Comments on the KMY Model of 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]

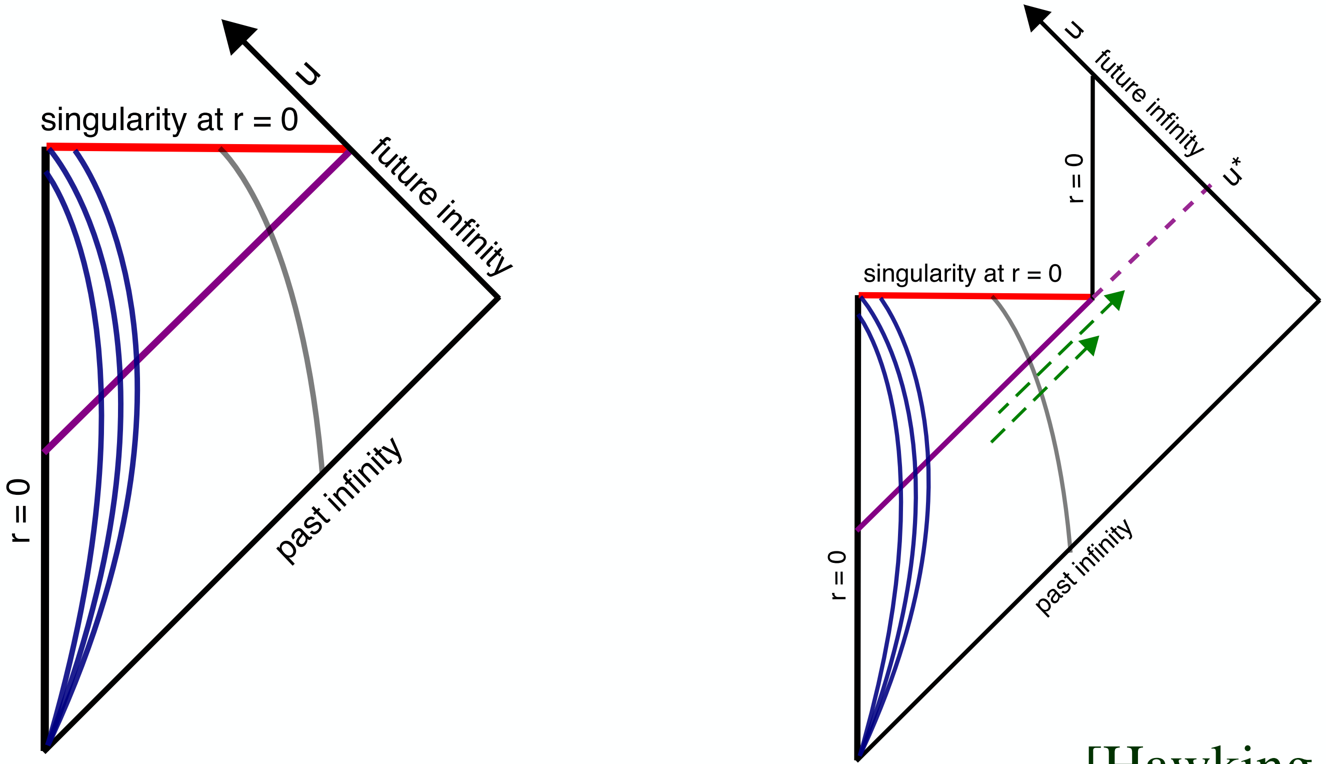
Ho: [arXiv: 1505.02468]
[arXiv: 1510.07157]
[arXiv: 1609.05775]

In the conventional model of BH:

Infalling observer: finite proper time to cross the horizon.

