Black Holes and Vacuum Energy

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arXiv:1710.10390
arXiv:1804.04821 with Pei-Ming Ho (NTU)

and arXiv:1807.11352 with Pei-Ming Ho (NTU),
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Introduction

Black hole evaporation

Gravitational Collapse + Quantum effect

Black hole + Hawking radiation → Black hole evaporation

Information loss problem

Classical BH geometry → Information cannot get out from horizon

↕ Contradiction

Quantum theory → Information must not be lost

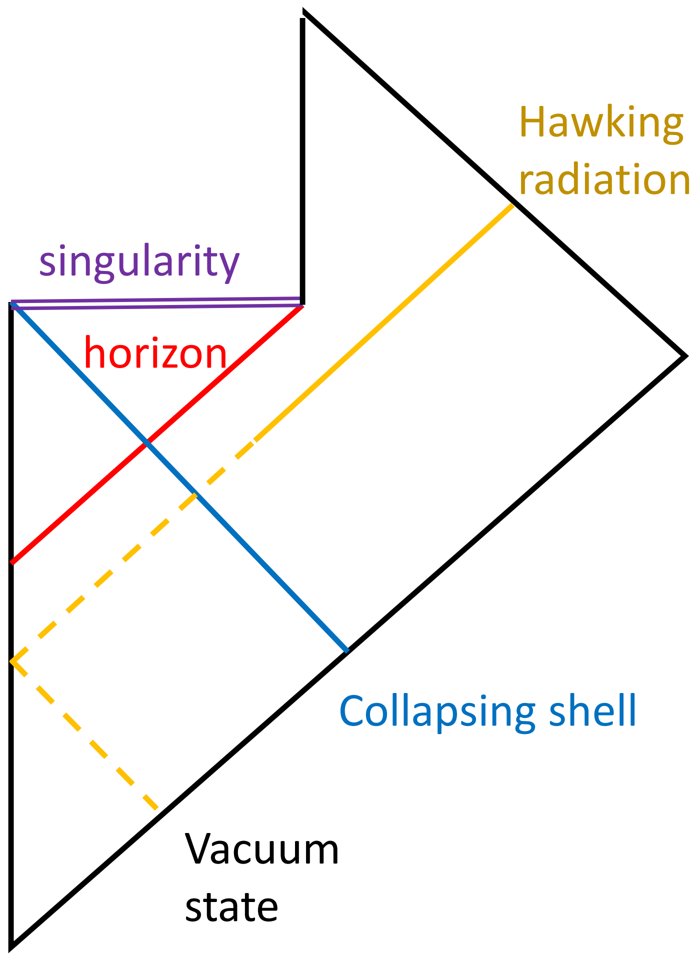
Quantum effects to BH geometry play important role.

We consider the semi-classical Einstein equation.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \langle T_{\mu\nu} \rangle$$

Quantum energy-momentum

Hawking radiation



Hawking radiation appears because the vacuum states before and after the gravitational collapse are different.

