Asymptotic Black Holes

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

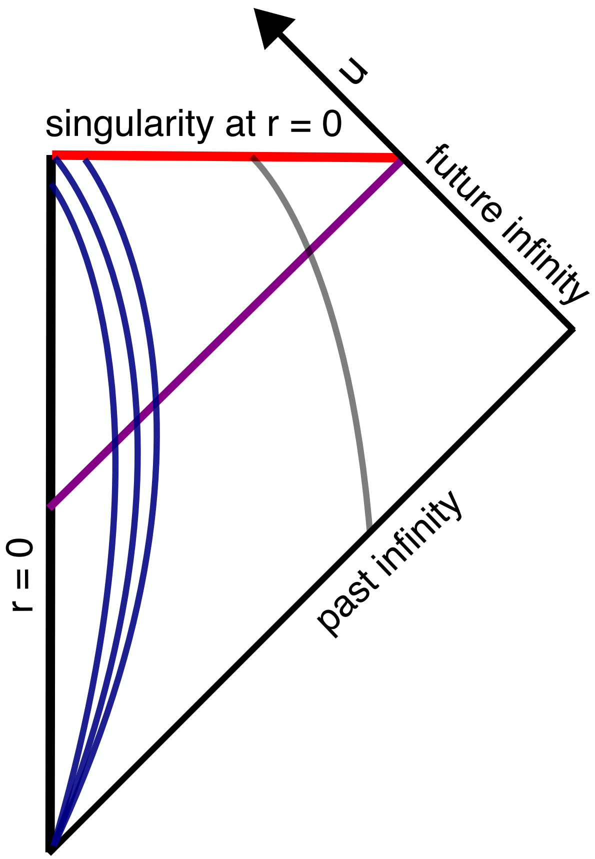
Ho: [arXiv: 1505.02468]
[arXiv: 1510.07157]
[arXiv: 1609.05775]

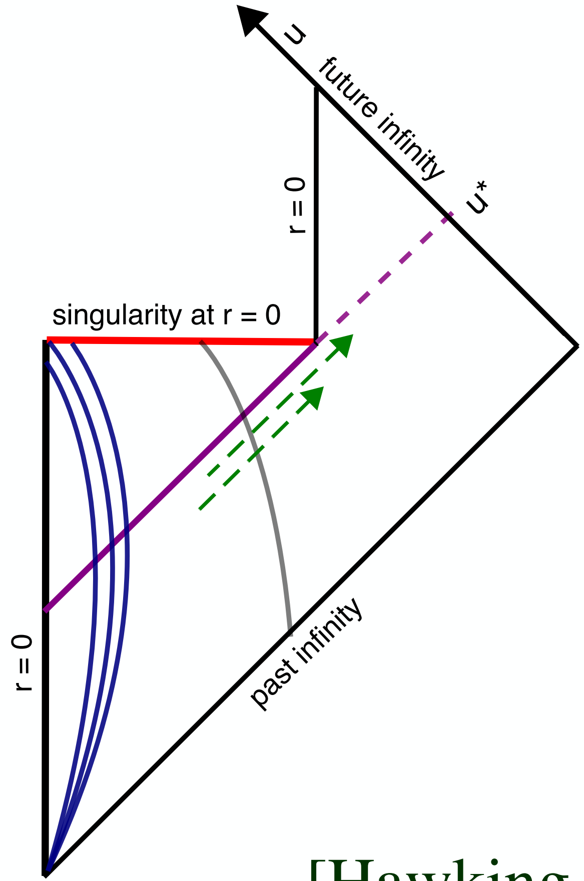
In the conventional model of BH:

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]

conventional model

1. 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.

