation for white-hole horizon?

same spectrum of Hawking radiation [KMY2013]

Generalization

incomplete evaporation

generalized solution w. spherical symmetry

general Hawking radiation

more general energy-momentum tensor

[Ho2015]

The arguments are robust.

geometry inside the collapsing sphere

Decompose the collapsing sphere into infinitely many infinitesimally thin shells.

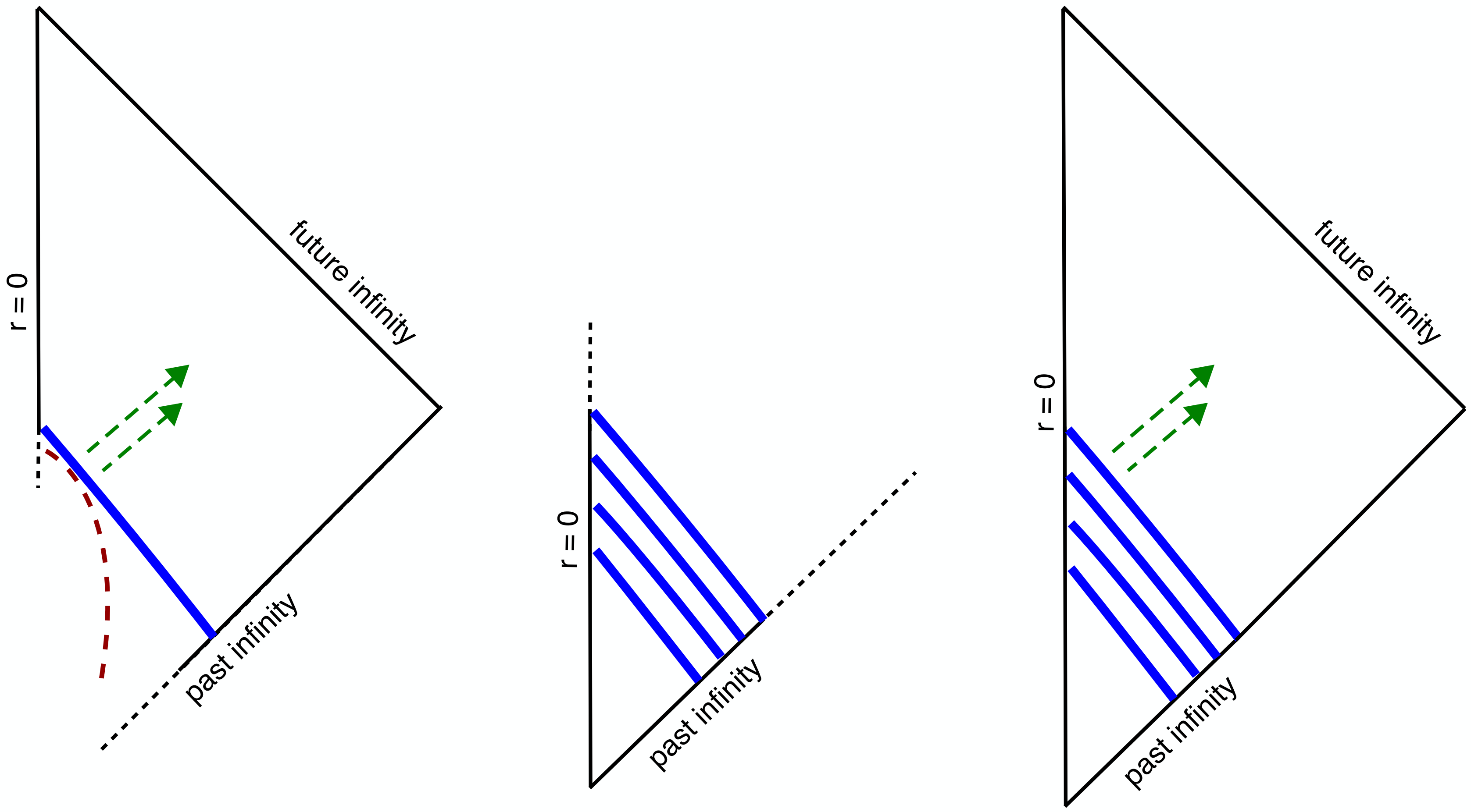
Every layer approaches to the Schwarzschild radius.

Huge red-shift => everything inside is frozen.

[KMY2013,KY2014,KY2015]

KMY Model:
Patching Penrose diagrams together

[KMY2013]



Asymptotic Black Holes

Surface stays at $\Delta r \sim 2\sigma/a$

away from the Schwarzschild radius a.

~ Brick Wall Model and Membrane Paradigm.

[Ho2016]

* Thin-shell model is not reliable.