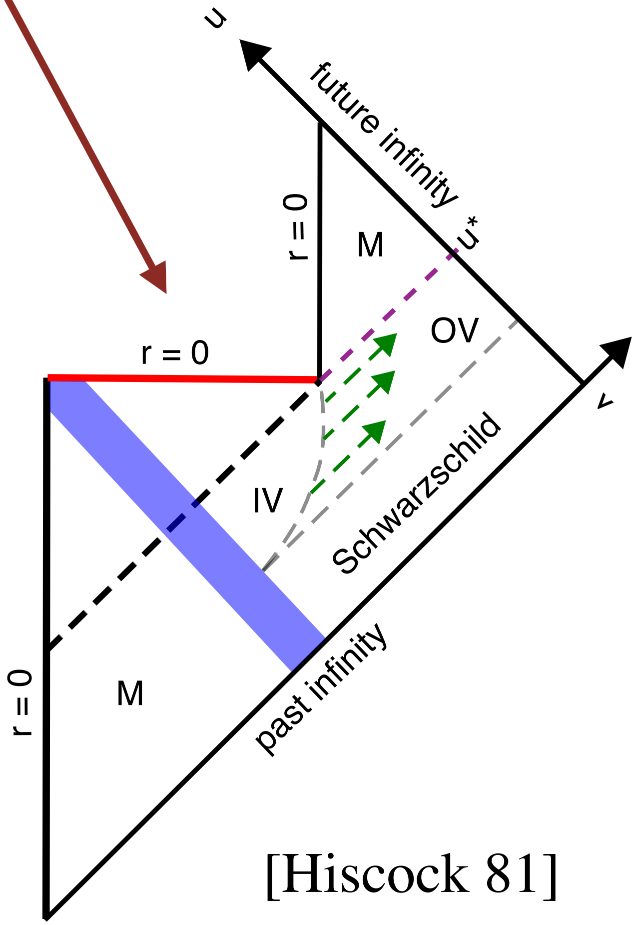
Distant observer: infinite time without Hawking radiation.

Hawking radiation ⇒ Horizon shrinks, but finite time!

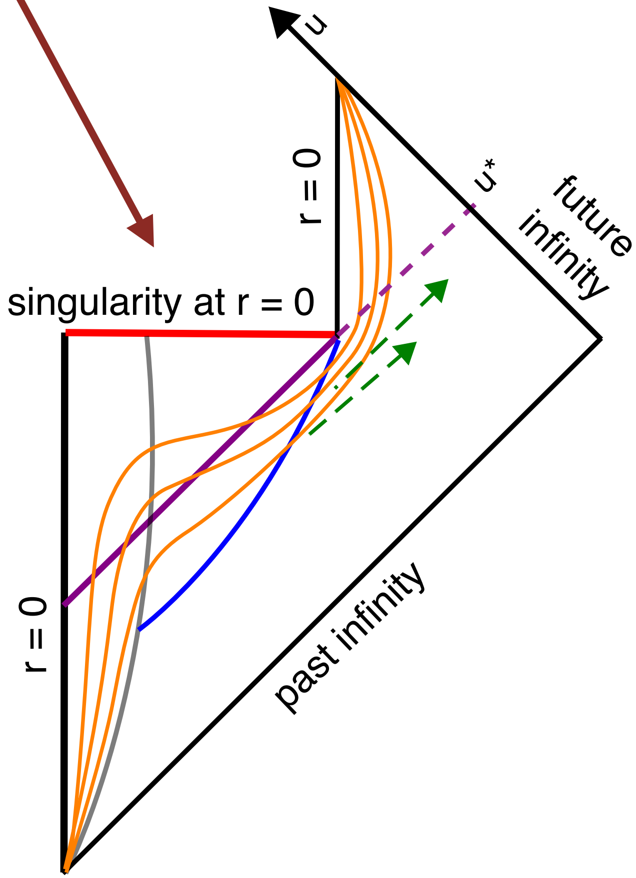


[Hawking 1976]

Failure of physics, unless it is resolved by UV physics.