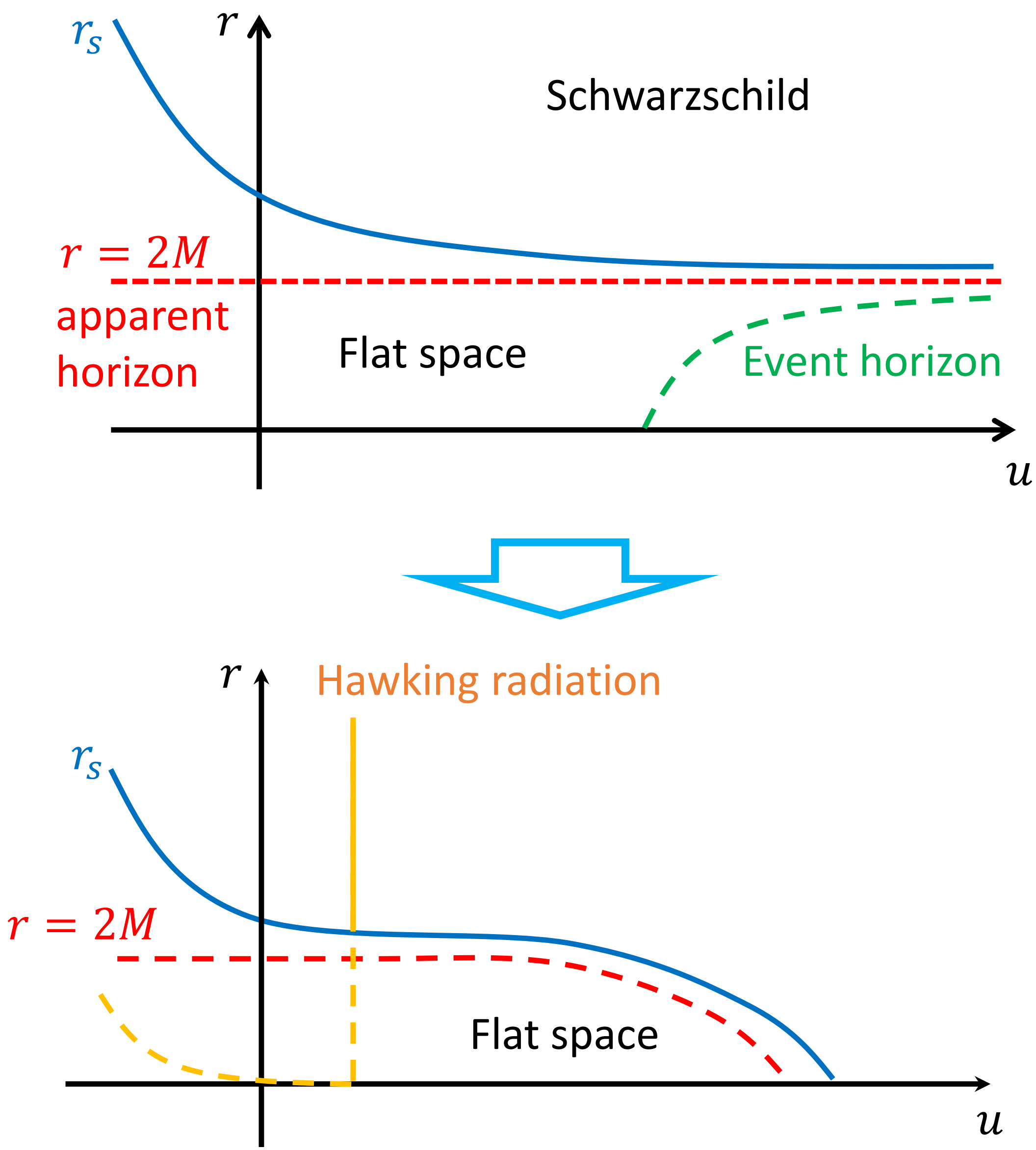
Event horizon is not necessary for Hawking radiation.

Hawking radiation always appears in causal past of the event horizon.

Event horizon must be irrelevant for Hawking radiation.

Hawking radiation appears before horizon forms.

Back reaction from Hawking radiation



Horizon appears when collapsing matter get inside the horizon.

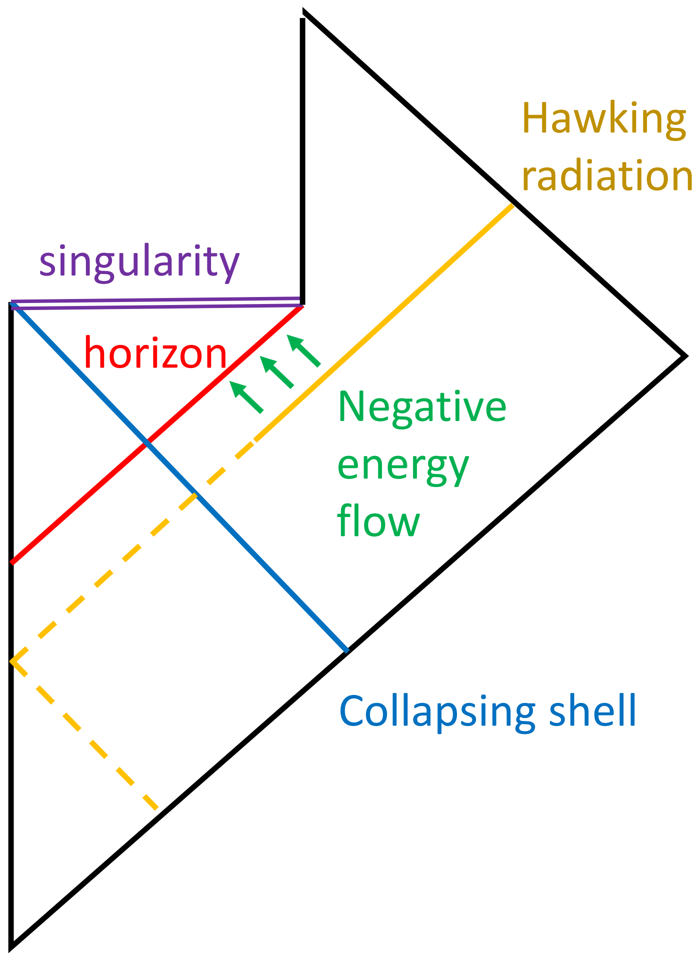
It takes infinitely long time for the collapsing matter to get inside the horizon.