Black Hole (Non-) Formation

Trapping region: Frolov, Vilkoviski (81)

Domain wall: Vachaspati-Stojkovic-Krauss [0609024]

Collapsing star: Mersini-Houghton [1406.1525]

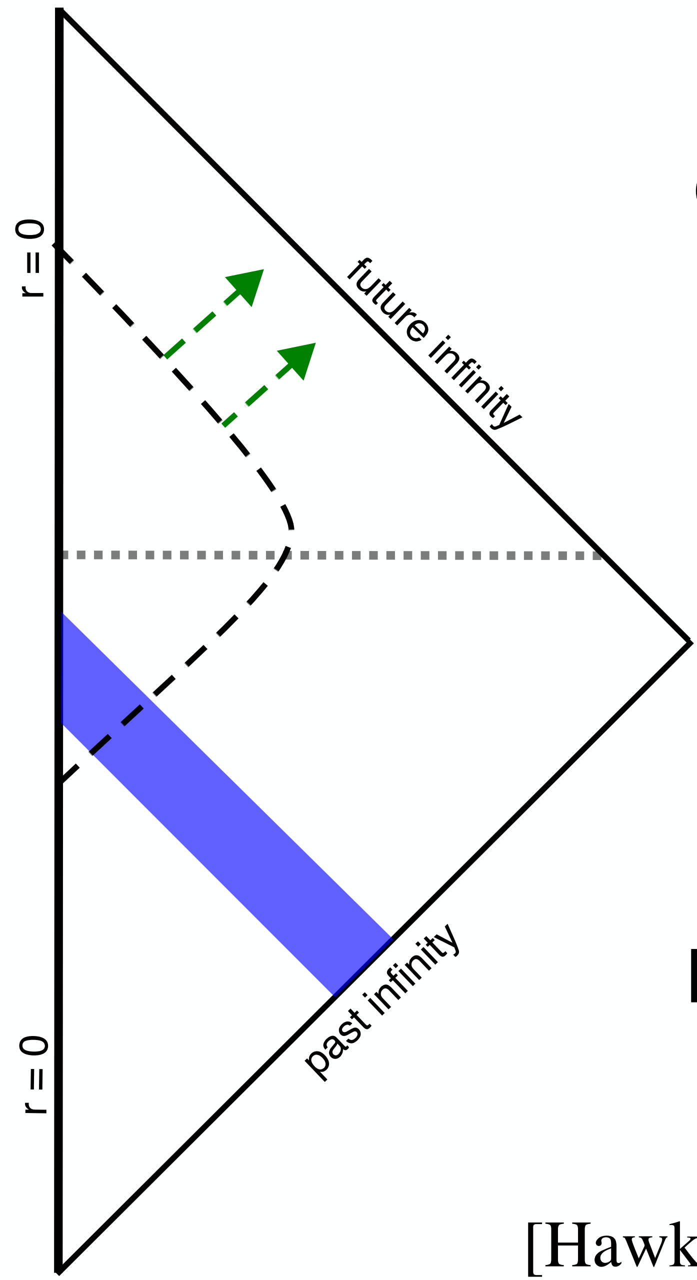
Fuzzball: Lunin-Mathur [0109154, 0202072]

Firewall: Almheiri-Marolf-Polchinski-Sully [1207.3123]; Braunstein [0907.1190]

Review: Mathur [09091038]

“No drama at horizon” vs “Order 1 correction”

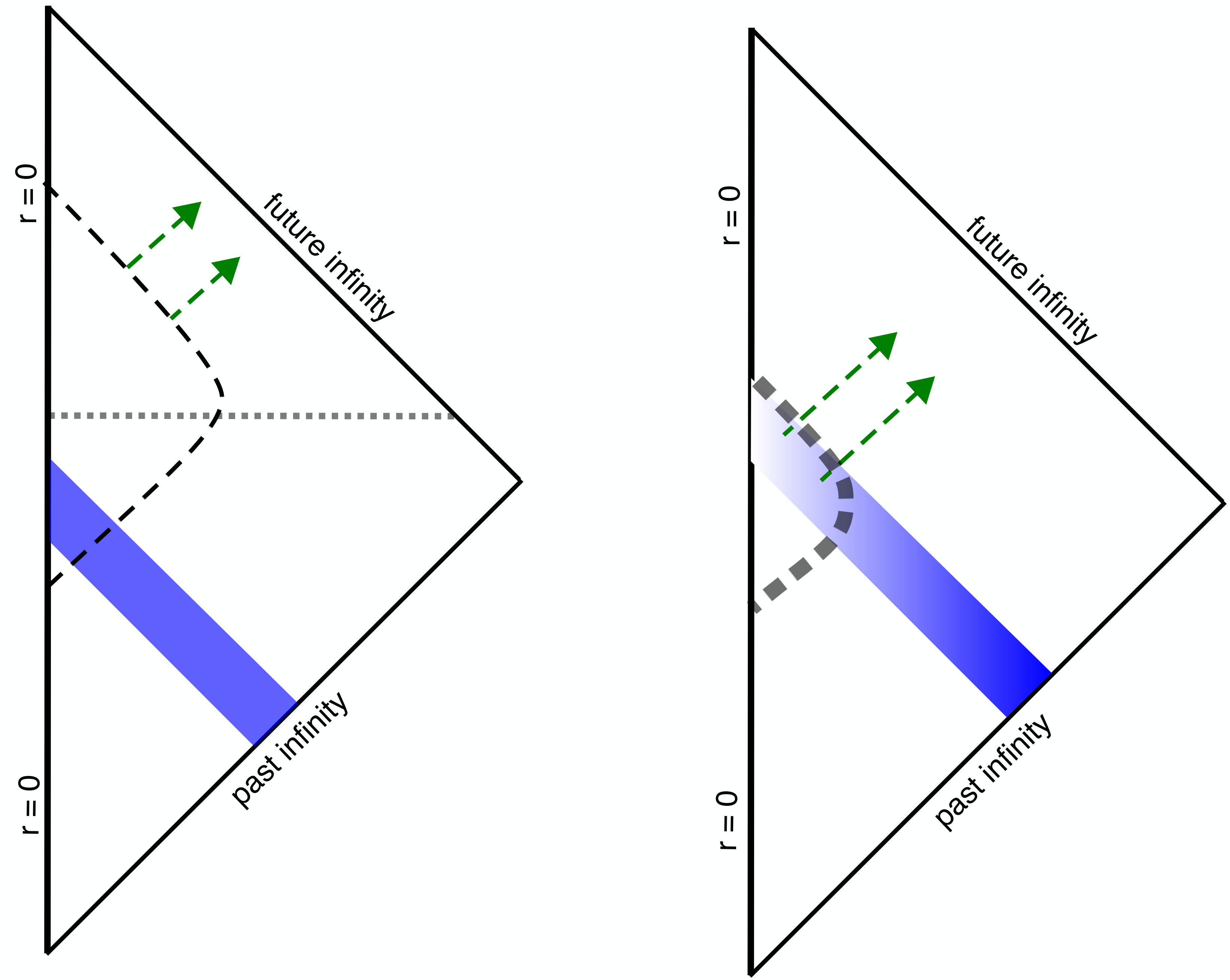
What’s new: robust semi-classical arguments.