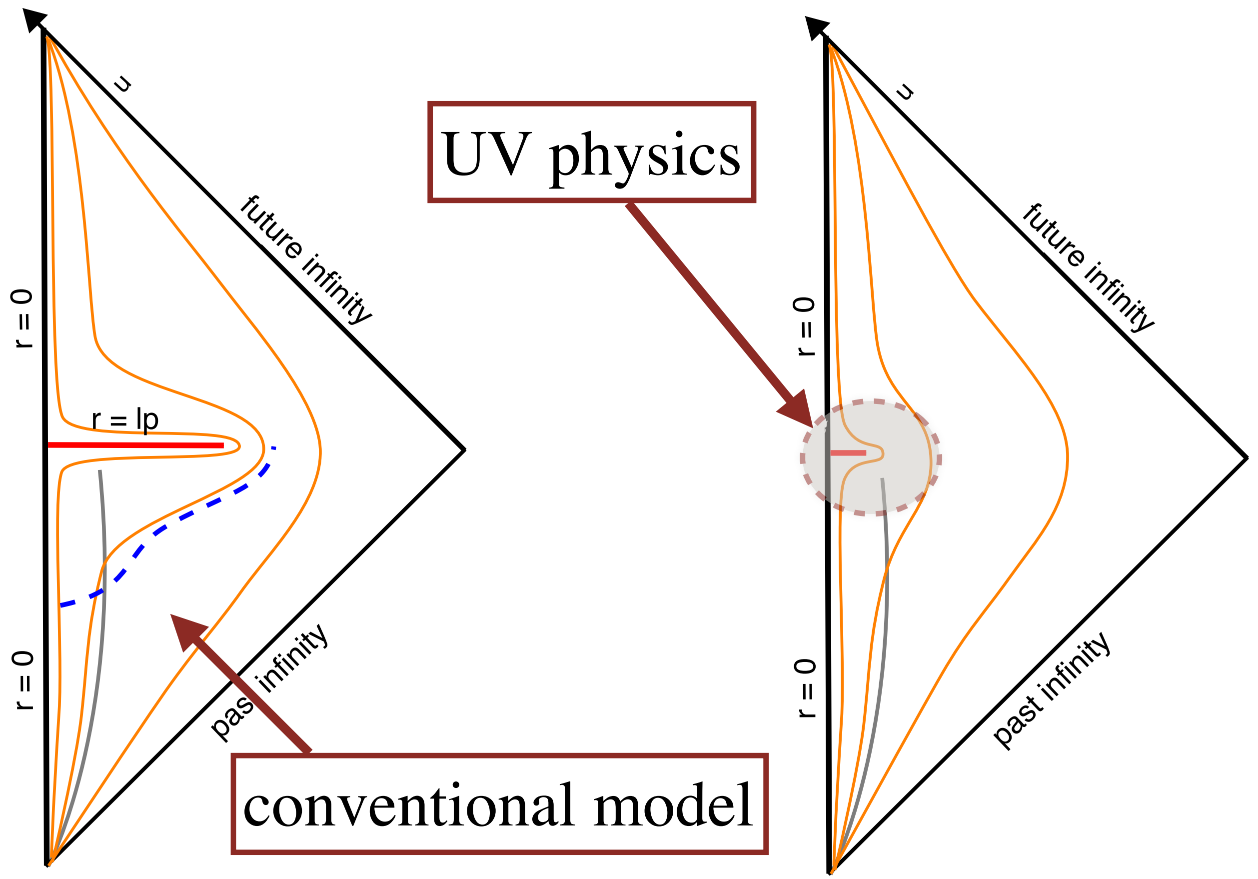


[Hiscock 81]



