UV Origin of Late-Time Hawking Radiation

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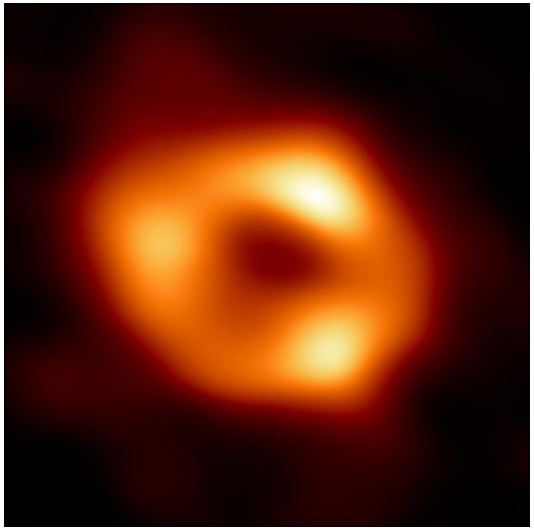
Based on:
"UV Dispersive Effects on Hawking Radiation" Phys.Rev.D 109 (2024) 2, 025001
"Hawking radiation under generalized uncertainty principle" Eur.Phys.J.C 83 (2023) 12, 1118
''UV Origin of Late-Time Hawking Radiation'' NTU master thesis

KEK Theory Workshop 2024 Dec. 12th

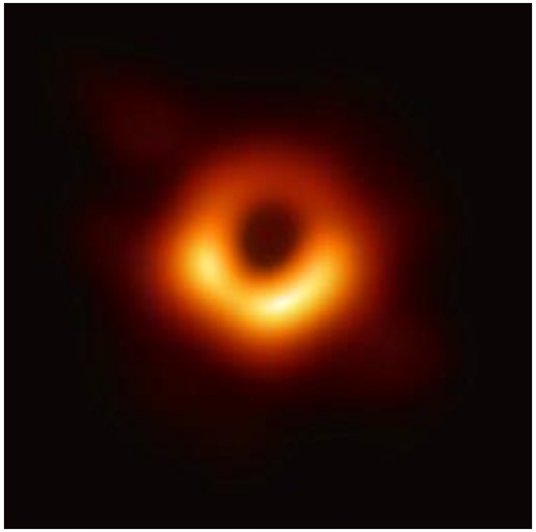
Plan of talk

- Introduction
  - Hawking Radiation(HR) & Information Loss Paradox
- Trans-Planckian problem
- HR as wavepacket distortion
- HR of Modified Dispersion Relation
  - Monotonic
  - Non-monotonic
- Conclusion