2. For an infalling observer, the near horizon region is a vacuum state. Hawking radiation appears only at distance.

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:

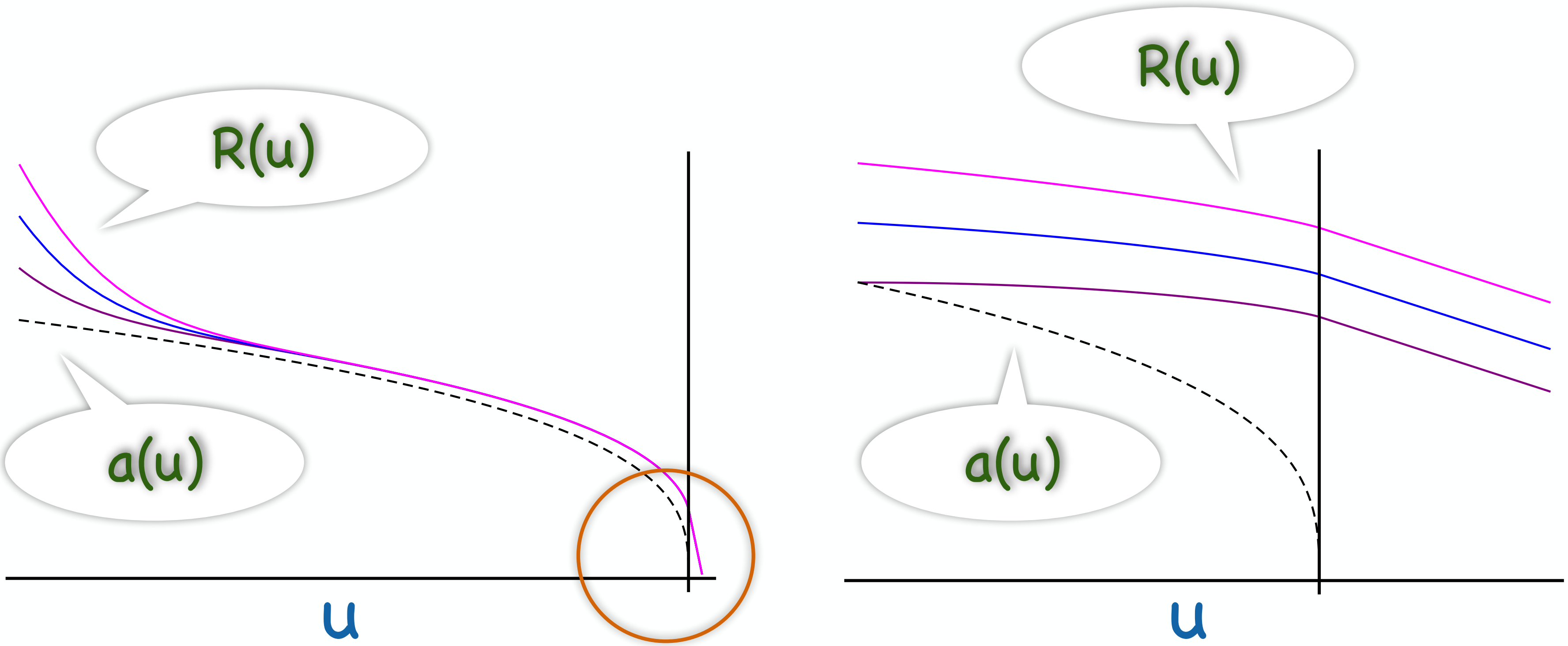
$$du = 0 \qquad \left(1 - \frac{a(u)}{r}\right) du + 2dr = 0$$