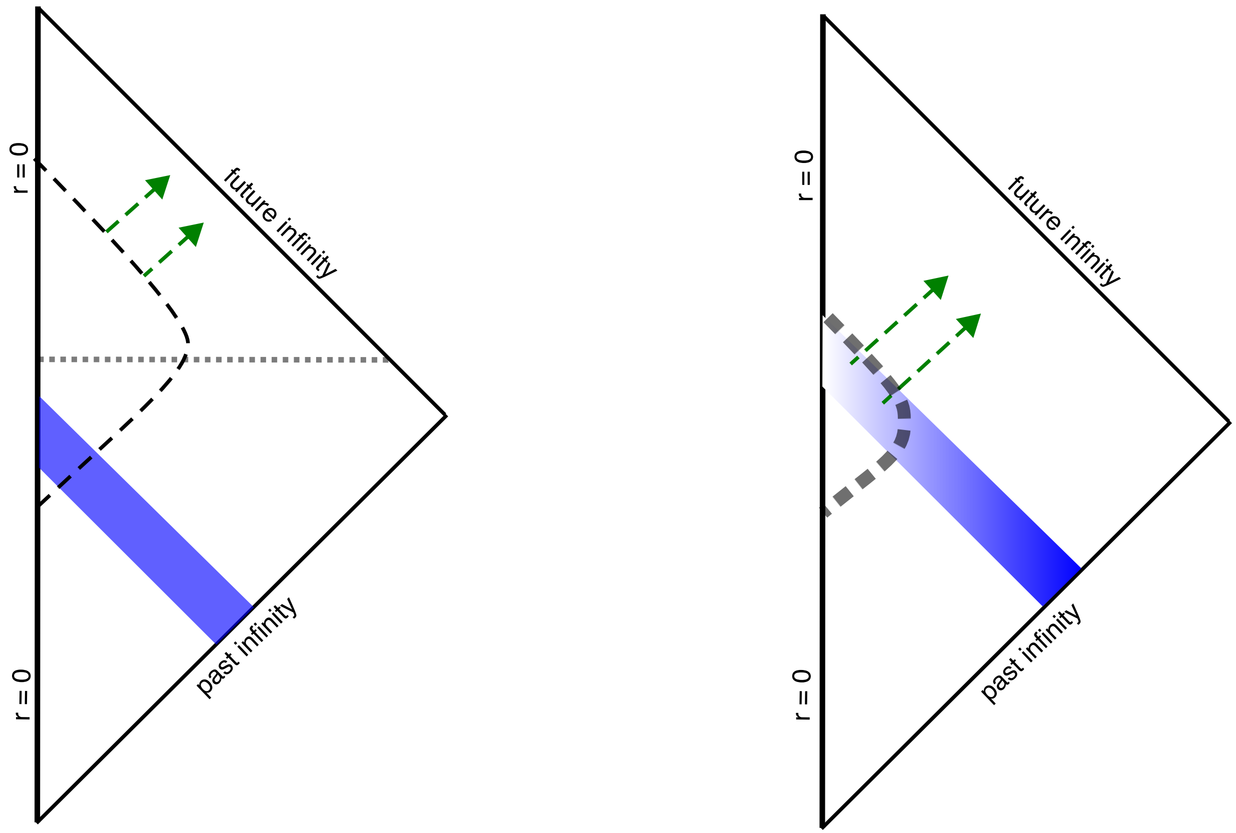
conventional model

conventional model with singularity resolved

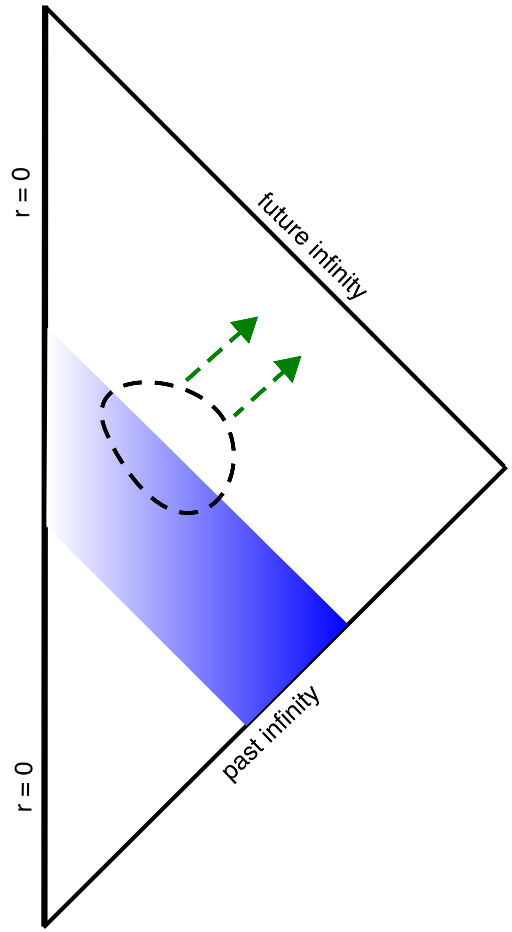


The existence of the event horizon relies on UV physics.

[Hawking, Perry, Strominger 2016]



Firewall appears after the Page time for a pure state.
It can appear earlier for a mixed state.
Can it appear before the collapsing crosses the horizon?