Introduction

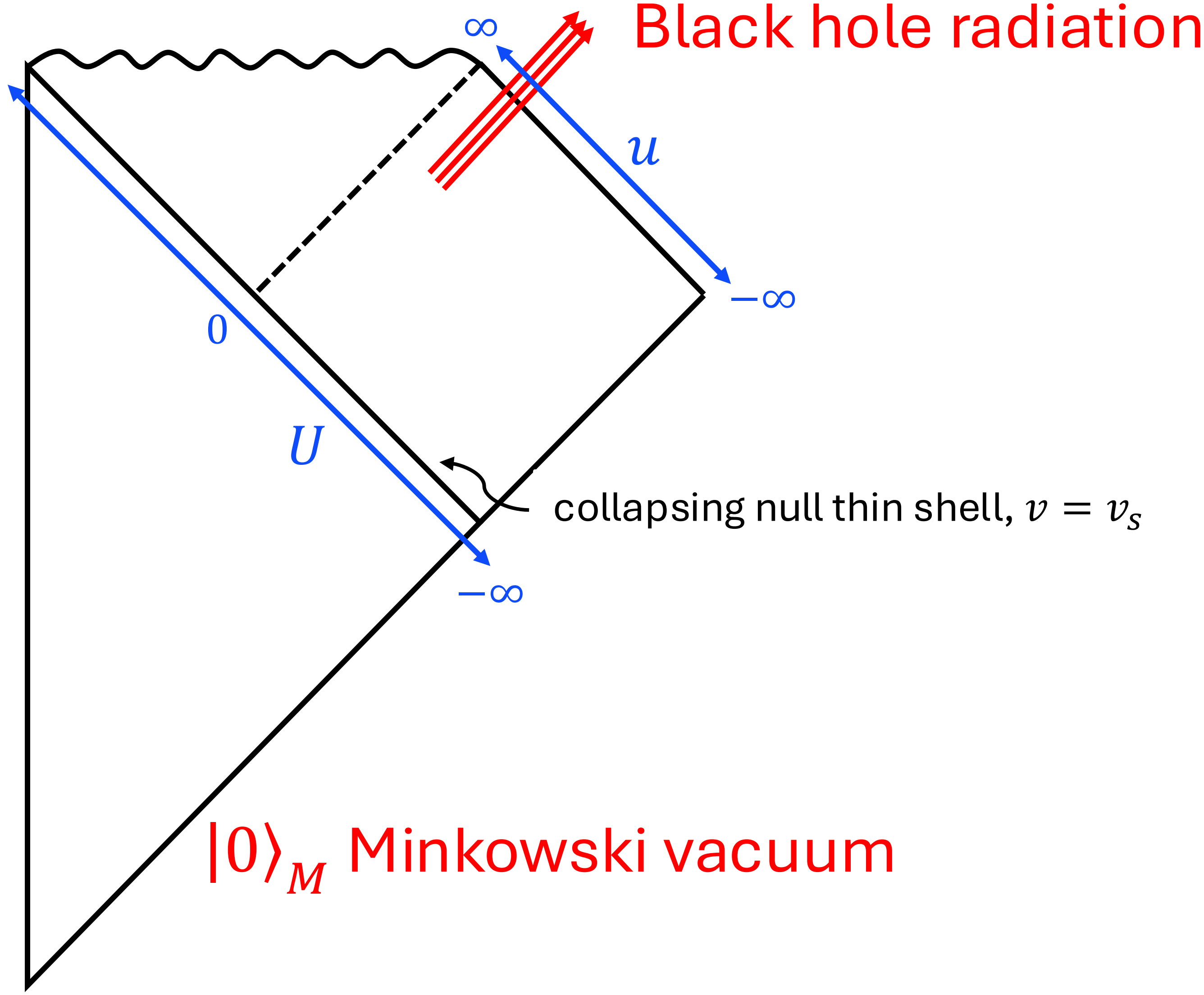


Sgr A* Event Horizon Telecope

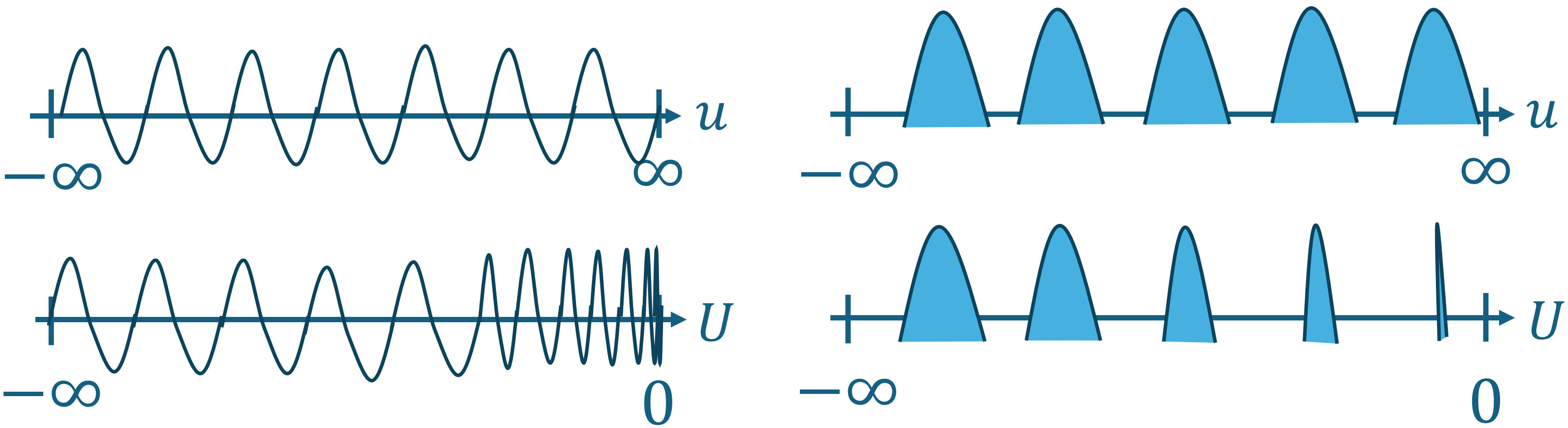


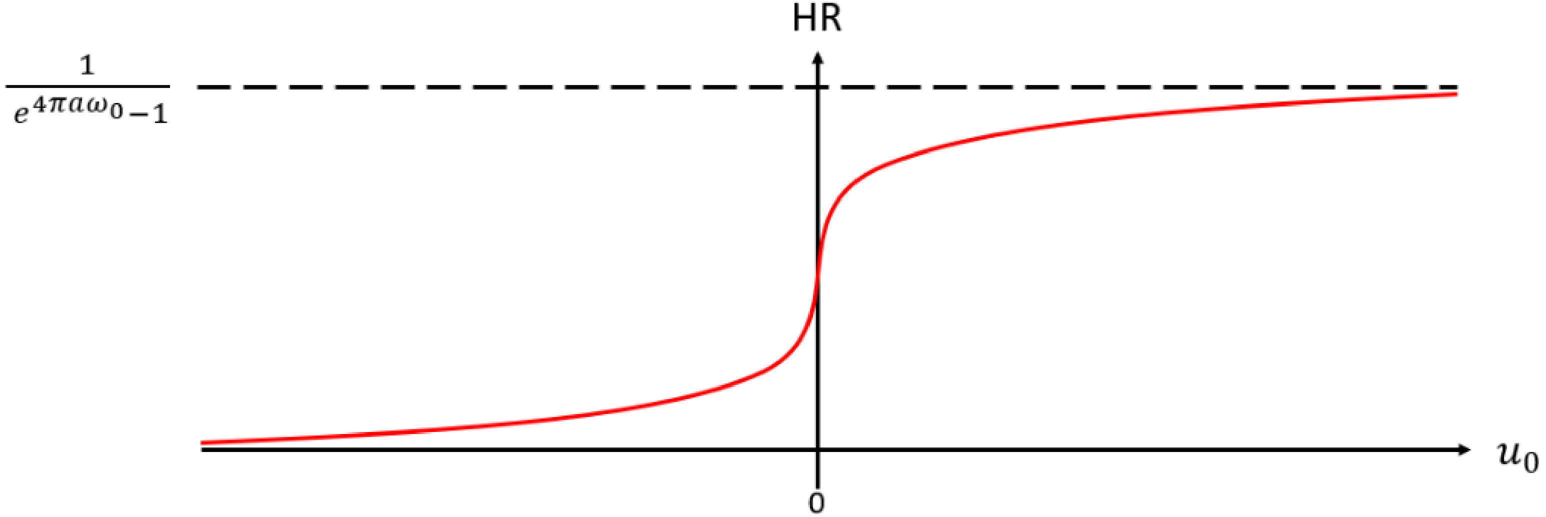
M87* Event Horizon Telecope

Hawking Radiation (1/3)



Hawking Radiation (2/3)





Hawking Radiation (3/3)

$$\langle 0 | N_{\omega_0} | 0 \rangle \Big|_{u_0 \gg a} \simeq \frac{1}{e^{4\pi a \omega_0} - 1}$$

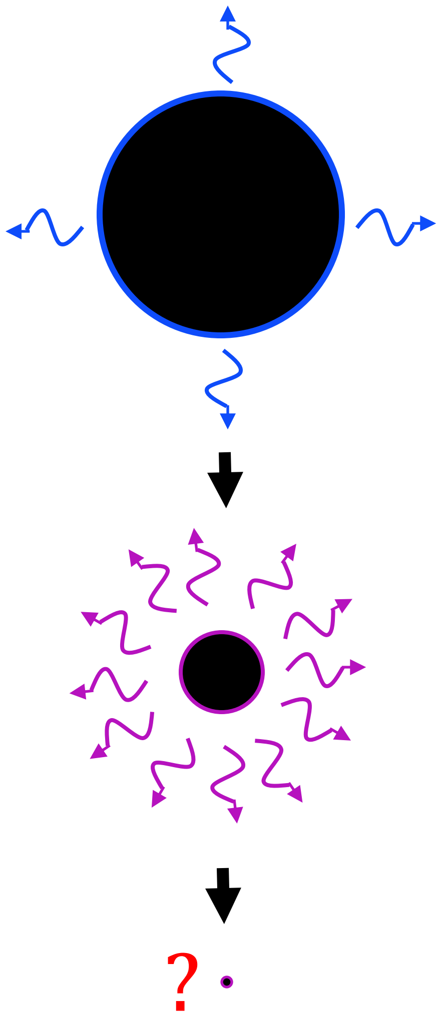
$a = 2GM$: Schwarzschild radius

Hawking Radiation is thermally distributed with temperature:

$$T = \frac{1}{4\pi a}$$

Hawking (76)

Information Loss Paradox



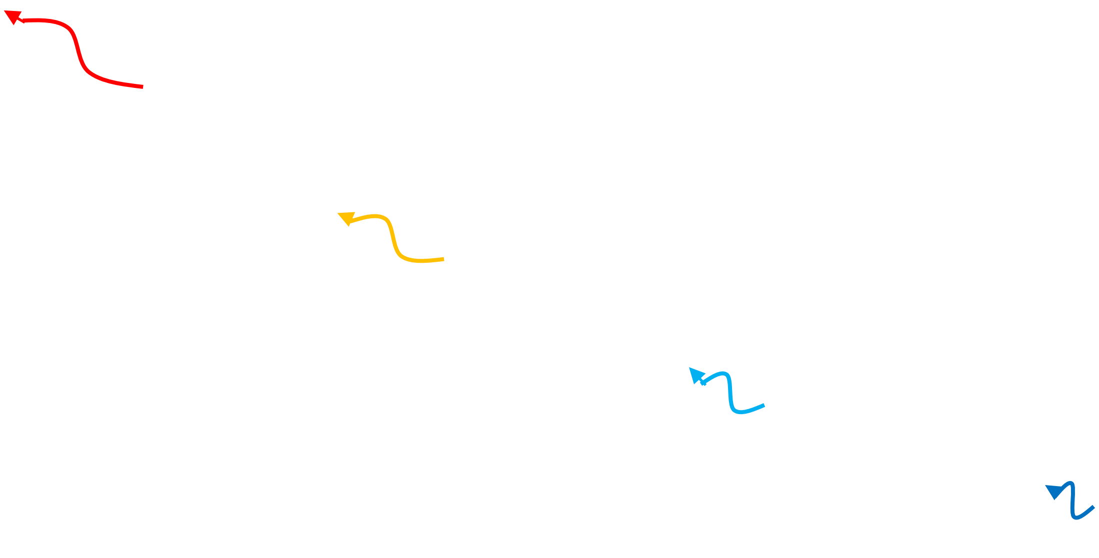
Thermal distribution $N_{\omega_0} \approx \frac{1}{e^{\omega/T}-1}$
with temperature $T = 1/4\pi a$.