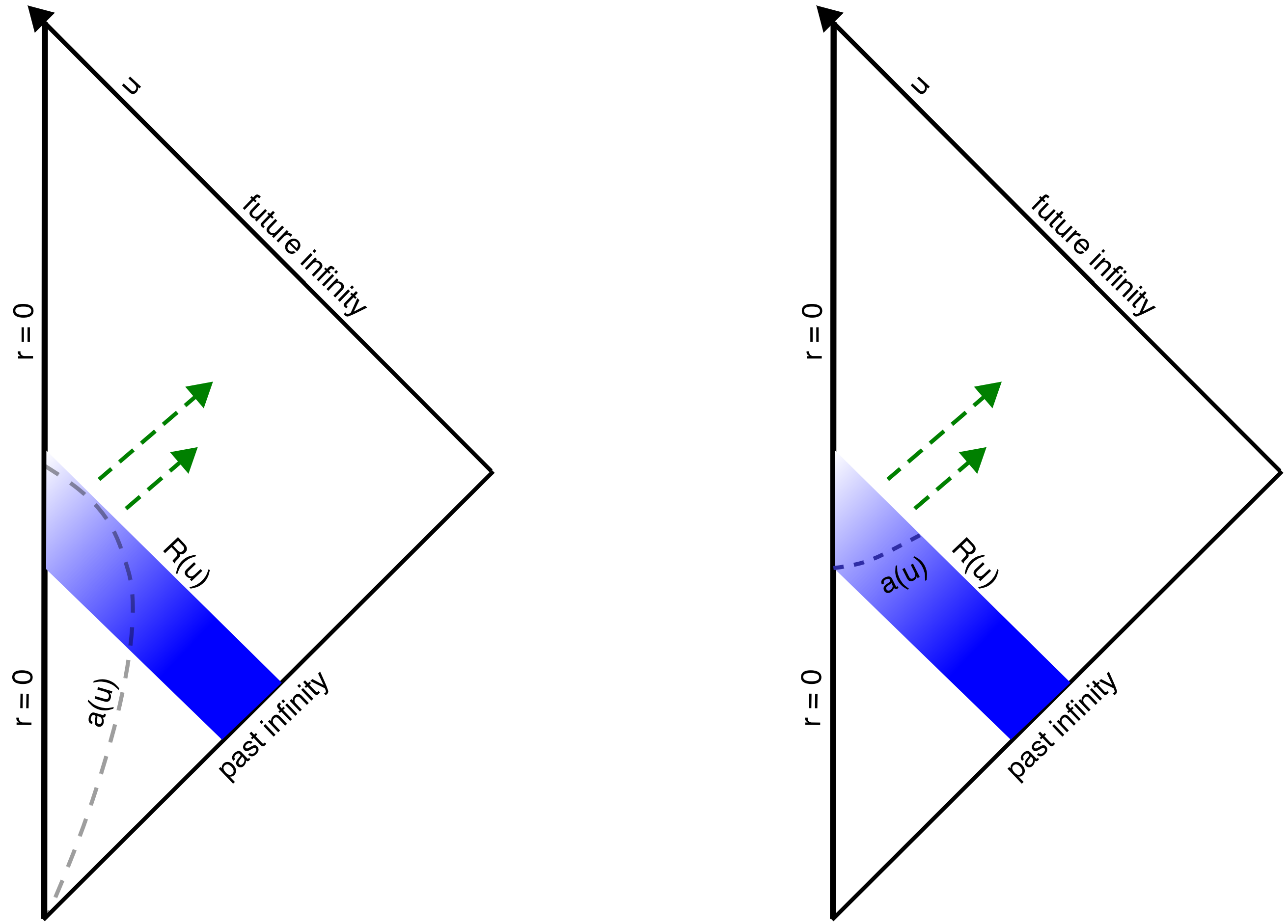
If there is classical radiation coming out of the horizon, it is a *white-hole* horizon.