Hawking radiation appears before horizon forms

If the black hole evaporates within finite time, it is before the horizon forms.

Geometry of the black hole evaporation is horizonless.

Hawking radiation from Bulk?



It is sometimes discussed that Hawking radiation appears in bulk

In this picture, Hawking radiation does not take energy from the collapsing matters.

There is also ingoing negative energy flow to satisfy the conservation law.

Because of the ingoing negative energy, black holes lose their energy and eventually evaporates in this picture.

However, the negative energy flow exists even in static backgrounds.

2D model for 4D black hole

We focus on s-waves and approximate them by 2D scalar fields.

Energy momentum tensor can be calculated by using conservation law and Weyl anomaly.

$$ds^2 = -C(r)dudv + r^2 d\Omega^2$$

$$\langle T_{uv}^{(2D)} \rangle = -\frac{1}{12\pi}(C\partial_u\partial_v C - \partial_u C \partial_v C)$$

$$\langle T_{uu}^{(2D)} \rangle = -\frac{1}{12\pi} C^{1/2}\partial_u^2 C^{-1/2} + T(u)$$

$$\langle T_{vv}^{(2D)} \rangle = -\frac{1}{12\pi} C^{1/2}\partial_v^2 C^{-1/2} + \bar{T}(v)$$

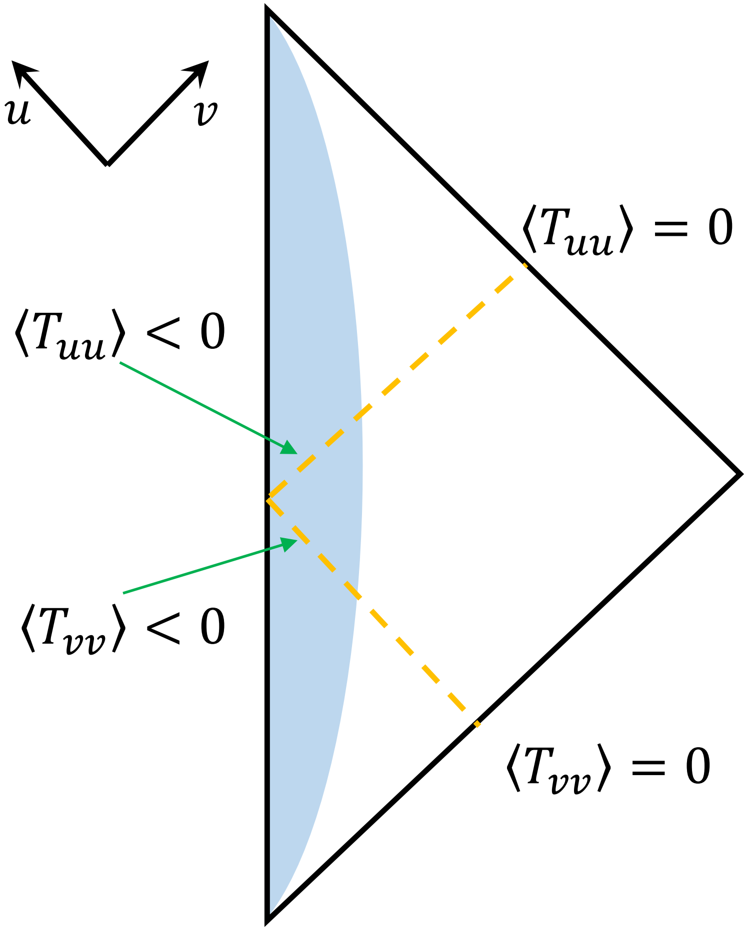
Integration constants which depend on physical state.

