UV Physics and Information Paradox

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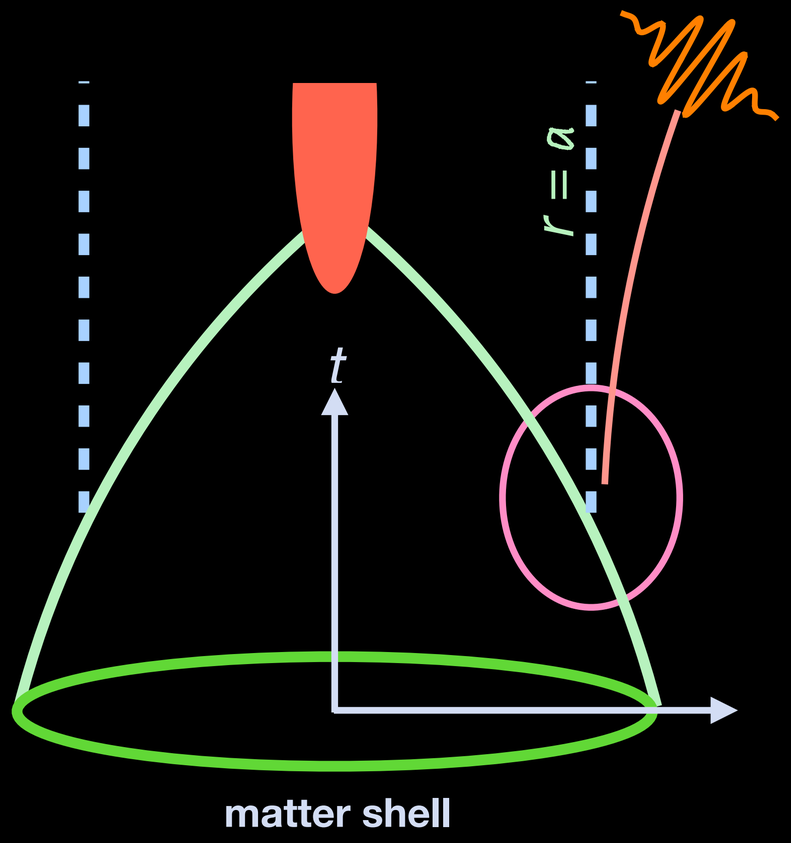
[PMH-Kawai-Yokokura 2111.01967][PMH-Kawai 2207.07122]
[Chau-PMH-Kawai-Shao-Wang 2309.01638]
[PMH-Imamura-Kawai-Shao 2309.12936]
[PMH-Kawai-Shao 2411.01105]
[Chang-PMH-Lee-Shao 2412.02577]
[Ho-Shao-Yoda …][Cheng-Ho-Shao …]

black hole formation and evaporation: conventional model

[Hawking 76]

$$a = 2\ell_p^2 M$$



Hawking radiation: mostly geometric information

info. in matter $\rightarrow$ radiation?

same as burning a piece of coal?