Outgoing
e.g. HR

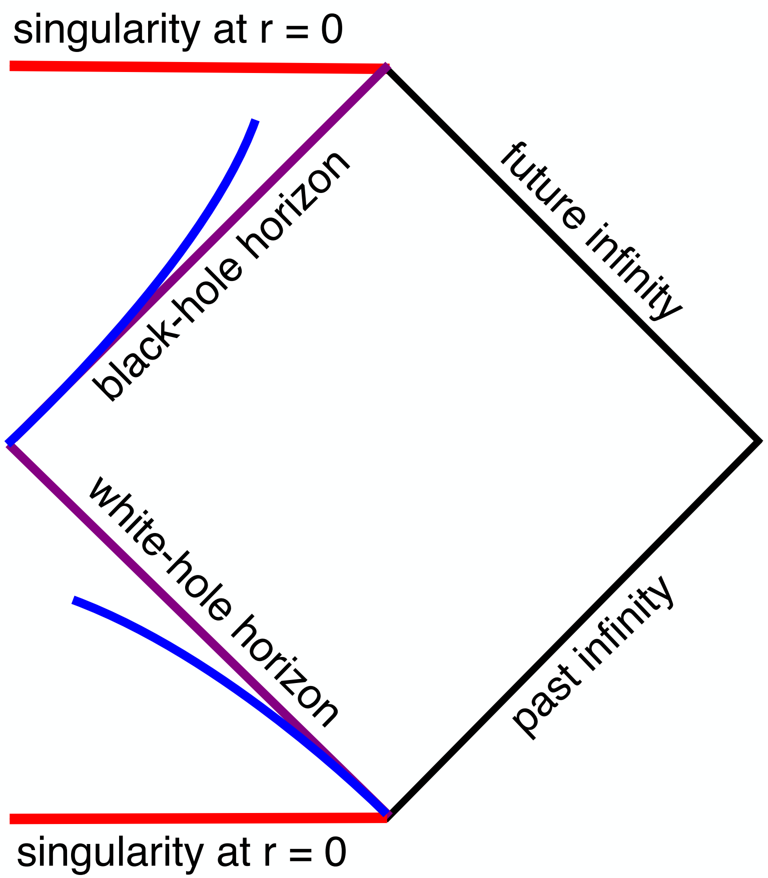
Ingoing for $r > a$

e.g. r = R(u)

R(u) vs a(u)



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



Black-hole apparent horizon vs white-hole apparent horizon

[KMY2013][Ho2015]

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

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]

perturbative argument

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

Hawking radiation is weak for distant observers.

Horizon is crossed within finite proper time for infalling observers.

conventional model

1. Gravitational collapse of matter
without Hawking radiation.

2. Turn on Hawking radiation,
without back-reaction near horizon.
(otherwise a diverging energy flux.)

-> breaks weak energy condition
or energy conservation,
violates unitarity or has firewall.

inconsistent!

self-consistent approach

- Einstein's equations are satisfied with the energy-momentum tensor including both the collapsing matter and Hawking radiation.
- By Hawking radiation, we mean not only the creation of particles but also the VEV of the energy-momentum tensor.

self-consistent approach

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].

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

Important features:

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

2. 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 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]

information loss paradox resolved

- Infalling matter evaporate into pre-Hawking radiation before entering the apparent horizon.
- The pre-Hawking radiation is created near the collapsing matter, like peeling off an onion.

[KY2015]