Firewall persists?

[Hawking-Perry-Strominger 2016]


r = 0
future infinity
r = 0
past infinity
r = 0
future infinity
r = 0
past infinity

KMY Model


u
future infinity
r = 0
R(u)
r = 0
a(u)
past infinity
u
future infinity
r = 0
R(u)
a(u)
r = 0
past infinity

Conclusion

Consistent model of black holes

Semi-classical, large scale physics

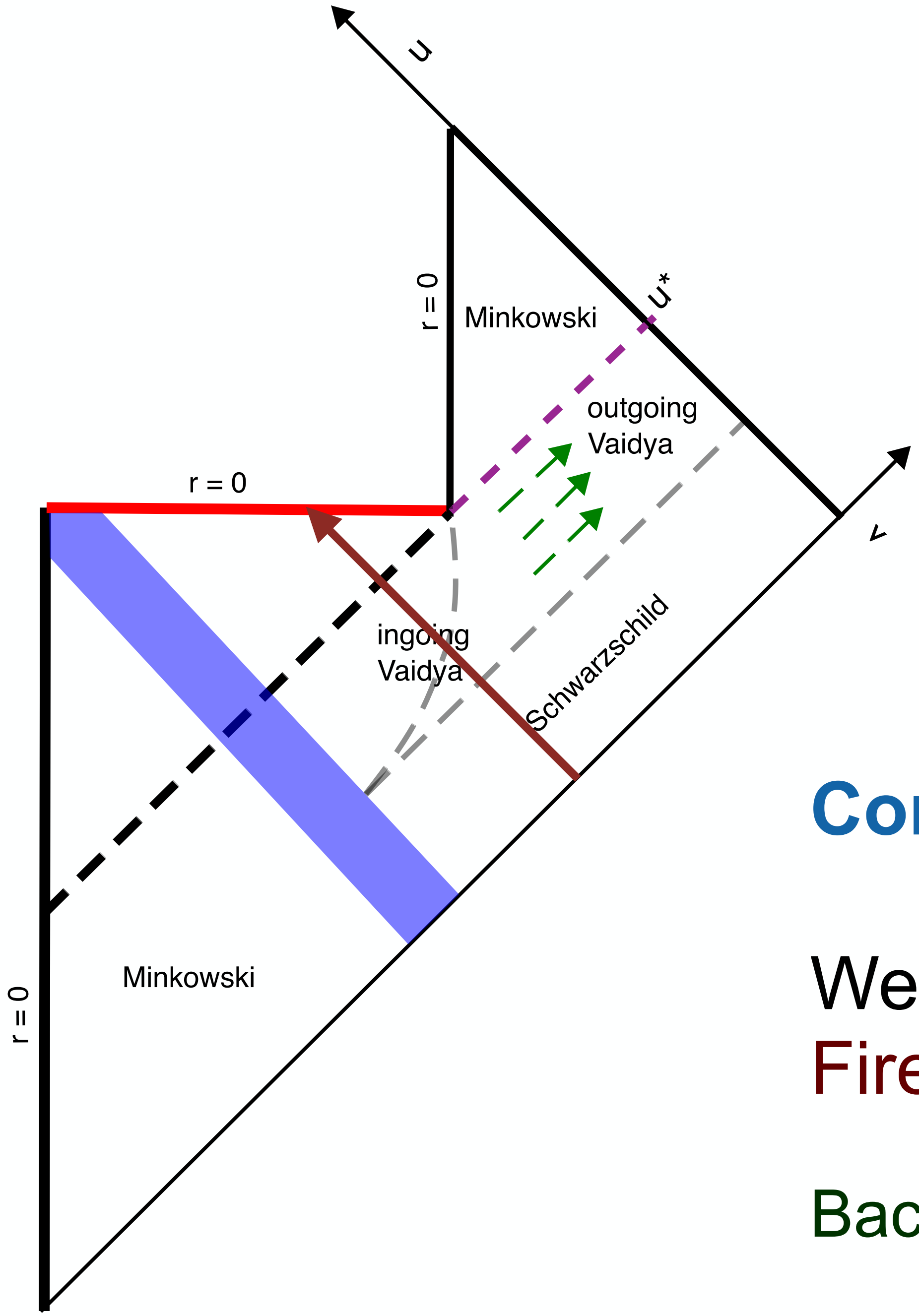
No firewall

No horizon (if not already there)

No Information loss paradox

Asymptotic black holes in observations

Thank you!