$$G_N = \ell_p^2, \quad \hbar = 1, \quad c = 1$$

black hole formation and evaporation: conventional model

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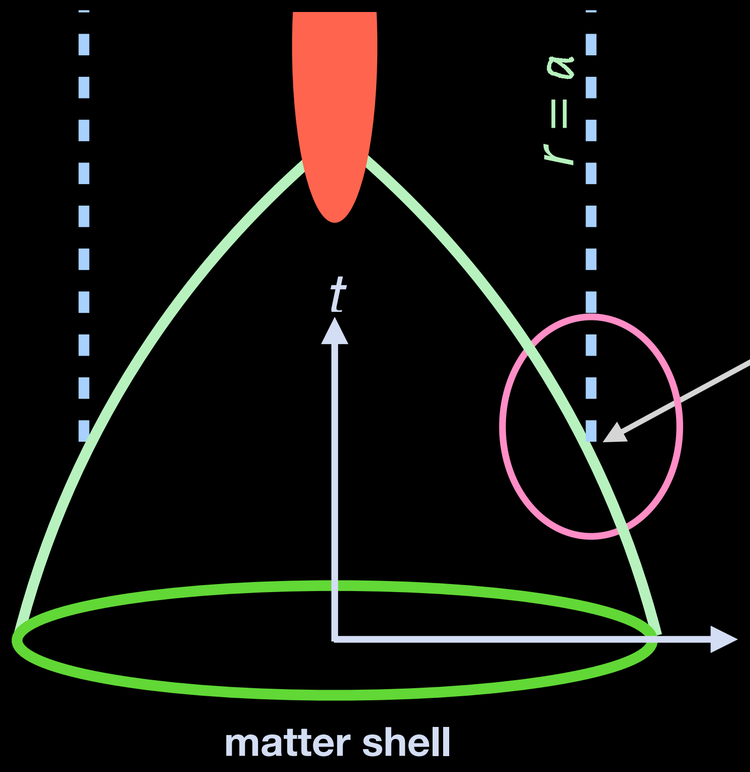
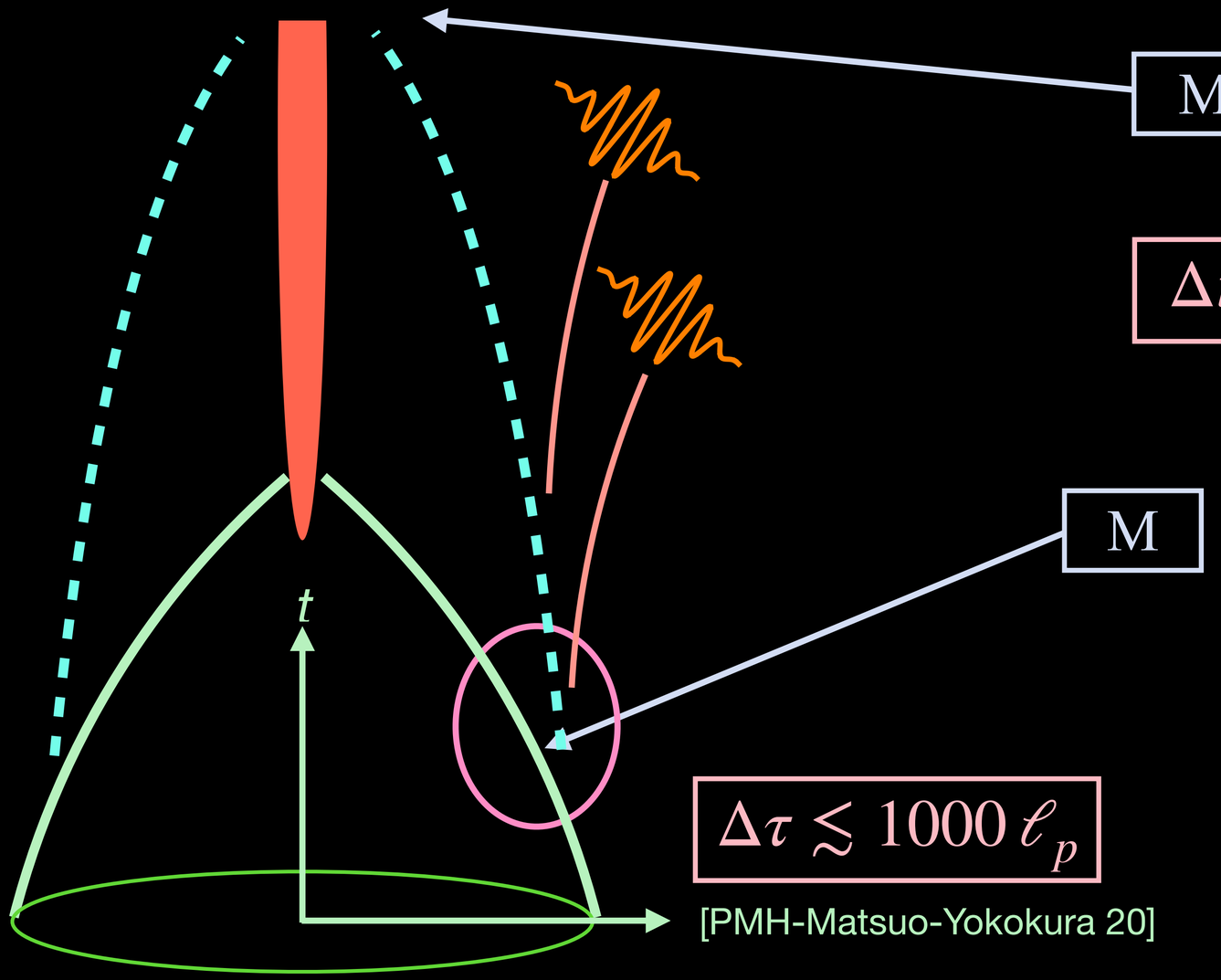


General Relativity ⇒ “uneventful” horizon

Equivalence principle:

We may have just crossed the horizon.

Information transfer in the conventional model



M/100

$\Delta t \sim a^3/\ell_p^2 \;=\;$ Page time

M

$\Delta\tau \lesssim 1000\,\ell_p$

[PMH-Matsuo-Yokokura 20]

Through Hawking rad. ⇒
99% of mass/information in the collapsing matter comes out within $1000\,\ell_p$!!!