Black hole evaporates
but without information being carried out

Information of the collapsing matter lost

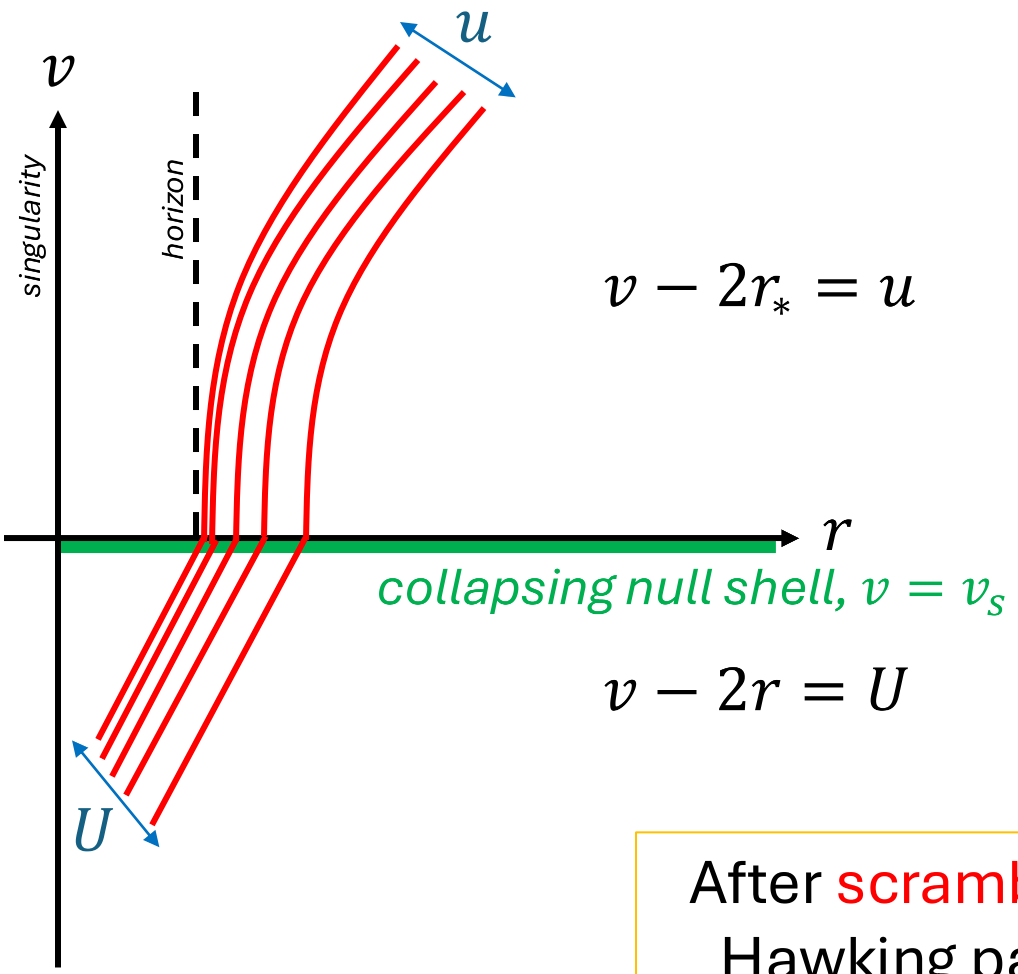
Black hole lifetime$\sim O(a^3/L_P^2)$

Trans-Planckian problem



Unruh (76)
Jacobson (91)

Blue shift to UV



After scrambling time $u \sim O(a \ln(a/L_P))$, Hawking particles reach the shell with trans-Planckian energy.

UV physics

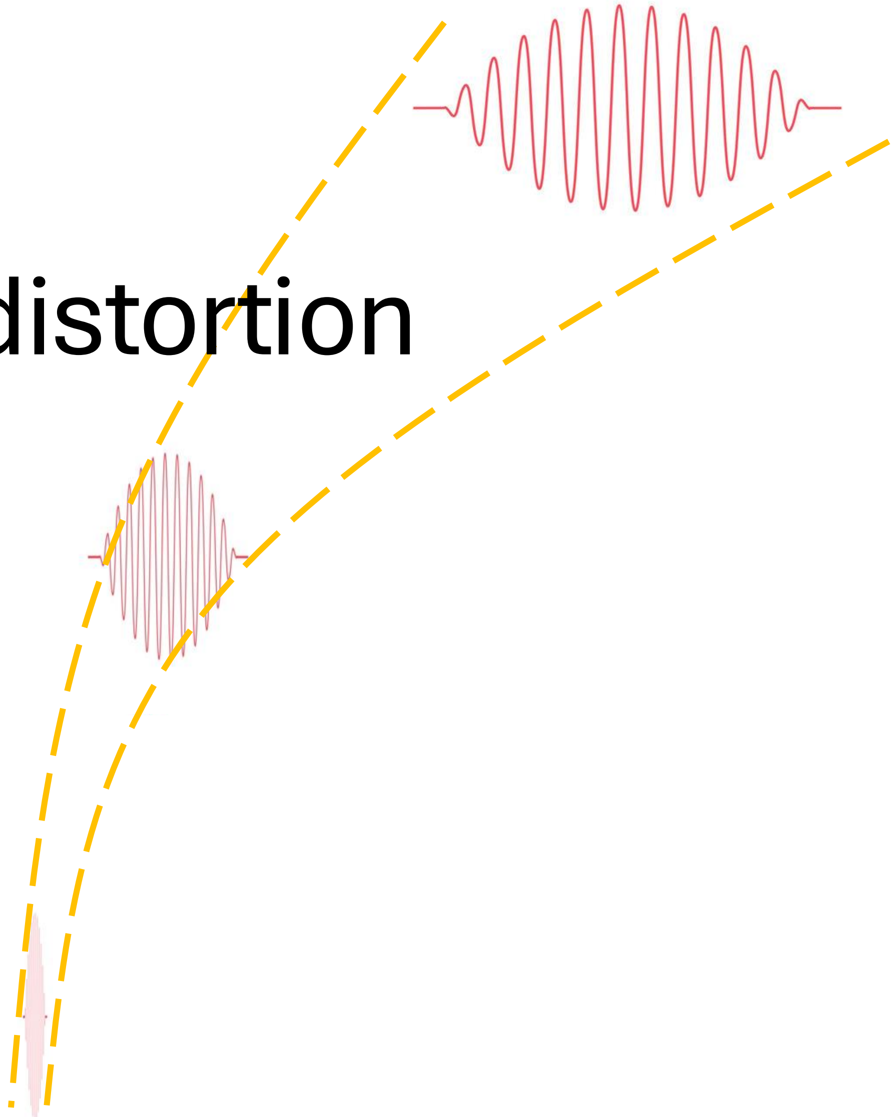
- Q: Does Hawking radiation sustain to the final stage of evaporation? $O(a^3/L_P^2)$
- If one can show the UV sensitivity of late-time HR, the information loss paradox is dismissed. $O(a\ln(a/L_P))$
- Many examples have been provided in recent years supporting this idea.