Comments:

Apparent horizon is well defined only when there is spherical symmetry.

Hawking radiation outside the apparent horizon has to break locality to carry information of the collapsing matter.

Hayward 05, Torres, Fayos 15

conventional model

For an infalling observer, Hawking radiation is extremely weak. It does not change the fact that he falls inside the horizon within finite proper time. (However, he does not know it.)

For an infalling observer, the near horizon region is in vacuum. Hawking radiation appears only at distance. (modified in KMY.)

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]

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

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

Light-like geodesics:

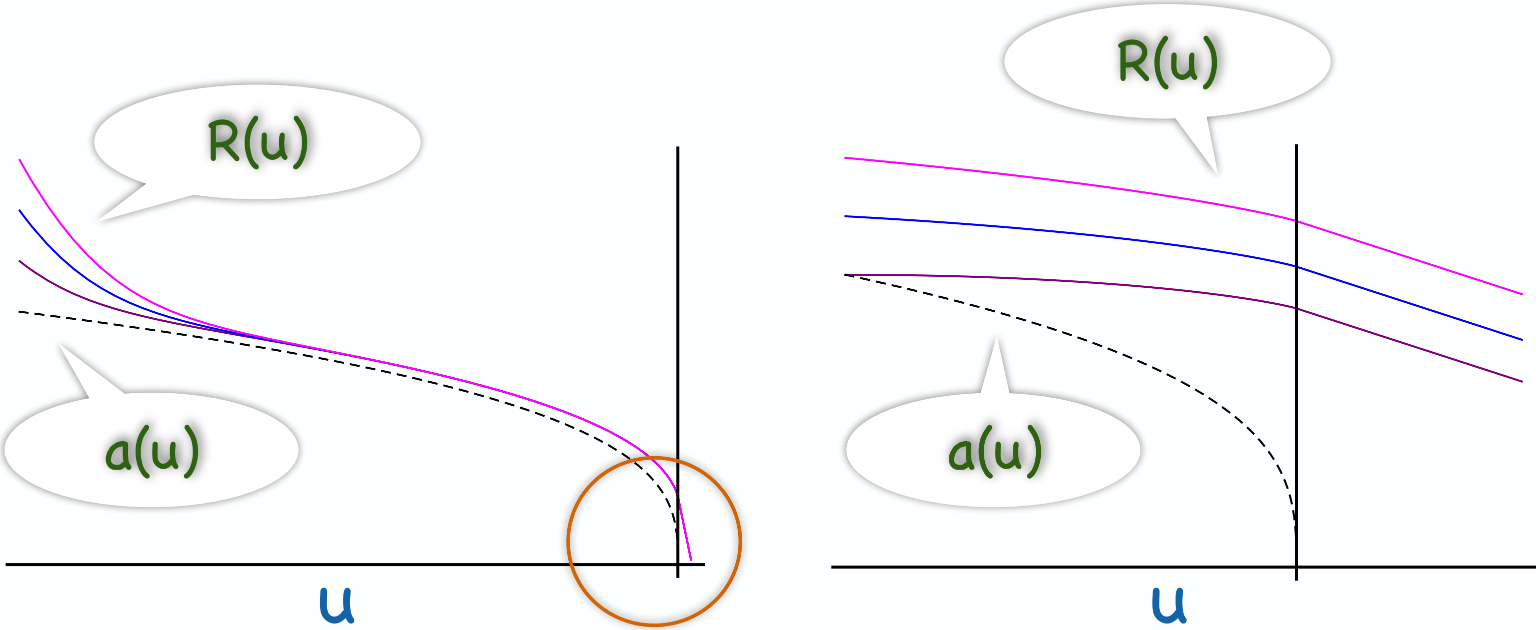
$$du = 0 \qquad \left(1 - \frac{a(u)}{r}\right) du + 2dr = 0$$