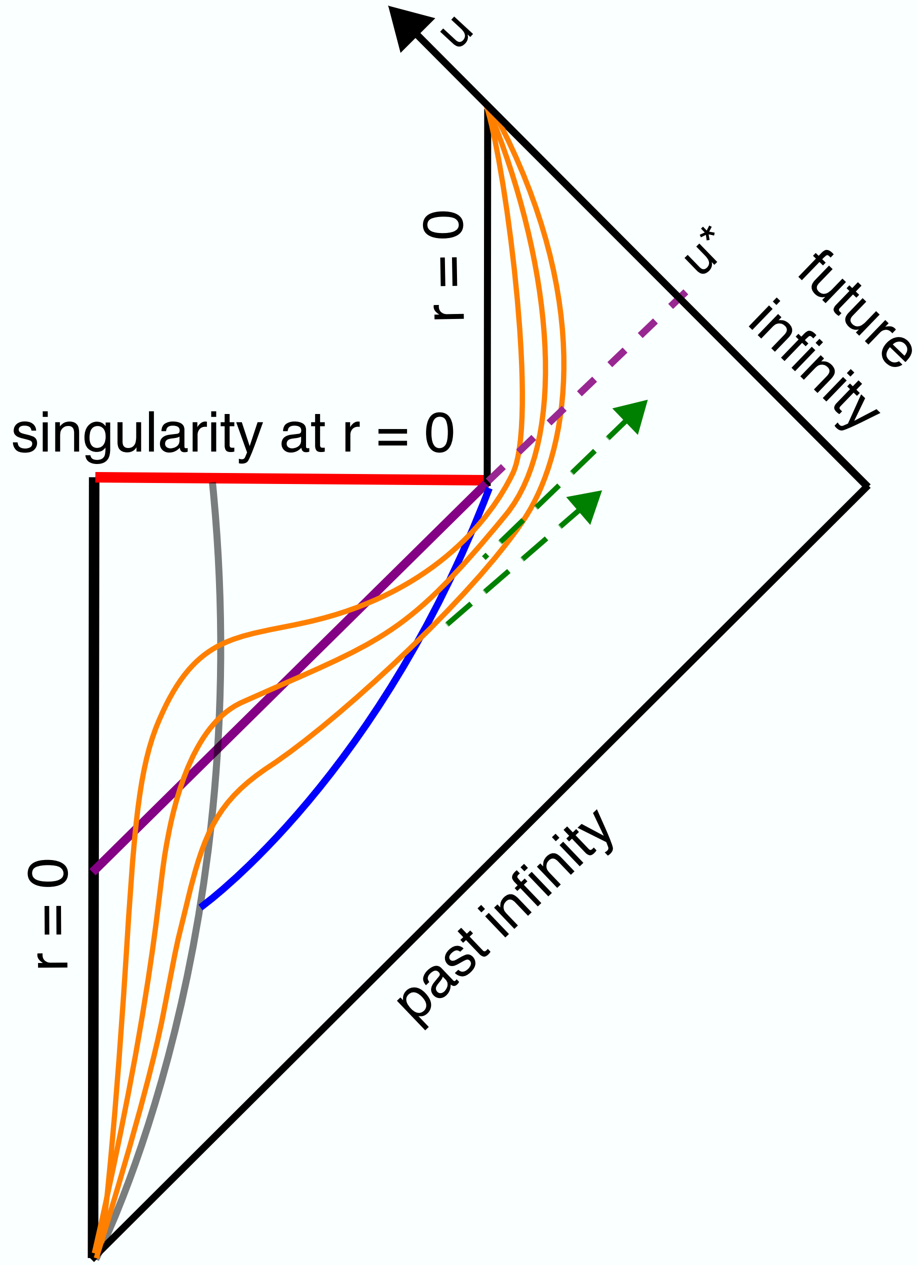


Conventional Model:

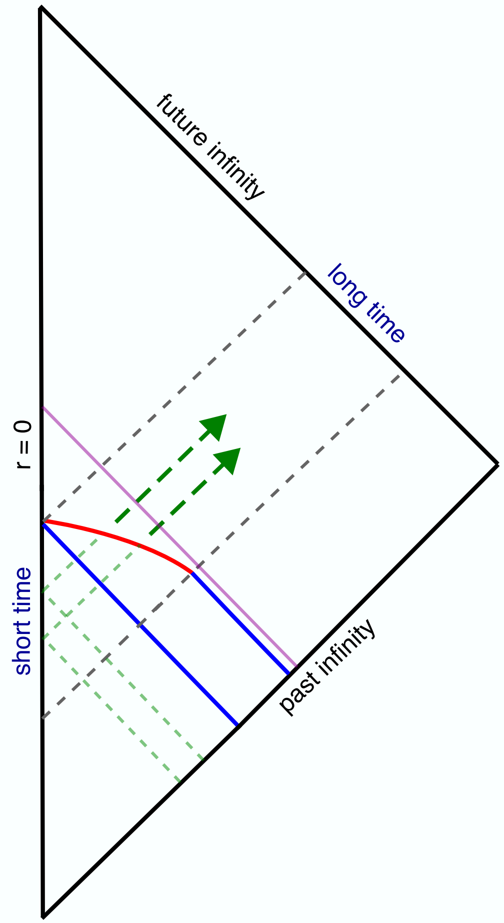
Weak energy condition violated.
Firewall at the horizon.