Ho, Kawai, Yokokura (22)
Ho, Kawai (23)
Chau, Ho, Kawai, Shao, CTW(23)
Akhmehdov, Chau, Ho, Kawai, Shao, CTW(24)
Ho, Imamura, Kawai, Shao(24)
Ho, Kawai, Shao(24)

- I will discuss another such possible UV schemes:
  - ➢Breakdown of local Lorentz symmetry at Planck scale

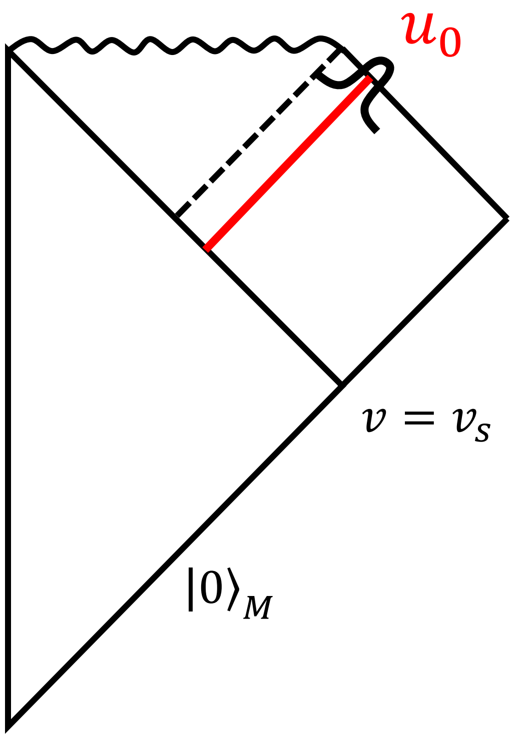
Existence of the minimal length (Discussed by Tin-Long Chau)

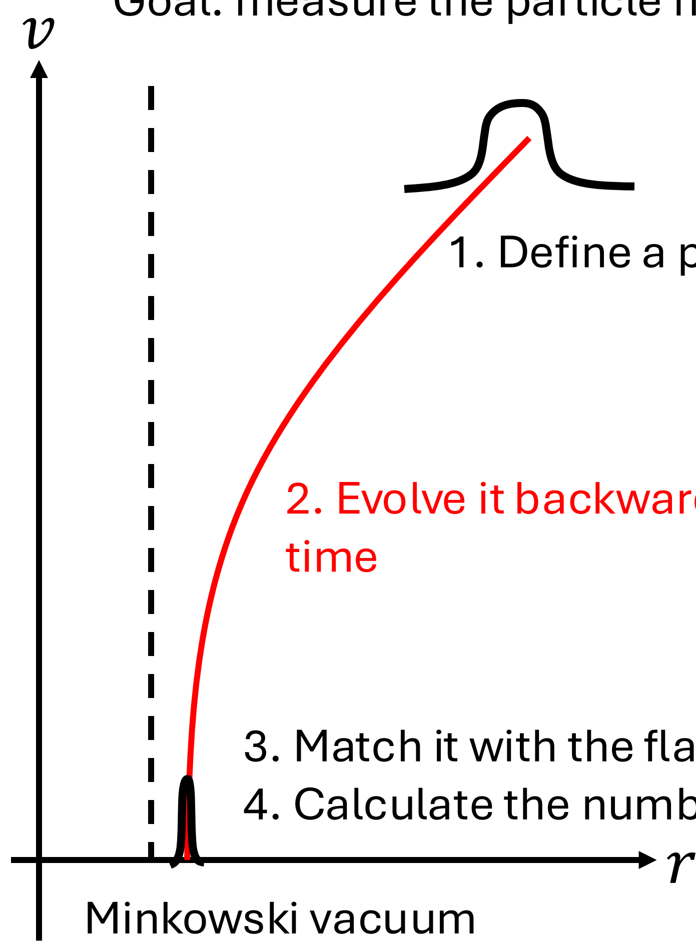
HR as wavepacket distortion



HR in Vaidya metric (setup)