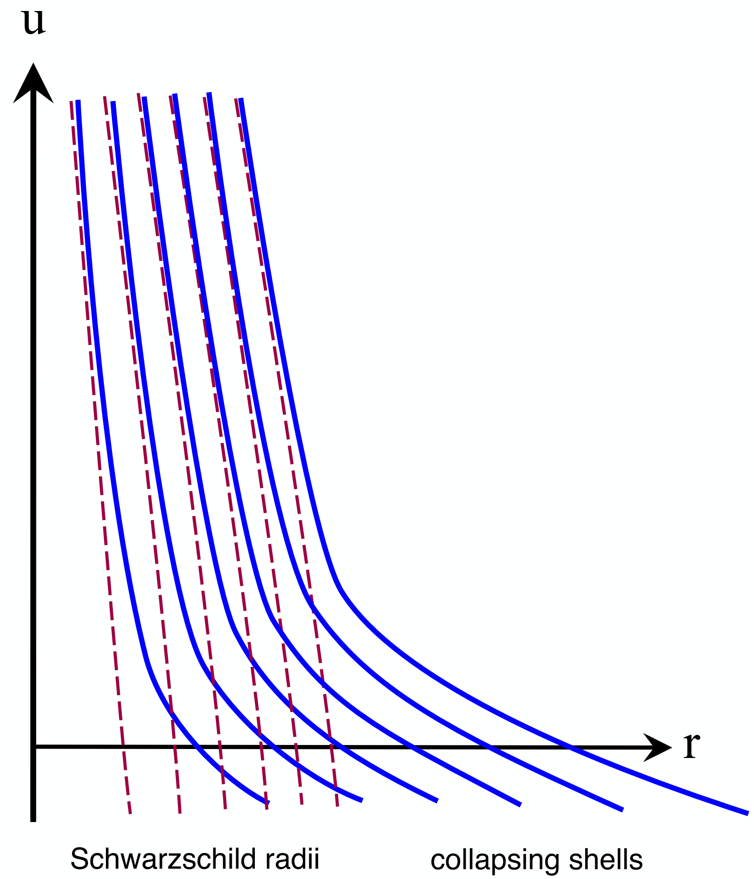
inside collapsing sphere

Every layer approaches to its Schwarzschild radius.

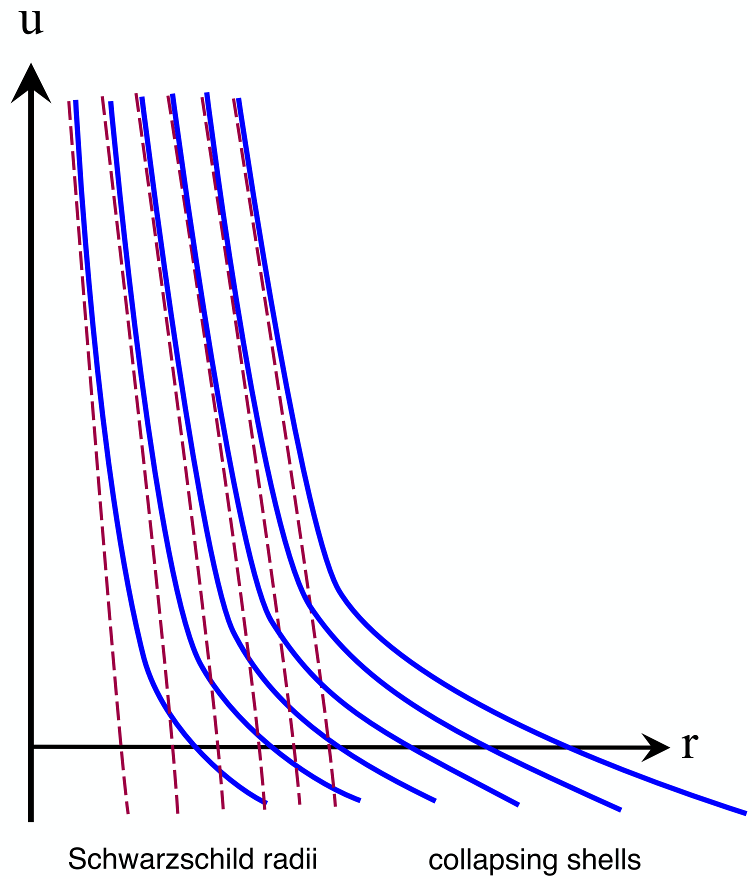
Huge red-shift => everything inside is frozen.

[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]

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

Inside the collapsing sphere:

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

Comoving time derivative:

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

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

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

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

Asymptotic Black Holes

- 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]

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.