We consider static black holes without incoming or outgoing energy flow at infinity

come from Weyl anomaly and does not depend on physical state.

Negative energy is not physical excitation but simply the vacuum has negative energy, like Casimir effects.

Boulware vacuum



Vacuum state with $\langle T_{\mu\nu} \rangle = 0$ in $r \to \infty$

Vacuum state for static star without horizon

Negative energy at finite r

$\langle T_{uu} \rangle < 0 \qquad \langle T_{vv} \rangle < 0$

"Divergence" at horizon in classical geometry

⇩

We consider semi-classical Einstein eq. with quantum effects in $\langle T_{\mu\nu} \rangle$.

$$G_{\mu\nu}^{(4D)} = \alpha \langle T_{\mu\nu}^{(4D)} \rangle$$

There is no divergence at finite r (radius of 2 sphere) if back reaction from vacuum energy is taken into account

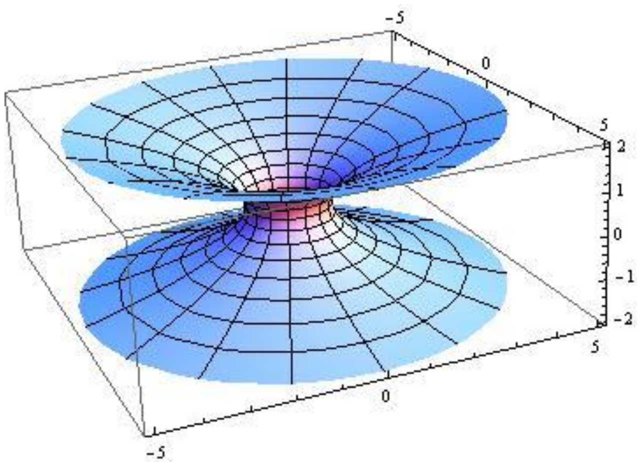
Back reaction from negative vacuum energy

For fixed background of Schwarzschild, negative vacuum energy is finite from the viewpoint of fiducial observer.

For freely falling observer, the negative vacuum energy is infinitely large.

Vacuum energy becomes very large near horizon $\Rightarrow$ Back reaction from vacuum energy is no longer negligible.

By taking the back reaction into account, the horizon cannot appear if there is negative vacuum energy.



Local minimum of radius r, as wormhole, appear instead of the Killing horizon.

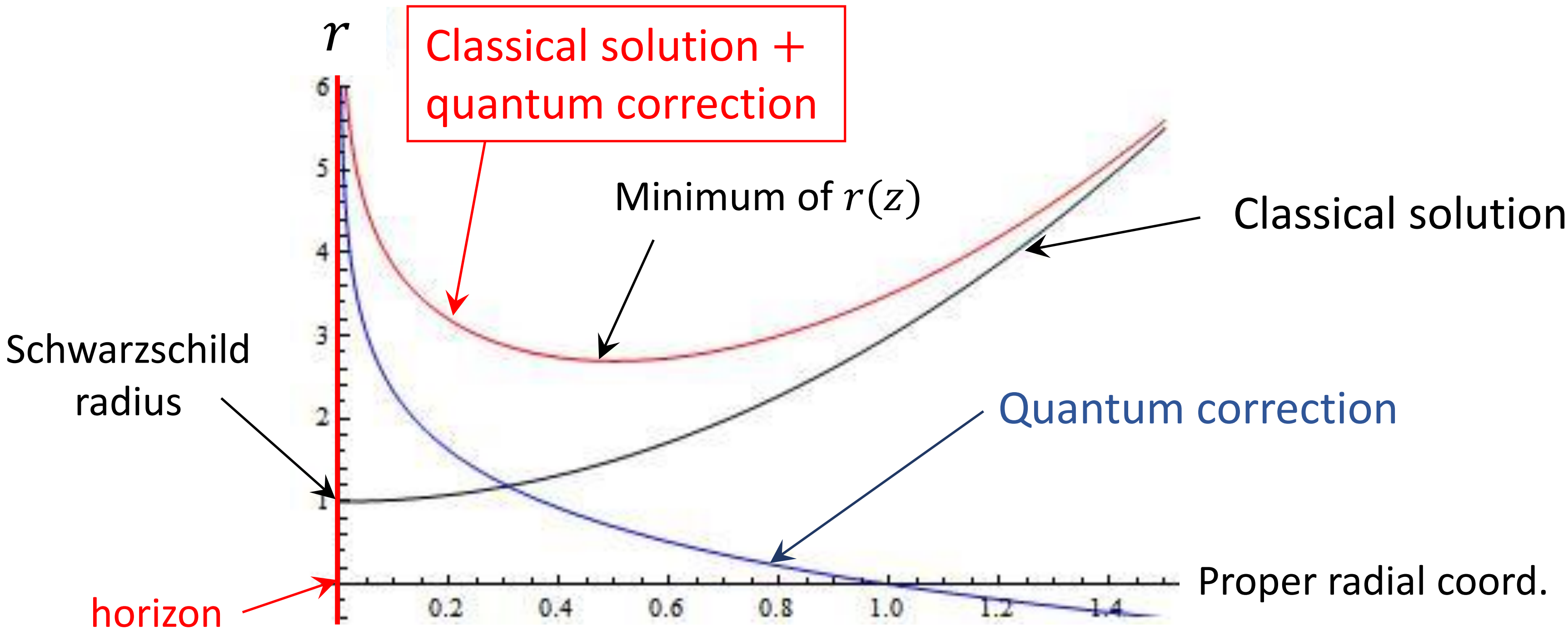
Note: The other side of this “wormhole” is not asymptotically flat.