[AMPS: 1207.3123]

Back-reaction?



u
r = 0
u*
future infinity
singularity at r = 0
r = 0
past infinity

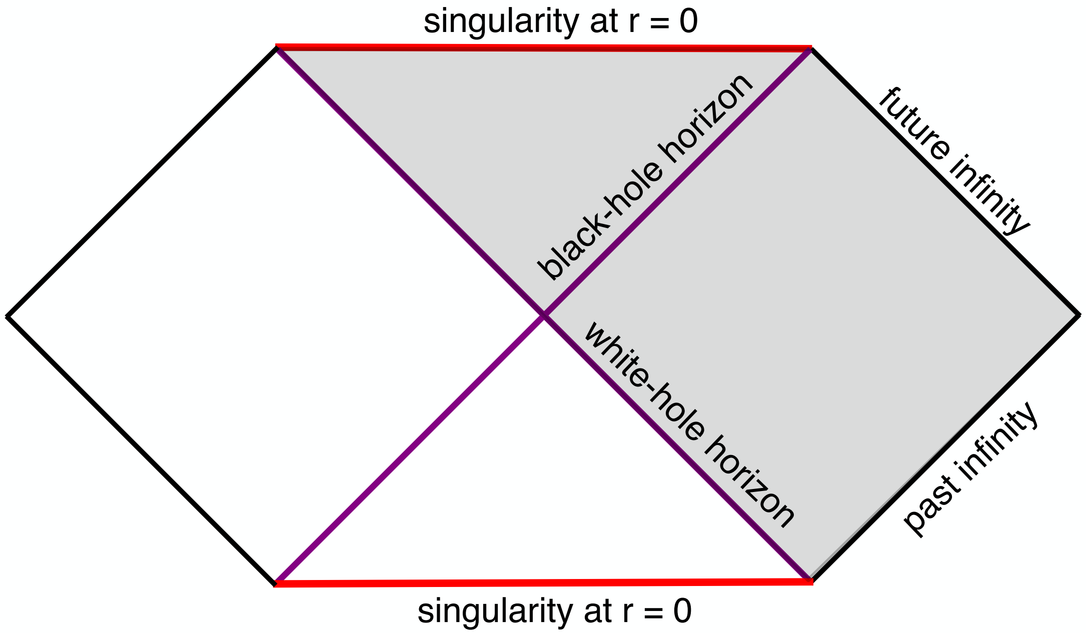

future infinity
long time
r = 0
short time
past infinity

Thin Shell and Time Scale

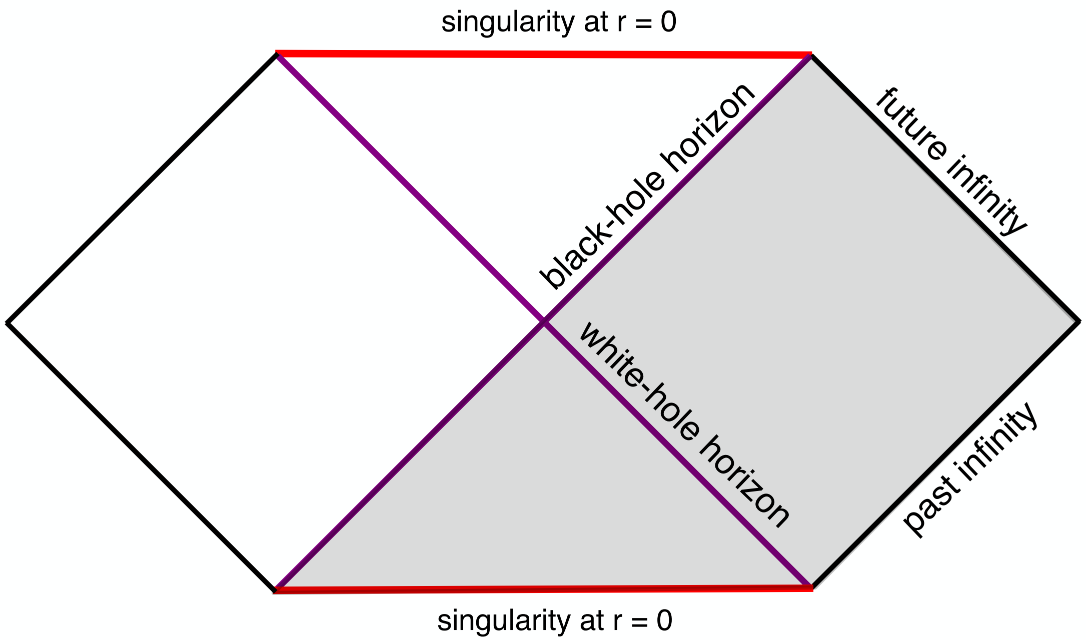
The thin shell model is not a good approximation
because over a long period of time
the inner surface and the outer surface
must be separated by the Schwarzschild radius.