Conclusion

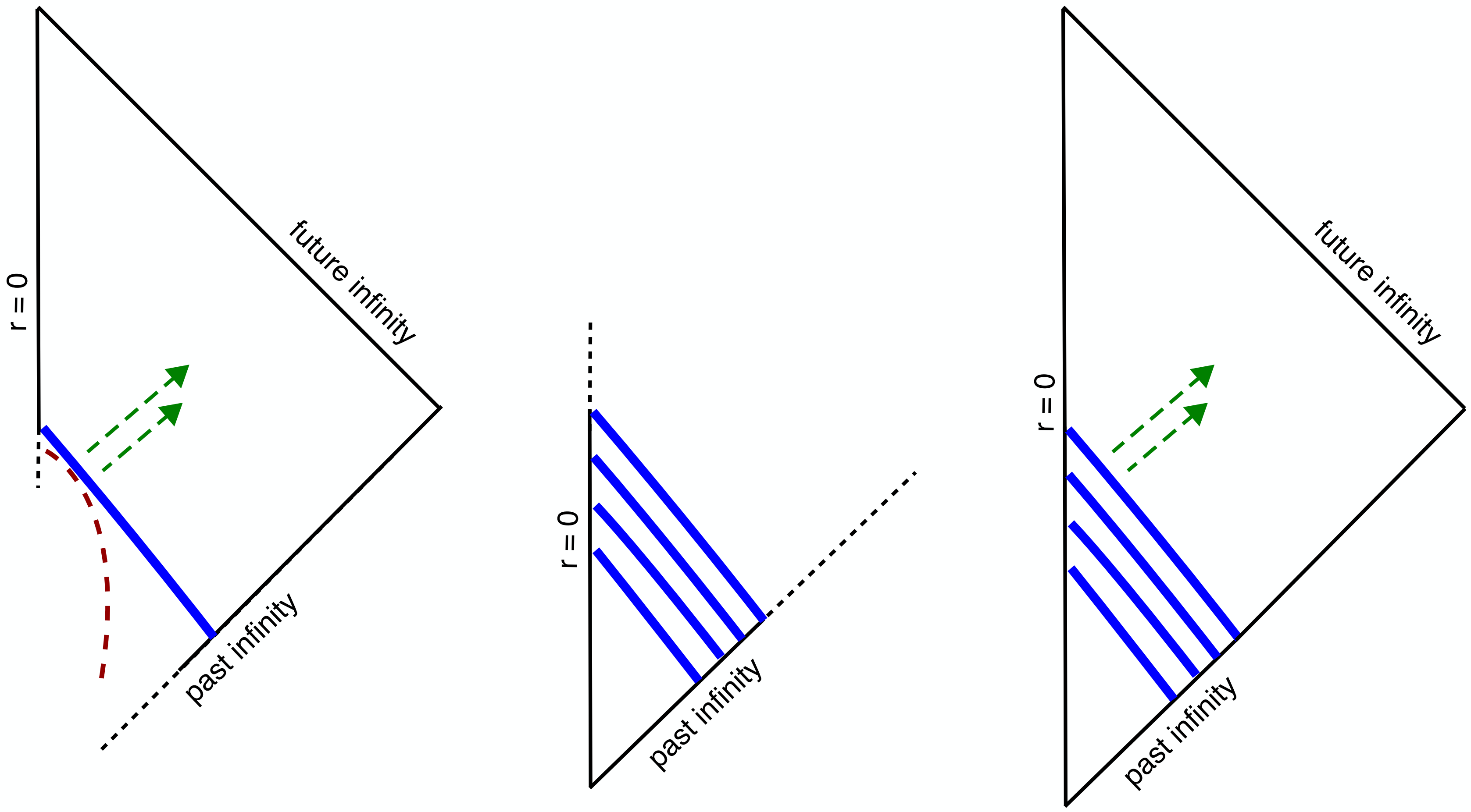
- Self-consistent model of black holes
- Semi-classical, large scale physics only
- No firewall (unless you move towards it at speed of light)
- No horizon (if not already there)
- No Information loss paradox
- Asymptotic black holes in observations

There is an <u>explicit metric</u> and you can verify every statement by explicit calculation.

Thank you!

KMY Model:
Patching Penrose diagrams together

[KMY2013]



Inside the collapsing sphere:

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

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

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

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

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

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

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