Outgoing
e.g. HR

Ingoing for $r > a$

e.g. $r = R(u)$

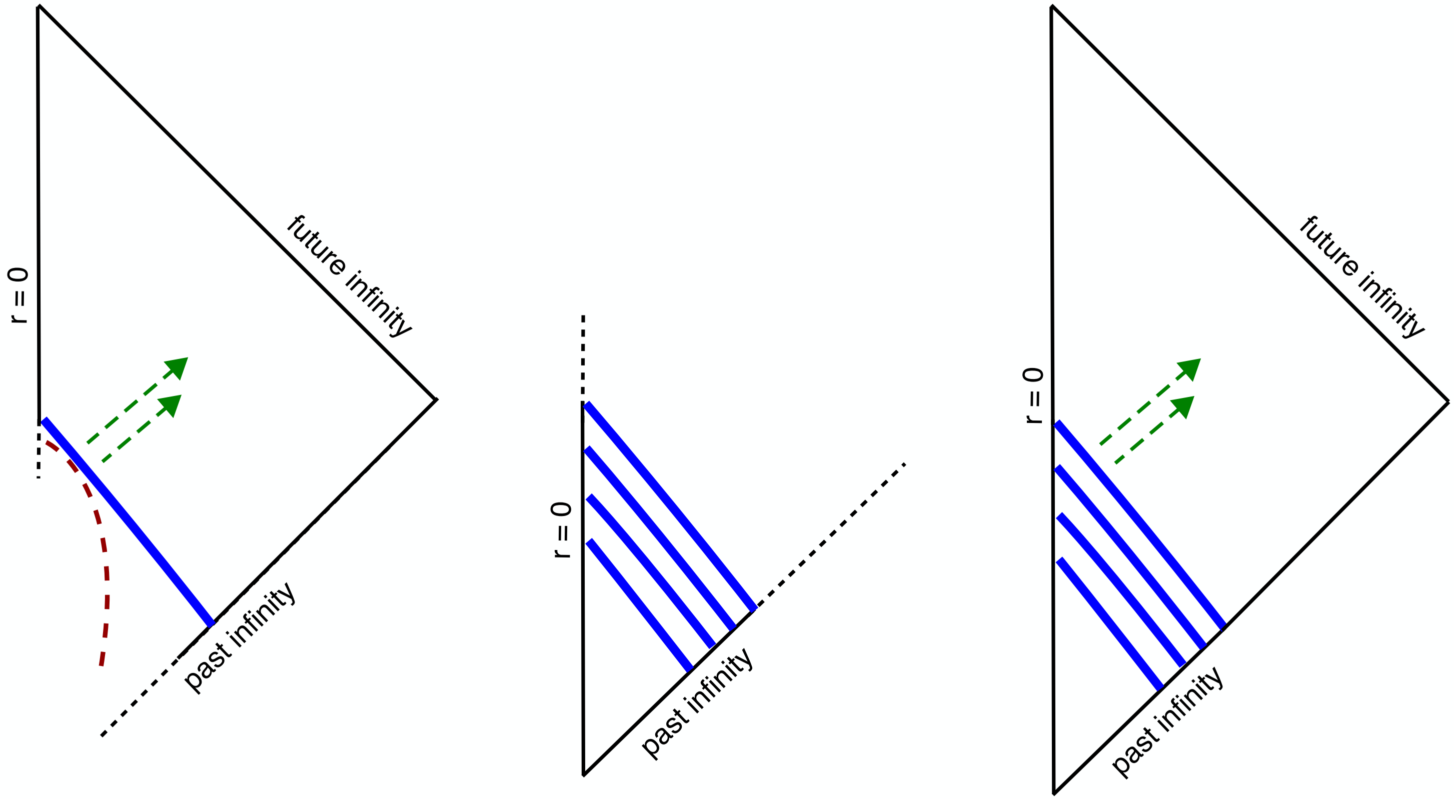
R(u) vs *a*(u)



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

KMY Model:
Patching Penrose diagrams together

[KMY2013]



information loss paradox

- conflict between locality and unitarity.
- Infalling matter evaporates into pre-Hawking radiation before entering the apparent horizon. [KMY2013]
- The pre-Hawking radiation is created near the collapsing matter, "like peeling off an onion". [KY2015]
- Global charge conservation?

comments on perturbation theory

A small perturbation for an observer is not necessarily a small perturbation for another observer.

Hawking radiation is weak for distant observers.

Horizon is crossed within finite proper time for infalling observers.