Geometry in proper (radial) coordinate

Horizon is at the Schwarzschild radius in classical geometry

⇨ Horizon moves to $r \to \infty$ in the other side of "wormhole."

Perturbative expansion of r in proper radial coordinate

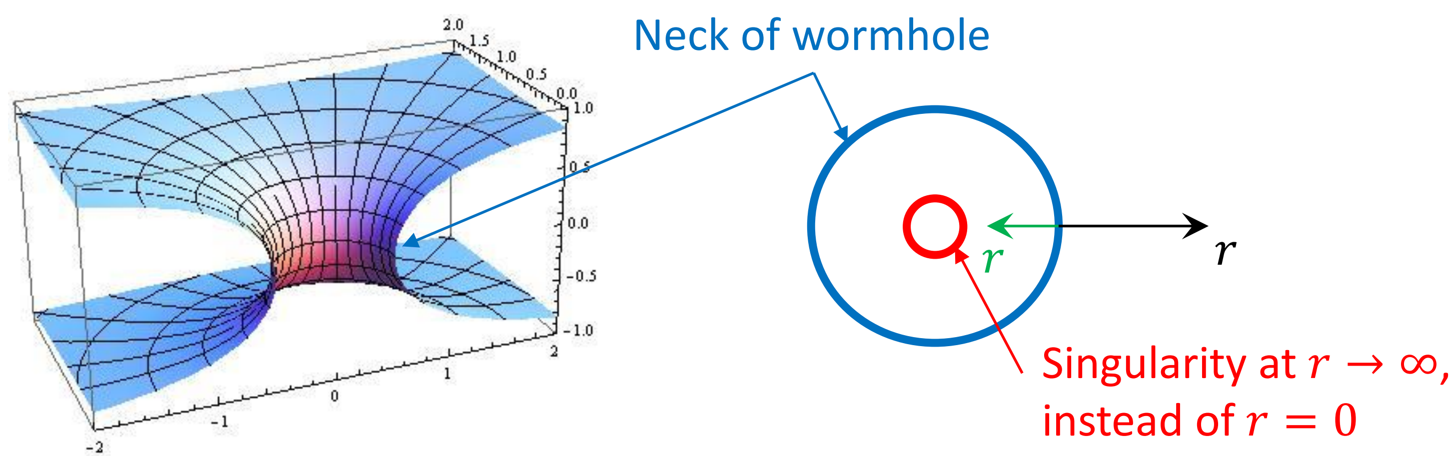


There are no singularity near the Schwarzschild radius or at finite r.