Goal: measure the particle number at time u_0

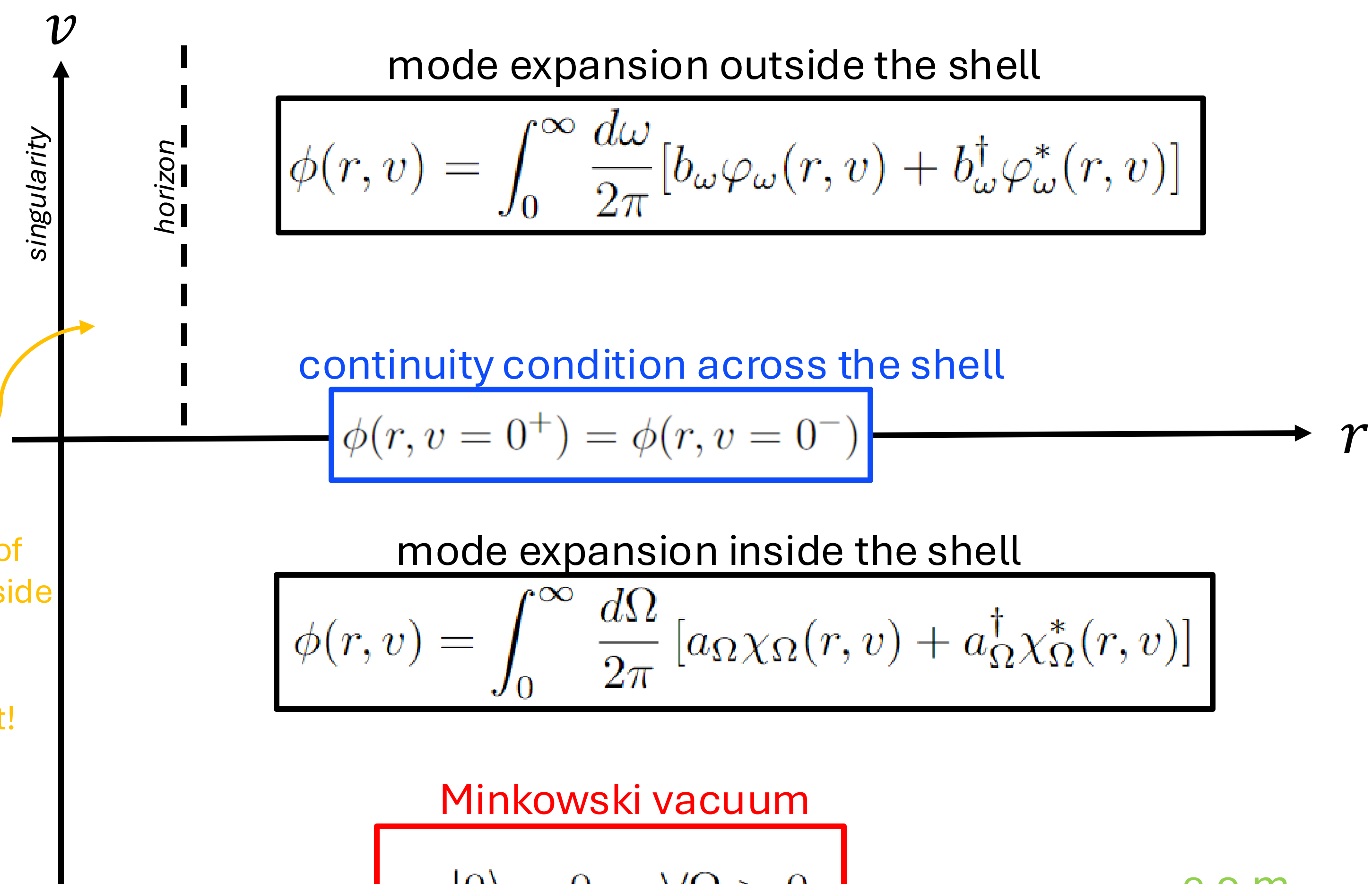




1. Define a particle at time u_0
2. Evolve it backward in time
3. Match it with the flat-space mode
4. Calculate the number operator VEV

$$ds^2 = -\left(1 - \Theta(v - v_{\rm s})\frac{a}{r}\right) dv^2 + 2dvdr$$

Bogoliubov transf. (technical)



mode expansion outside the shell

$$\phi(r,v) = \int_0^\infty \frac{d\omega}{2\pi}\left[b_\omega \varphi_\omega(r,v) + b_\omega^\dagger \varphi_\omega^*(r,v)\right]$$

continuity condition across the shell

$$\phi(r, v=0^+) = \phi(r, v=0^-)$$

There is another set of solutions inside the horizon. Causally independent!

mode expansion inside the shell

$$\phi(r,v) = \int_0^\infty \frac{d\Omega}{2\pi}\left[a_\Omega \chi_\Omega(r,v) + a_\Omega^\dagger \chi_\Omega^*(r,v)\right]$$

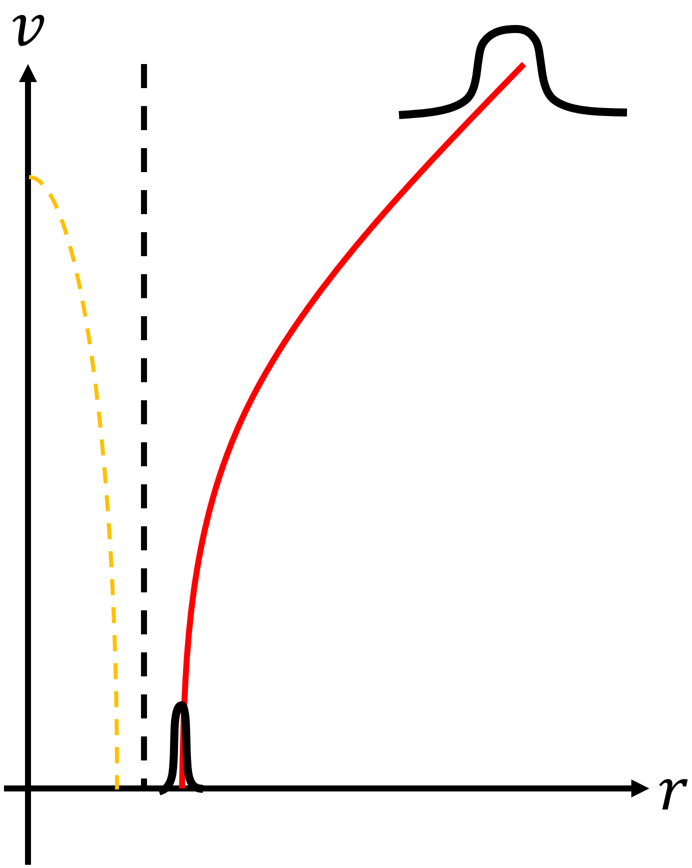
Minkowski vacuum

$$a_\Omega|0\rangle = 0, \quad \forall \Omega > 0,$$

e.o.m.

$$\left[2\partial_v + \left(1 - \Theta(v - v_s)\frac{a}{r}\right)\partial_r\right]\phi_{out}(v,r) = 0$$

Distortion & Frequency mixing



Due to the uncertainty principle

$$\Delta r \Delta p \geq \frac{1}{2}$$

Δp becomes exponentially large, and wavepacket gains negative support in momentum space.

$\Rightarrow$ *Hawking Radiation*

$$\langle 0| N_{\omega_0} |0\rangle \Big|_{u_0 \gg a} \simeq \frac{1}{e^{4\pi a \omega_0} - 1}$$

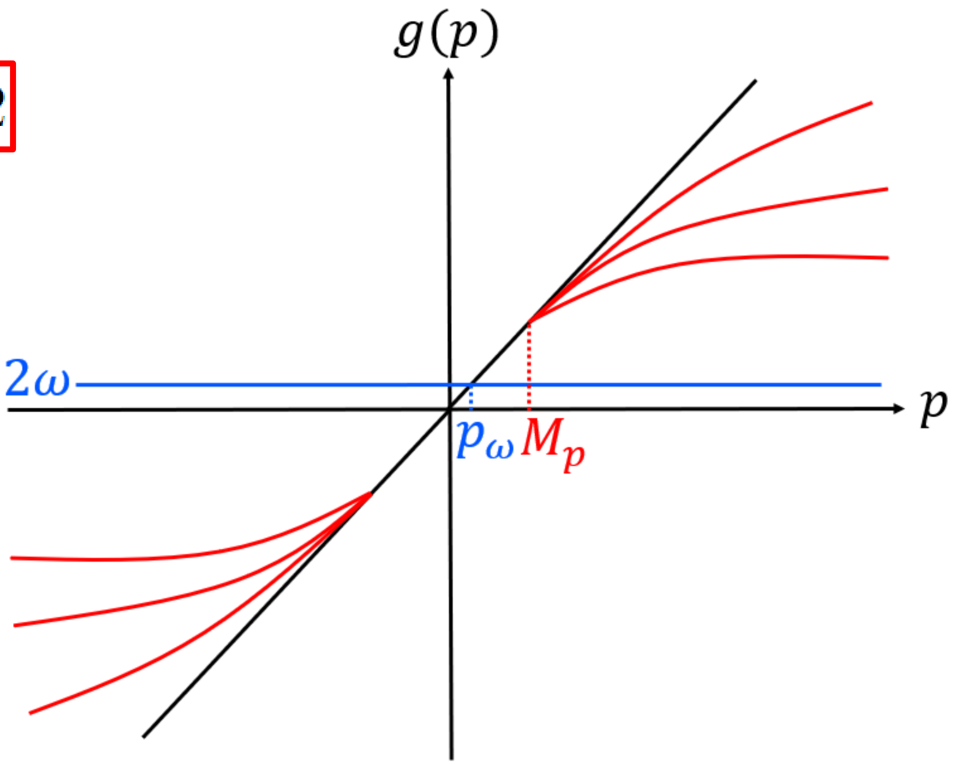
HR of Modified Dispersion Relation

Modified Dispersion Relation

$\omega = p/2$ → $\omega = g(p)/2$

⇒ group velocity becomes smaller for $p > M_p$

⇒ Hawking particle slows down within the Planck distance from the horizon



$$\frac{1}{2}\left(1-\frac{a}{r}\right) g(-i\partial_r)\phi(r,v) - i\partial_v\phi(r,v) = 0.$$