Perturbative Approximation?

Schwarzschild solution is degenerate. [Ho2015]
Gravitational collapse ~ critical phenomenon



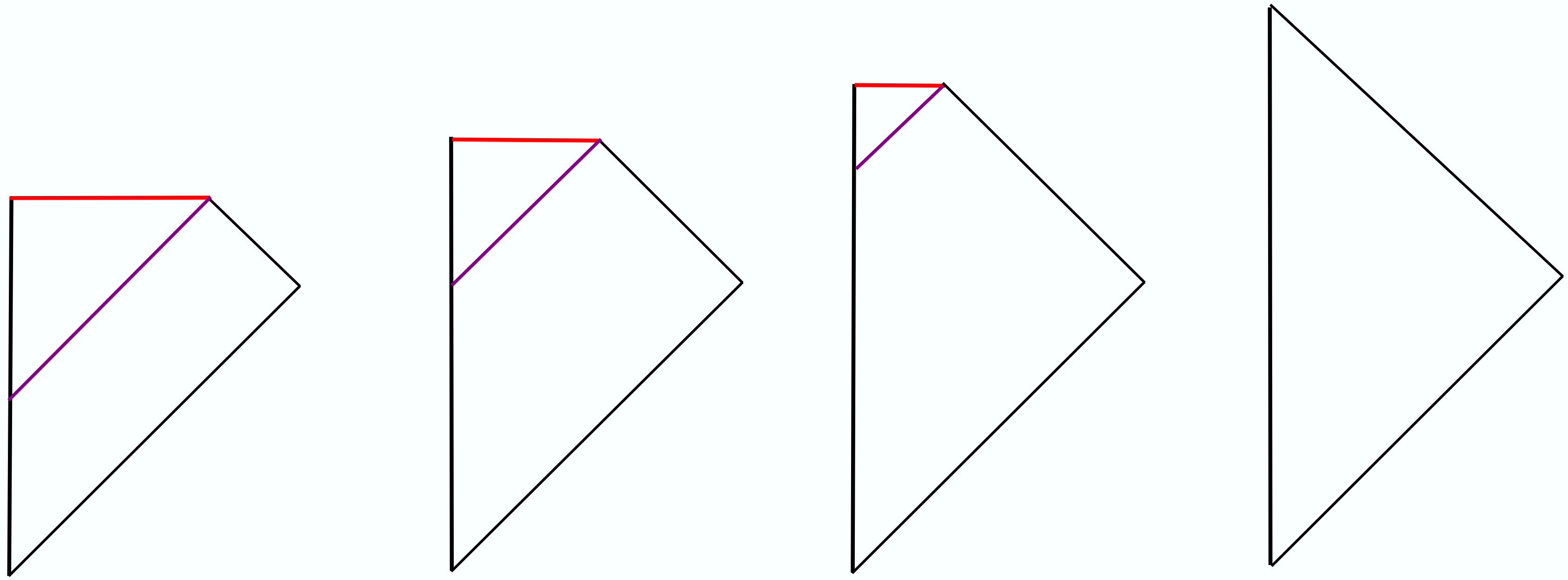
black-hole



white-hole

Continuous Deformation of Classical Black Hole by Hawking Radiation

From a classical black hole without HR to larger and larger HR,
to complete evaporation.



The coordinate system of (u, r) only covers the part visible to a distant observer (outside the horizon).

Infalling observer's crossing in (in)finite time:

$$ds^2 = -\left(1 - \frac{a(u)}{r}\right) du^2 - 2du dr + r^2 d\Omega^2$$

Recall that if a = constant,

$$u = t - r^* \qquad r^* = r + a_0 \log\left|\frac{r}{a_0} - 1\right|$$

For an infalling observer, the relevant time coordinate is

$$v = t + r^*$$

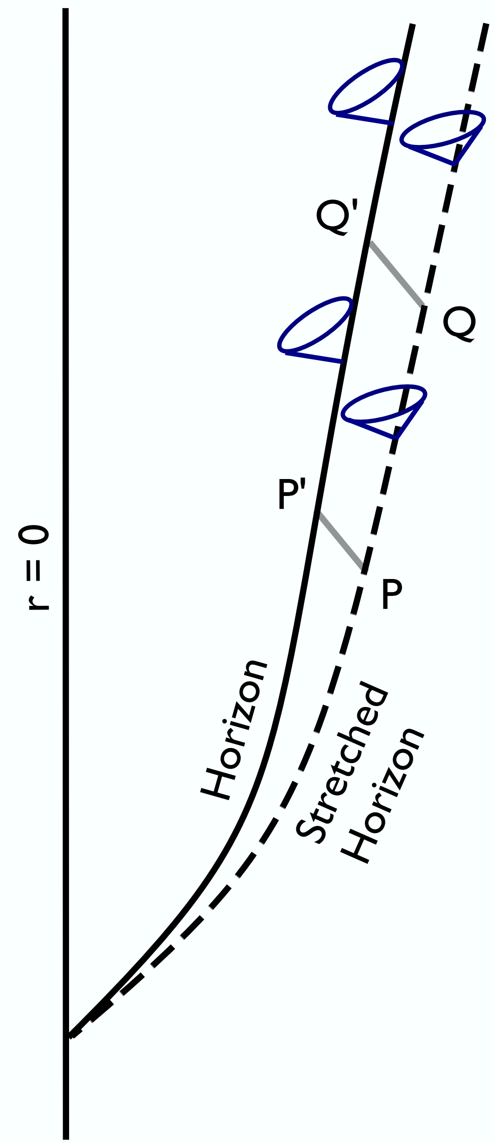
It can be finite when t is infinite if $r = a$.
But it works only if there is no complete evaporation.