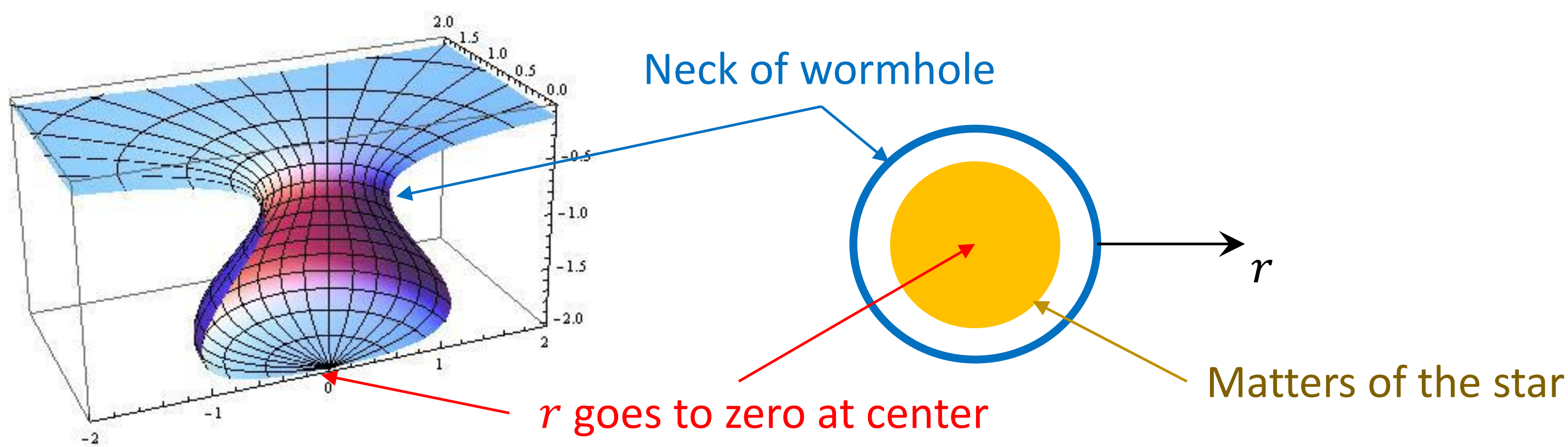
Singularity is in $r \to \infty$ in the other side in finite proper distance.

Interior of wormhole

Wormhole like solution is vacuum solution without matters of the star.

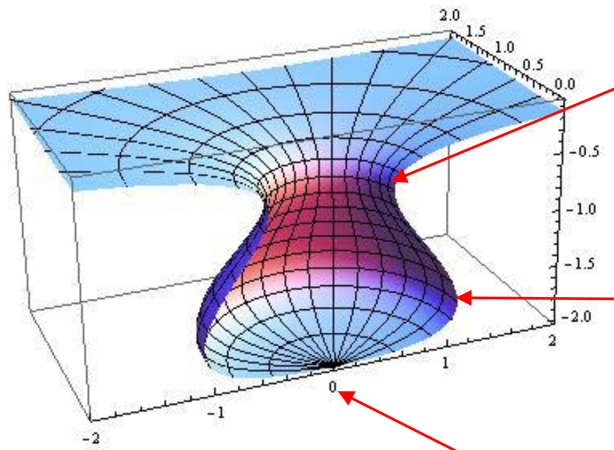


For physical situation, there is a star, where matters are distributed



Incompressible fluid

We consider (classical) incompressible fluid + vacuum energy from 2D scalar.



Wormhole-like structure (local minimum of r) instead of the Killing horizon

Local maximum of r is slightly inside the surface of the fluid. r is almost same to that at local minimum.

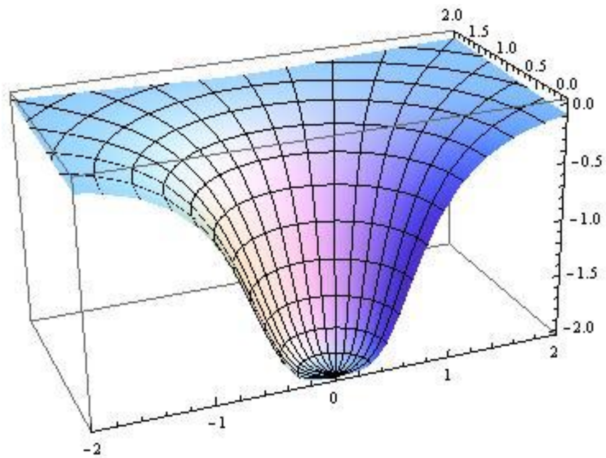
r goes to zero at the center.
Proper distance from Schwarzschild radius to $r = 0$ is of order of Planck length.