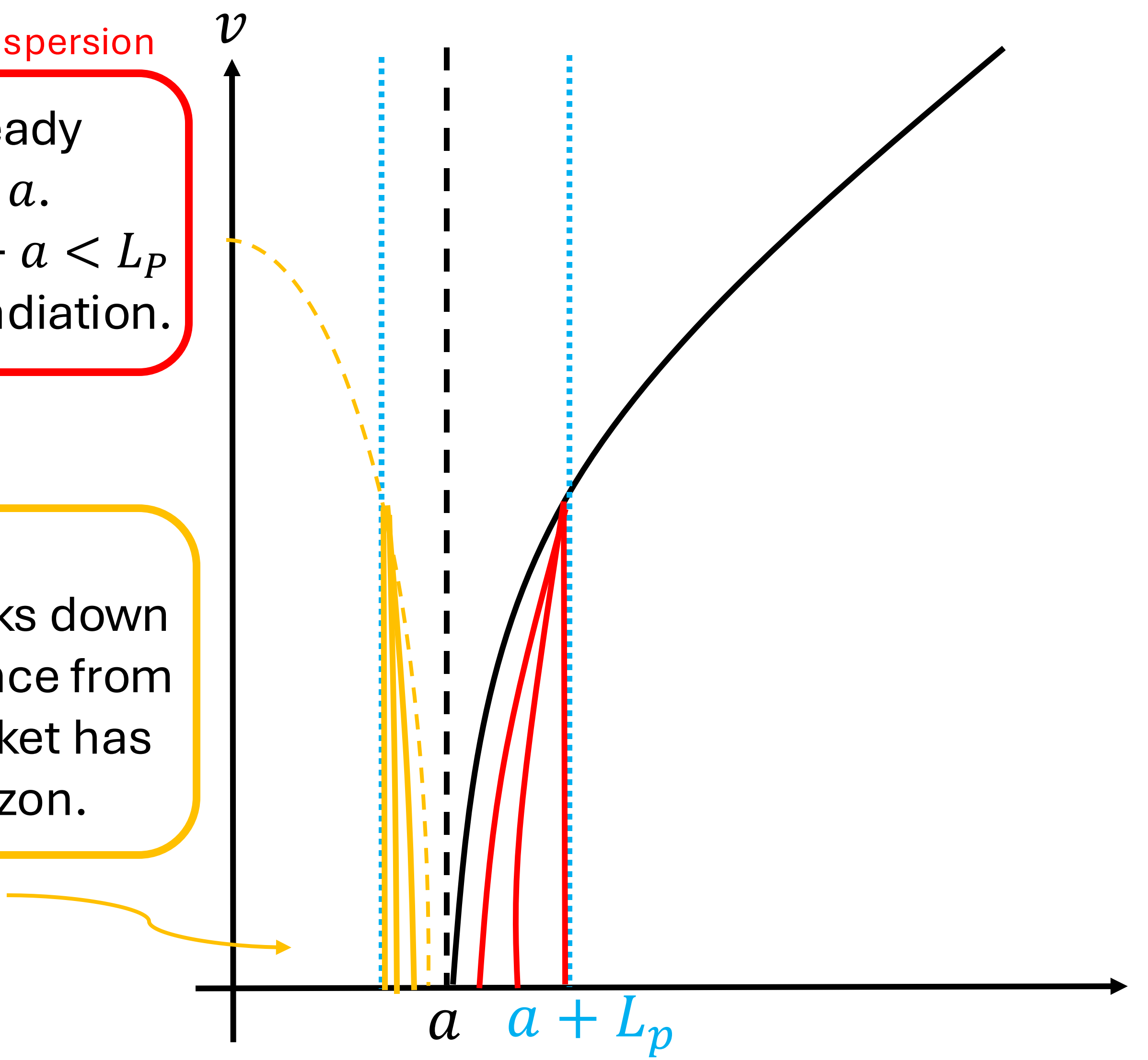
Monotonic dispersion

1. HR is still there for monotonic dispersion

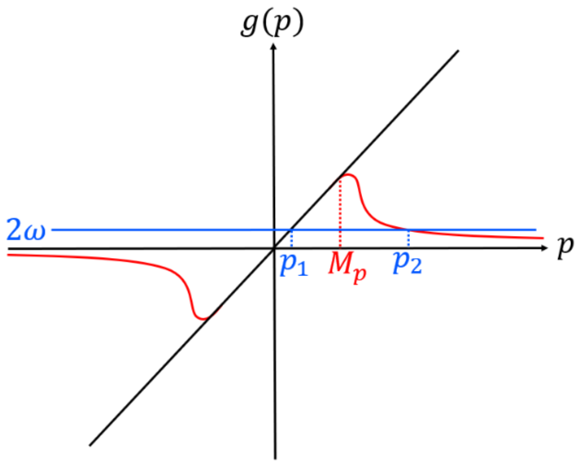
The wavpeacket is already distorted for $r - a \ll a$. Different trajectories in $r - a < L_P$ doesn't modify Hawking radiation.