→ firewall or nonlocality!

black-hole information paradox

Hawking's calculation in low-energy effective theory $\Rightarrow$

Hawking radiation carries (almost) no information

and persists until (almost) complete evaporation

$\rightarrow$ information paradox

Q: Is Hawking's LEET calculation reliable?

black-hole information paradox

[Quanta magazine “*The Fuzzball Fix for a Black Hole Paradox*" 2015]

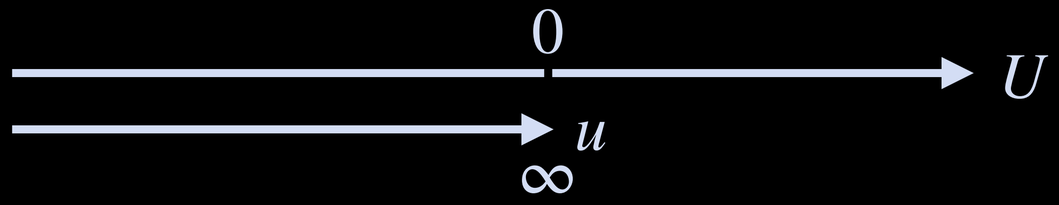
Polchinski said of Hawking’s original premise:

> *“… a situation that seems to violate the laws of quantum mechanics. … ‘Quantum mechanics is modified. Find my mistake.’ And nobody found his mistake.”*

There have been countless papers on how Hawking radiation is robust, insensitive to UV modifications of LEET.

Hawking radiation

[Hawking 74]