- There is no horizon for arbitrary density and position of the surface.
- Pressure and density are very large but finite.
- Entropy of the fluid agrees with Bekenstein-Hawking entropy.

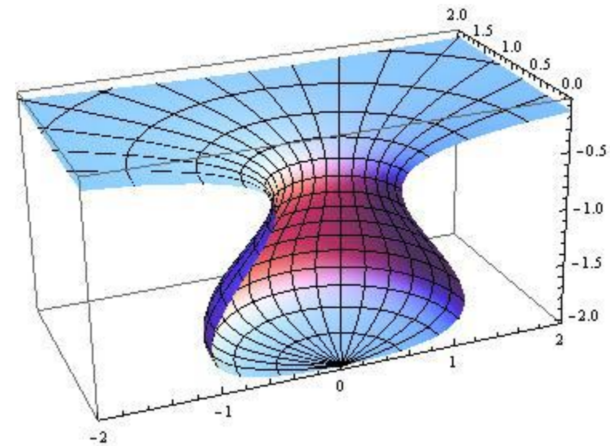
Density of star (incompressible fluid)

Geometry has neck (local minimum of r) if density is large as Planck scale

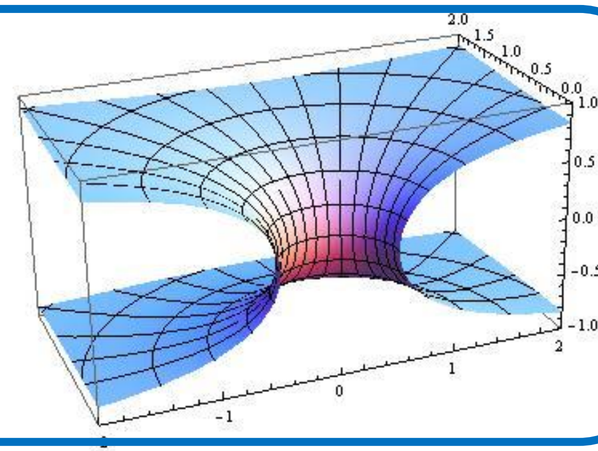
Density is smaller than Planck scale
(density) $< \ell_p^{-4}$



Density is smaller than Planck scale
(density) $> \ell_p^{-4}$



Density is infinity
(density) $\to \infty$



Density of

Hawking rad. $\sim a^{-4}$

Classical matter $\sim \ell_p^{-2} a^{-2}$

Apparent horizon as shrinking neck of wormhole

If we introduce the Hawking radiation, neck of wormhole decreases since mass decreases due to Hawking radiation.

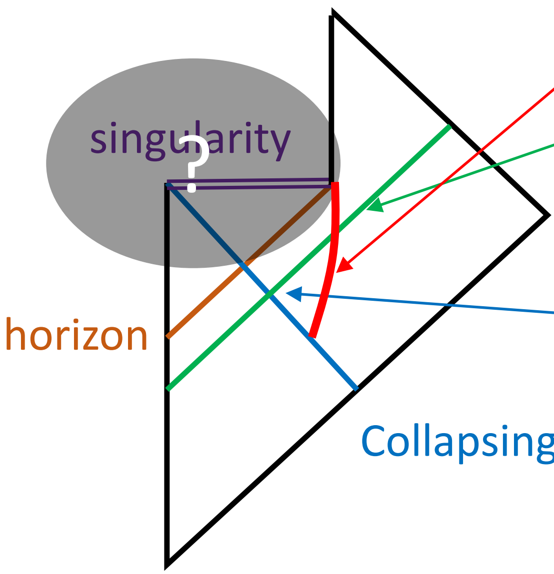
Inside the neck, r decreases along outgoing null line, $\frac{\partial r}{\partial v} < 0$

Inside but around the neck, r slightly increases along ingoing null line, $\frac{\partial r}{\partial u} \gtrsim 0$