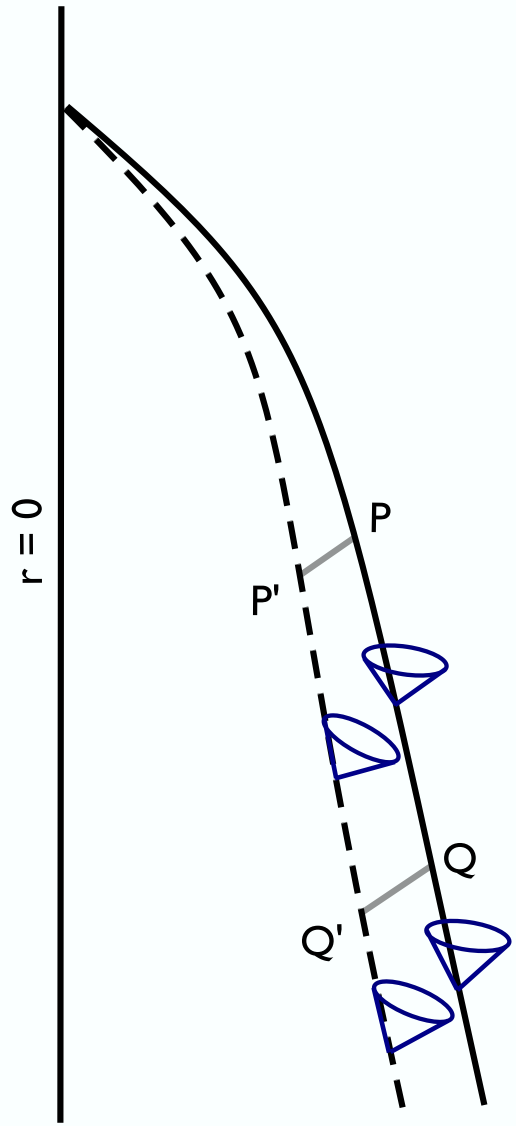
[Ho2015]

Semi-classical approximation

- Appearance of Planck scale may not have to do with Planckian physics. (e.g. constant acceleration towards light cone)
- Planck scale in 4D is not necessarily the string scale.
- Number of species N can be large.
- Large energy-momentum tensor only for $r < R$.

Membrane Paradigm





[Ho2015]

$$\hat{n}^\mu = (\hat{n}^u, \hat{n}^r, 0, 0) \qquad \hat{\ell}^\mu = \left(\hat{\ell}^u, \hat{\ell}^r, 0, 0\right)$$

$$\hat{n}^u = \frac{e^\zeta}{\sqrt{1 - a/r}} \qquad \hat{n}^r = -\sqrt{1 - a/r}\ \sinh\zeta$$

$$\hat{\ell}^u = \mp\frac{e^\zeta}{\sqrt{1 - a/r}} \qquad \hat{\ell}^r = \pm\sqrt{1 - a/r}\ \cosh\zeta$$

$$\hat{n}^\mu \hat{n}_\mu = -1 \qquad \hat{\ell}^\mu \hat{\ell}_\mu = 1 \qquad \hat{n}^\mu \hat{\ell}_\mu = 0$$

$$T_{\mu\nu}\hat{n}^\mu\hat{n}^\nu = T_{\mu\nu}\hat{\ell}^\mu\hat{\ell}^\nu = \mp T_{\mu\nu}\hat{n}^\mu\hat{\ell}^\nu$$

$$T_{\mu\nu}\hat{n}^\mu\hat{n}^\nu = -\frac{1}{8\pi G}\frac{\dot{a}}{r^2}\frac{e^{2\zeta}}{1 - a/r} \simeq \frac{1}{16\pi G}\frac{e^{2\zeta}}{a^2}$$

Hawking Radiation

[KMY2013]

$$\dot{a}(u) = -\frac{NG\hbar}{4\pi}\{u, U\} \qquad \{u, U\} \equiv \frac{\ddot{U}^2}{\dot{U}^2} - \frac{2\dddot{U}}{3\dot{U}}$$

$$\dot{a}(u) \simeq -\frac{\sigma}{a^2(u)} \qquad \sigma = \frac{NG\hbar}{48\pi}$$

$$a(u) \simeq \begin{cases} (3\sigma)^{1/3}(u^* - u)^{1/3} & u < u^* \\ 0 & u \geq u^* \end{cases}$$