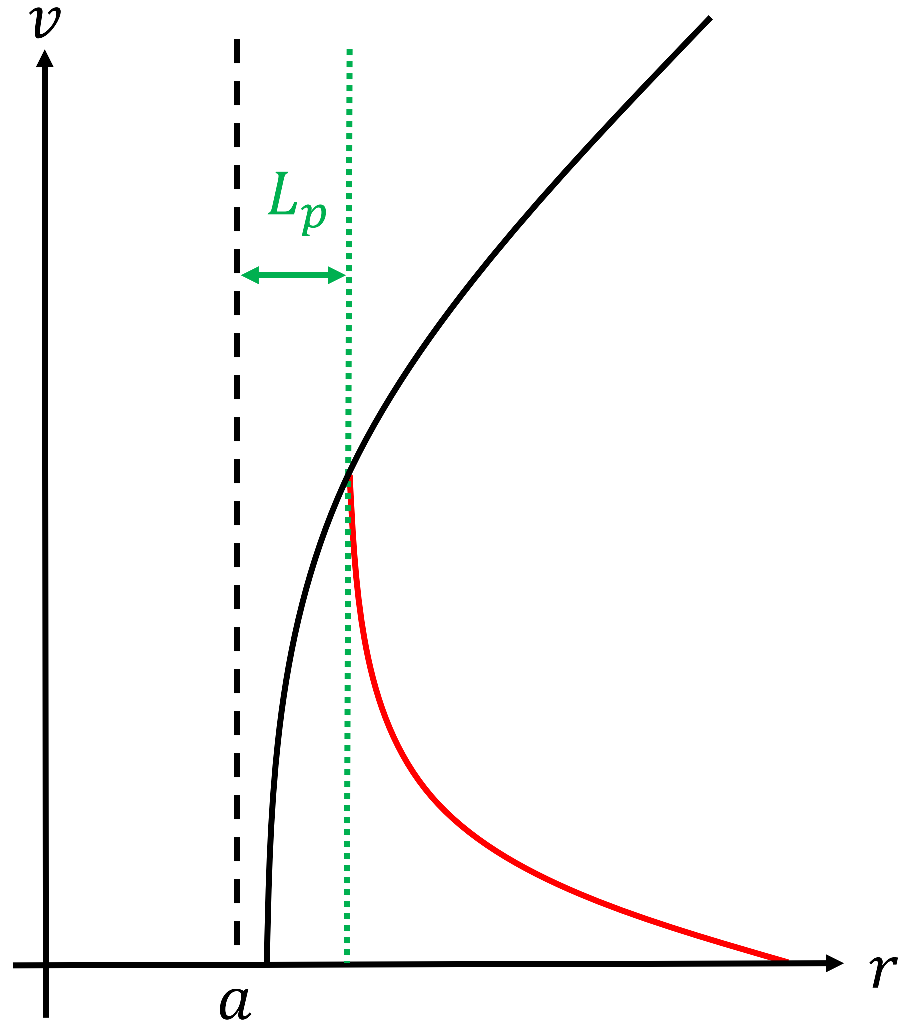
2. Inside horizon is no longer causally disconnected.

Interesting point:
The geometric optics breaks down within the Planckian distance from the horizon. The wavepacket has support inside the horizon.



Non-monotonic dispersion



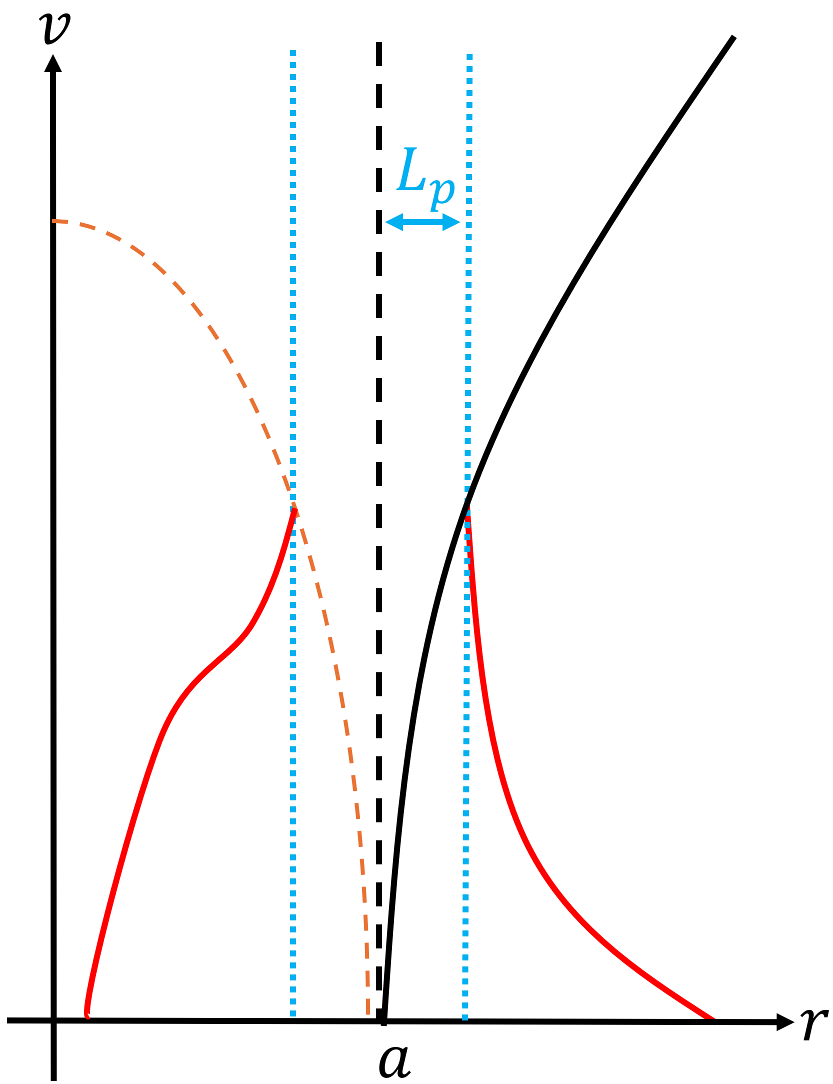


⇒ group velocity becomes negative for $p > M_p$

⇒ Hawking particle rebounce from the horizon

⇒Apart from horizon, distortion disappears. Hawking radiation vanishes?

Tunneling across horizon



non-local behavior within the Planck distance from the horizon

+

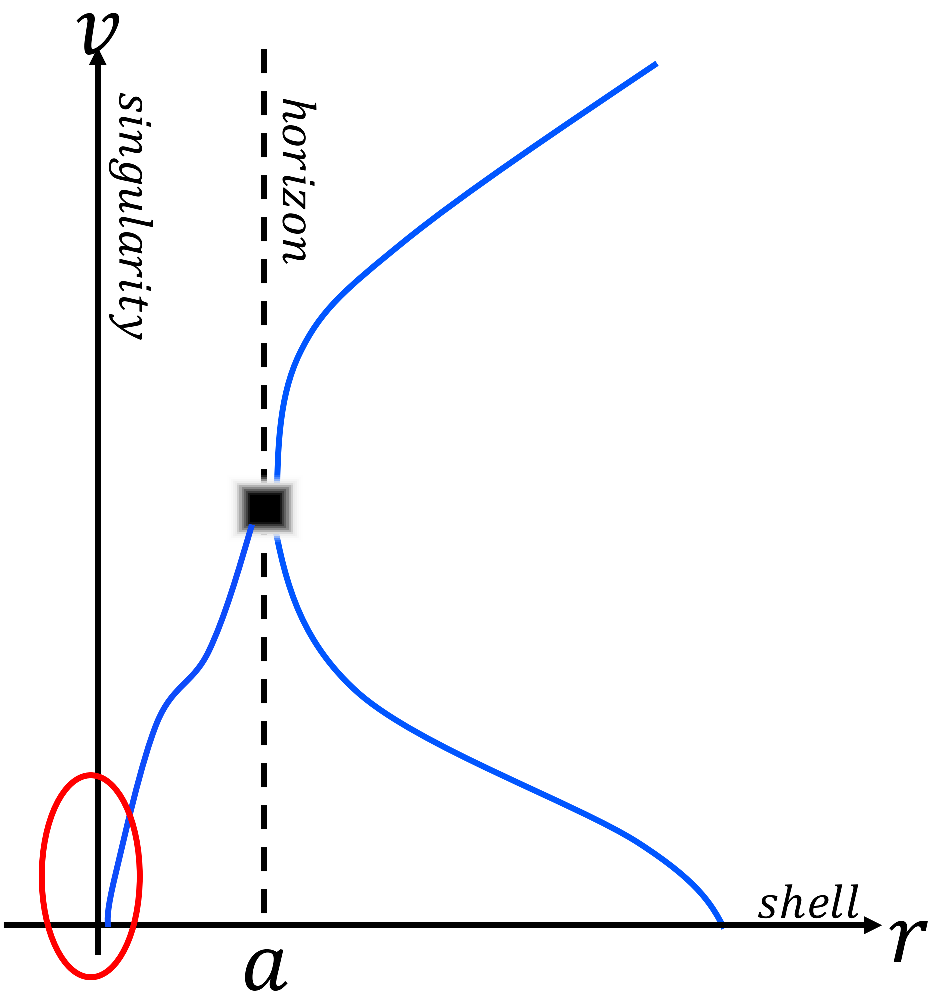
bouncing off trajectory inside the horizon

=

tunneling across the horizon!