If the neck reduces with time, r decreases along both outgoing and ingoing lines

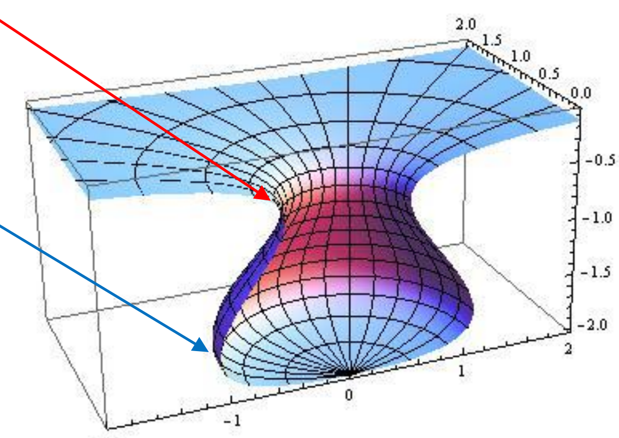
Neck is apparent horizon $\frac{\partial r}{\partial v} < 0$ and $\frac{\partial r}{\partial u} < 0$

At some constant-u slice, the geometry is given by



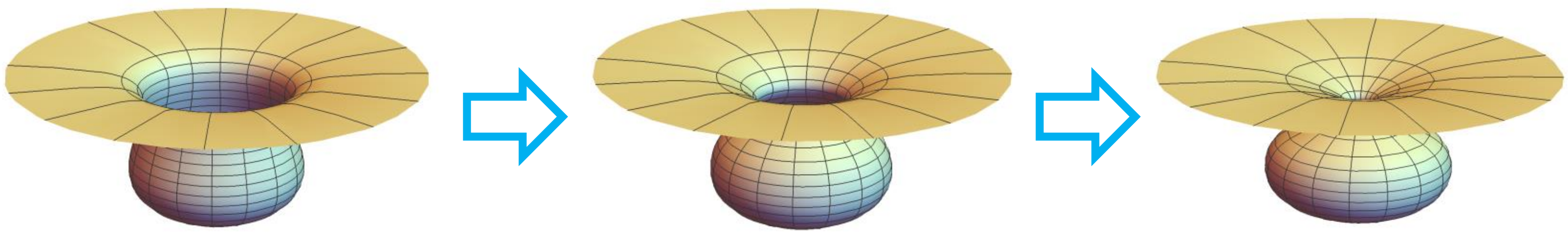
Local maximum of r

Collapsing shell



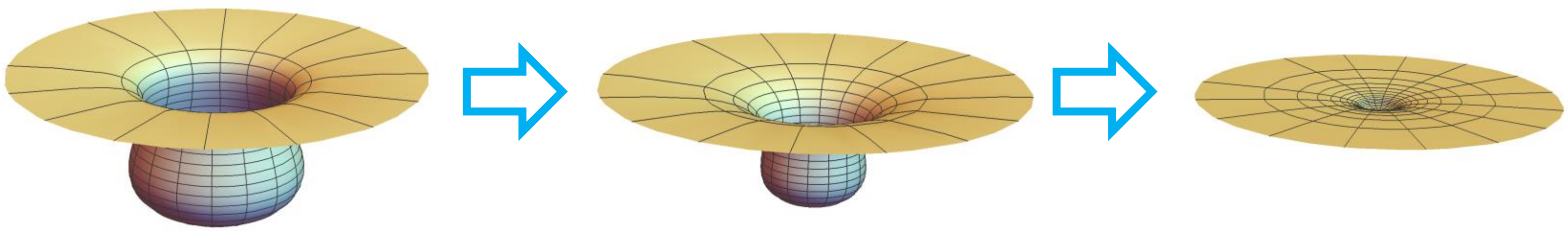
Apparent horizon as shrinking neck of wormhole

Apparent horizon appears simply because the neck is shrinking.



Interior might be disconnected from the outside of black hole after evaporation.

Result for fluid implies that neck and local maximum of r are almost same



In this case, interior will be of Planck scale when the neck is of Planck scale.

Full quantum effects of gravity becomes important and
geometry will simply goes to flat space.

Summary

Black hole evaporation

No negative energy ➡ No horizon ➡ No information loss

Negative vacuum energy

Static case ➡ No horizon, no singularity

Small density of matter ➡ same to ordinary stars

Large density of matter ➡ Geometry has "neck"

Dynamical case

Apparent horizon traps no information

Event horizon may or may not appear

Speculation

Small density of matter ➡ No event horizon

Large density of matter ➡ Event horizon may appear

Thank you