Important features of the KMY model:

1. Back-reaction of Hawking radiation is included in Einstein's equations.

2. There is Hawking radiation before the appearance of horizon. (pre-Hawking radiation).

3. The back-reaction of the pre-Hawking radiation keeps the collapsing surface above horizon at finite distance.

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 (even when collapsing at the speed of light) stays above the Schwarzschild radius by the separation:

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

energy flux at collapsing surface

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

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

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

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

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

It is generically very weak for a large aBH. [Ho2015]

conventional vs KMY

- fixed background calculation (for the Schwarzschild solution).
- initial state = Minkowski vacuum at past infinity.
- Outgoing energy-momentum tensor is finite on the future horizon, vanishes on the past horizon of the Schwarzschild solution.
  -> Negative energy.
  (Unruh vacuum)

- back-reaction fully incorporated in the geometry.
- initial state = Minkowski vacuum at past infinity
- Outgoing energy-momentum tensor is equivalent to classical radiation, finite and positive everywhere.

different regularisation

conventional vs KMY

conventional	KMY
Hawking radiation at distance.	Hawking radiation at distance.
horizon.	no horizon.
inconsistent with unitarity or locality.	consistent with unitarity and locality.
firewall. [AMPS 12]	weak radiation at the surface of collapse.
super-Planckian problem.	super-Planckian problem.
always complete evaporation.	not always complete evaporation.

KMY Model

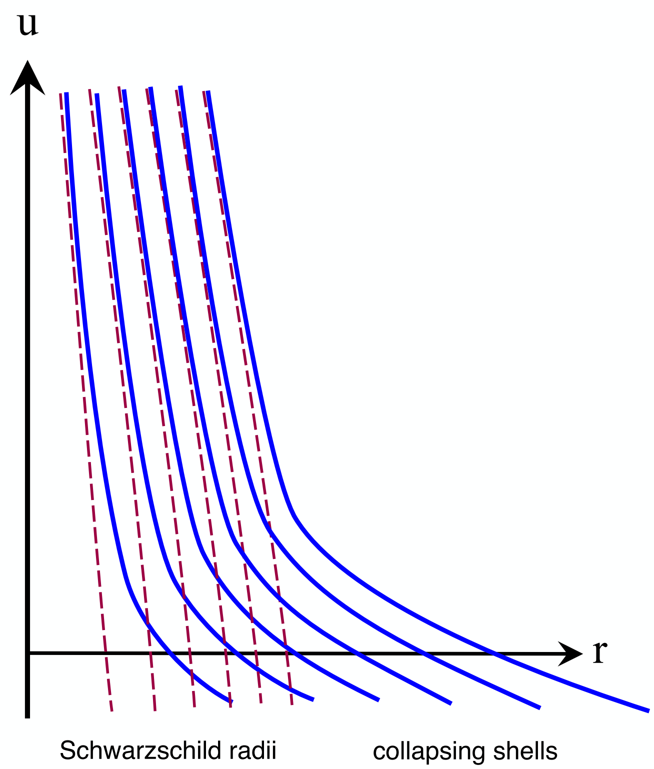
inside collapsing sphere

Every layer approaches to its Schwarzschild radius.

Huge red-shift => everything inside is frozen.

[KMY2013,KY2014,KY2015]

The time-like singularity at the origin is irrelevant to the information loss paradox.



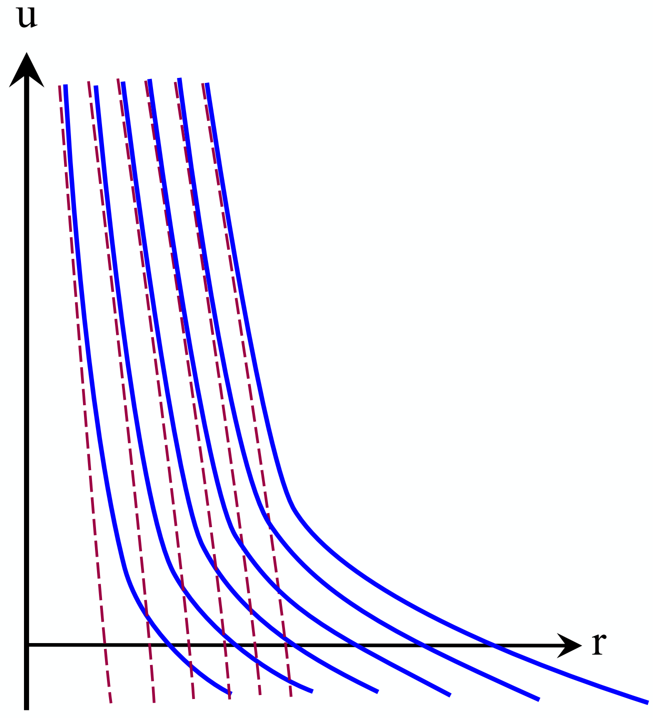
inside collapsing sphere:

Metric for arbitrary a(u, r), V(u, r).

a(u, r) = 2*energy inside r

V(u, r) = velocity

consistent with Lemaitre-Tolman.



$$\psi(u,r) = -\frac{1}{2}\int_r^{R_0(u)} \frac{\partial_r a(u,r')}{r' - a(u,r') + r'V(u,r')} dr'$$ [Ho2016]

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

Asymptotic Black Holes

[Ho2015]

- If gravitational force dominates, eventually all matter collapses at the speed of light.

- Asymptotic form of the metric:

$$a(r) \simeq r - \frac{2\sigma}{a(r)} \qquad \psi(u,r) \simeq -\frac{1}{4\sigma}\left(R^2(u) - r^2\right)$$

- Evaporate almost like conventional BH's.

- Almost indistinguishable from a BH with horizon.

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]

Review: Mathur [09091038]

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

conclusion

- KMY is a self-consistent model of black holes.
- KMY involves only large scale physics.
- No horizon, no firewall except the final stage of free fall in KMY.
- Asymptotic black holes.

- There is an explicit metric and you can verify every statement by explicit calculation.
- Regularization of energy-momentum tensor needs clarification.
- Resolution to the information loss paradox still needs UV physics.

Thank you!

KMY Model

1. Write down the general metric g[T] for the energy momentum tensor

$$G = T = T(in) + T(out)$$

of an arbitrary distribution of collapsing dust and outgoing radiation.

2. Compute the energy flux T(HR) for Hawking radiation in the metric g[T].

3. Demand that T(out) = T(HR) and solve for g[T].

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]

Inside the collapsing sphere:

$$T = T^{(out)} + T^{(in)} + T_{\theta\theta} d\Omega^2,$$

$$T^{(out)} = T_{out}(e^{\psi} du \otimes e^{\psi} du),$$

$$T^{(in)} = T_{in} \zeta \otimes \zeta,$$

$$T_{out} = -\frac{1}{8\pi G} \frac{1}{r^2} Da,$$

$$T_{in} = \frac{1}{8\pi G} \frac{1}{2r} \psi',$$

$$T_{\theta\theta} = \frac{1}{8\pi G} \left[r\psi' + \frac{1}{2} a\psi' - \frac{3}{2} ra'\psi' + r^2 \left(1 - \frac{a}{r}\right) (\psi')^2 - \frac{1}{2} ra'' + r^2 \left(1 - \frac{a}{r}\right) \psi'' - e^{-\psi} r^2 \dot{\psi}' \right],$$

$$T_{\phi\phi} = \sin^2\theta T_{\theta\theta}$$

Inside the collapsing sphere:

$$Da(u,r) \simeq -\frac{\sigma}{a^2(u,r)}$$

Comoving time derivative:

$$Df(u,r) \equiv e^{-\psi(u,r)}\frac{\partial}{\partial u}f(u,r) + V(u,r)\frac{\partial}{\partial r}f(u,r).$$

$$T = T^{(out)} + T^{(in)} + T_{\theta\theta}d\Omega^2,$$

$$T^{(out)} = T_{out}(e^{\psi}du \otimes e^{\psi}du), \qquad T_{out} = -\frac{1}{8\pi G}\frac{1}{r^2}Da,$$

$$T^{(in)} = T_{in}\zeta \otimes \zeta, \qquad T_{in} = \frac{1}{8\pi G}\frac{1}{2r}\psi',$$