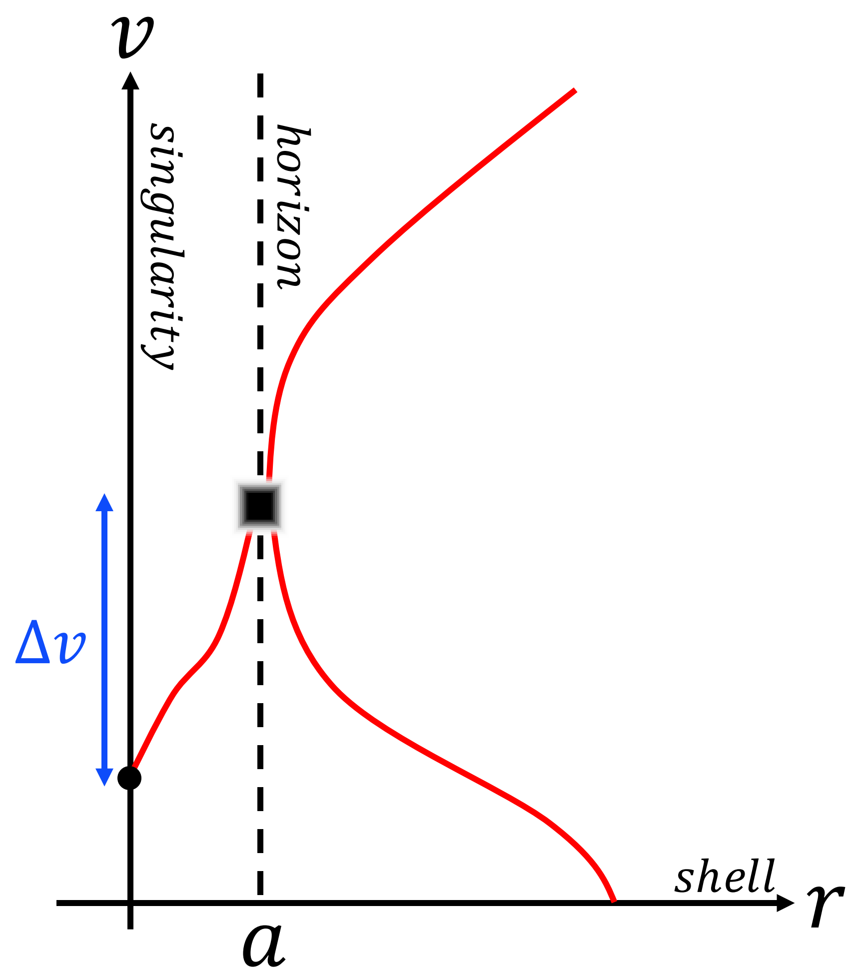
Approaching singularity

Part of the wavepacket tunnels across the horizon and approaches the singularity, which again becomes the source of HR.

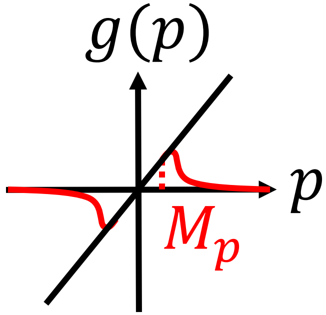


Touch singularity

However, if it hits the singularity within finite time, Hawking radiation hereafter depends on the singularity boundary condition.



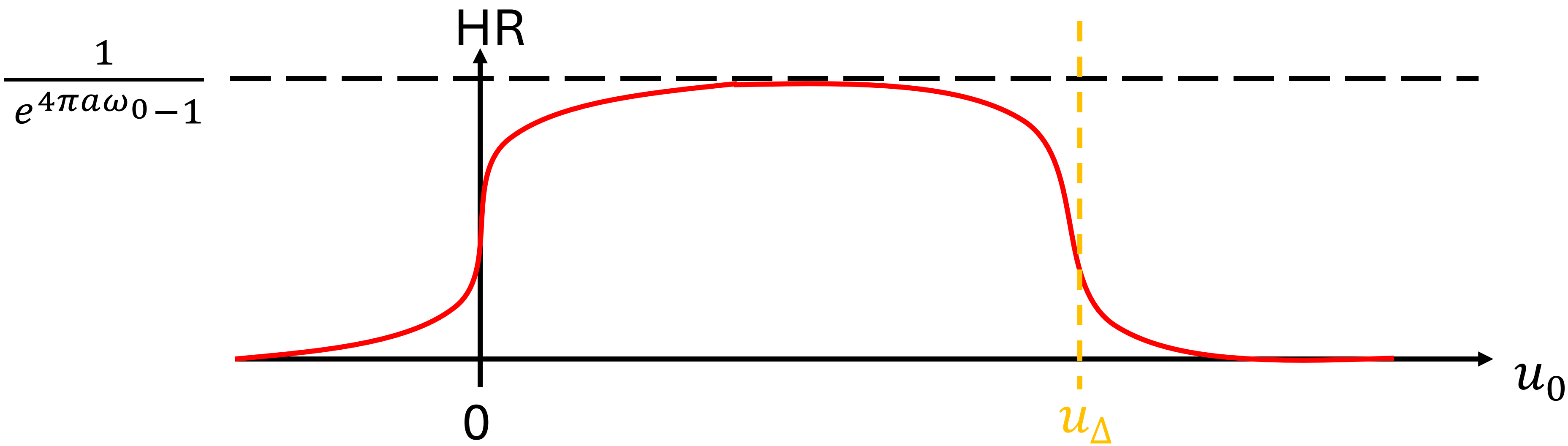
Late-Time turned-off



$$u_\Delta = 2a\int_0^{-\infty} dp\,\frac{g(p)}{[2\omega_0 - g(p)]^2} \simeq 2a\ln\left(\frac{M_p}{2\omega_0}\right) + 2a\int_{-M_p}^{-\infty} dp\,\frac{g(p)}{[2\omega_0 - g(p)]^2}$$

scrambling time

Δv travel time



Conclusion

- The UV origin of the late-time Hawking radiation is discussed for the modified dispersion relation.
- Hawking radiation is found to originate from the singularity after the scrambling time if the dispersion relation decays fast enough. HR would be largely suppressed if there is no description of the singularity.
- This exactly reflects the UV sensitivity and the trans-Planckian problem of Hawking radiation.
- The information loss paradox of low energy effective theory is dismissed.