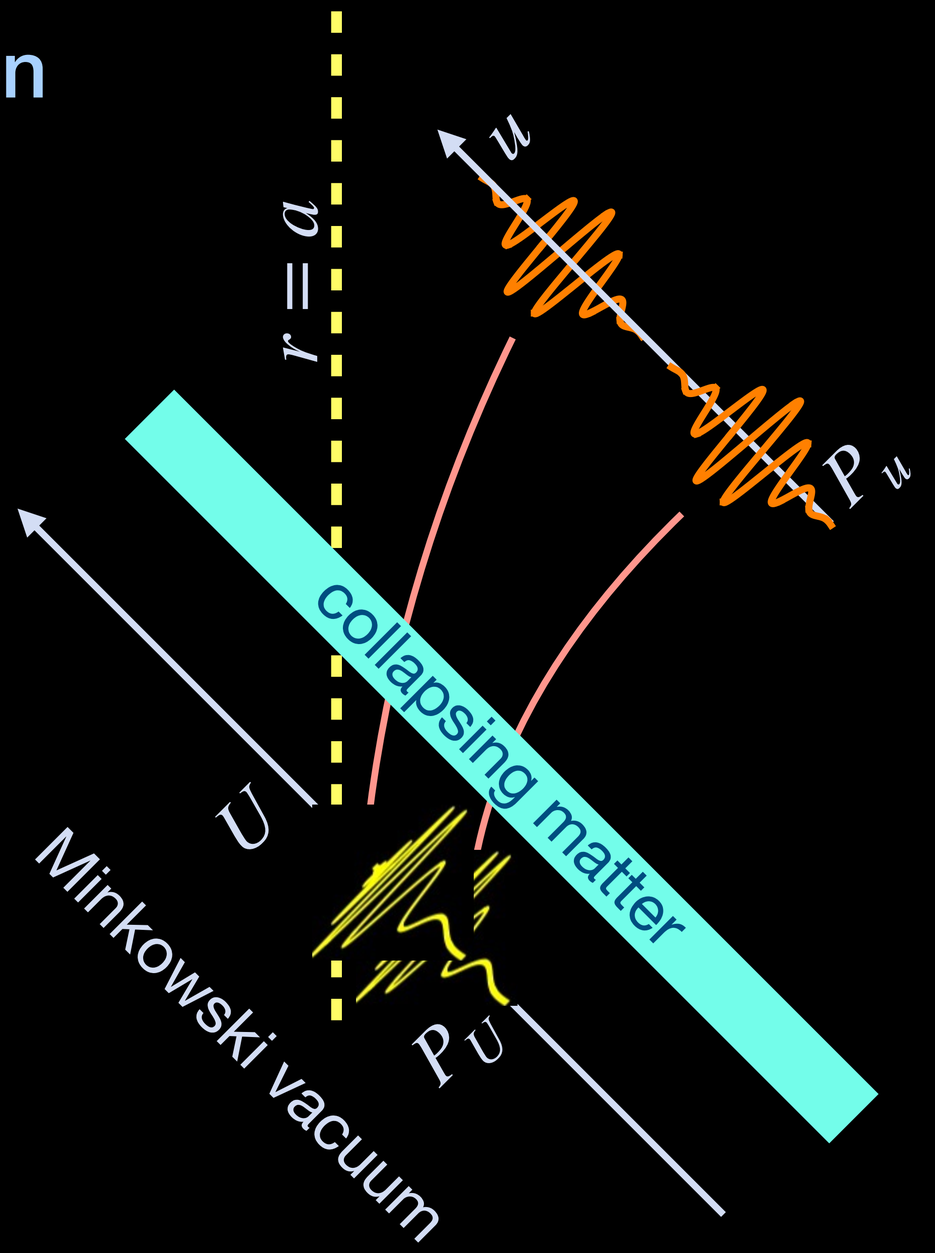
$$U = -2ae^{-u/2a}$$

$$\langle P_U \rangle \sim \langle P_u \rangle \, e^{u/2a}$$

Minkowski vacuum $|\,0\rangle$ of the infinite past

$\simeq$ Hawking radiation at large distance

Q: Is there a UV Lorentz-invariant?



higher-derivative interactions

[PMH-Yokokura 20][PMH-Kawai-Yokokura 21]

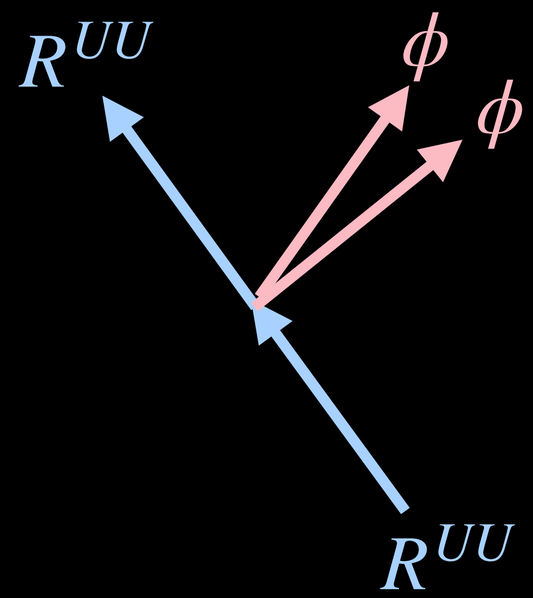
Ex:

$$S_n \equiv \frac{\lambda_n}{M_p^{4n-2}} \int d^4x \sqrt{-g}\, R^{\mu_1\nu_1} \cdots R^{\mu_n\nu_n} \left(\nabla_{\mu_1} \cdots \nabla_{\mu_n} \phi \right) \left(\nabla_{\nu_1} \cdots \nabla_{\nu_n} \phi \right)$$

$$\sim \lambda_n \left(\frac{s}{M_p^2} \right)^{2n-1}$$

$$s \equiv P_U P_V \sim \frac{1}{a^2} e^{u/2a}$$

$$u \sim a \log(a/\ell_p) \quad \Rightarrow \quad Ampl. \sim \mathcal{O}(1)$$



black-hole information paradox

Q: Is Hawking's calculation reliable?

No.

← Trans-Planckian local Lorentz inv. after scrambling time.

UV physics is relevant.

black-hole information paradox

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UV physics is relevant.

→ How does a given UV theory change HR?

- HR as in LEET ⇒ still a paradox.
- HR enhanced by informative radiation.

Q: Other logical possibilities?

alternative resolution

[Chau-PMH-Kawai-Shao-Wang 23][PMH-Imamura-Kawai-Shao 23][PMH-Kawai-Shao 24]

- Hawking radiation stops well before the Page time, say, around scrambling time:

$$t_{scr} \sim a \log(a/\ell_p) \quad \ll \quad t_{Page}$$

$\rightarrow$ HR is negligible.

alternative resolution

[Chau-PMH-Kawai-Shao-Wang 23][PMH-Imamura-Kawai-Shao 23][PMH-Kawai-Shao 24]

- Hawking radiation stops well before the Page time, say, around scrambling time:

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However, in the literature,

“HR is insensitive to UV theories.”

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However, in the literature,

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→ *Time-dependent* amplitude of HR.

stringy spacetime

[Chau-PMH-Kawai-Shao-Wang 23][PMH-Imamura-Kawai-Shao 23][PMH-Kawai-Shao 24]

String theory has a milder UV limit.

Scattering amplitudes are exponentially suppressed

in the limit $E \to \infty$.

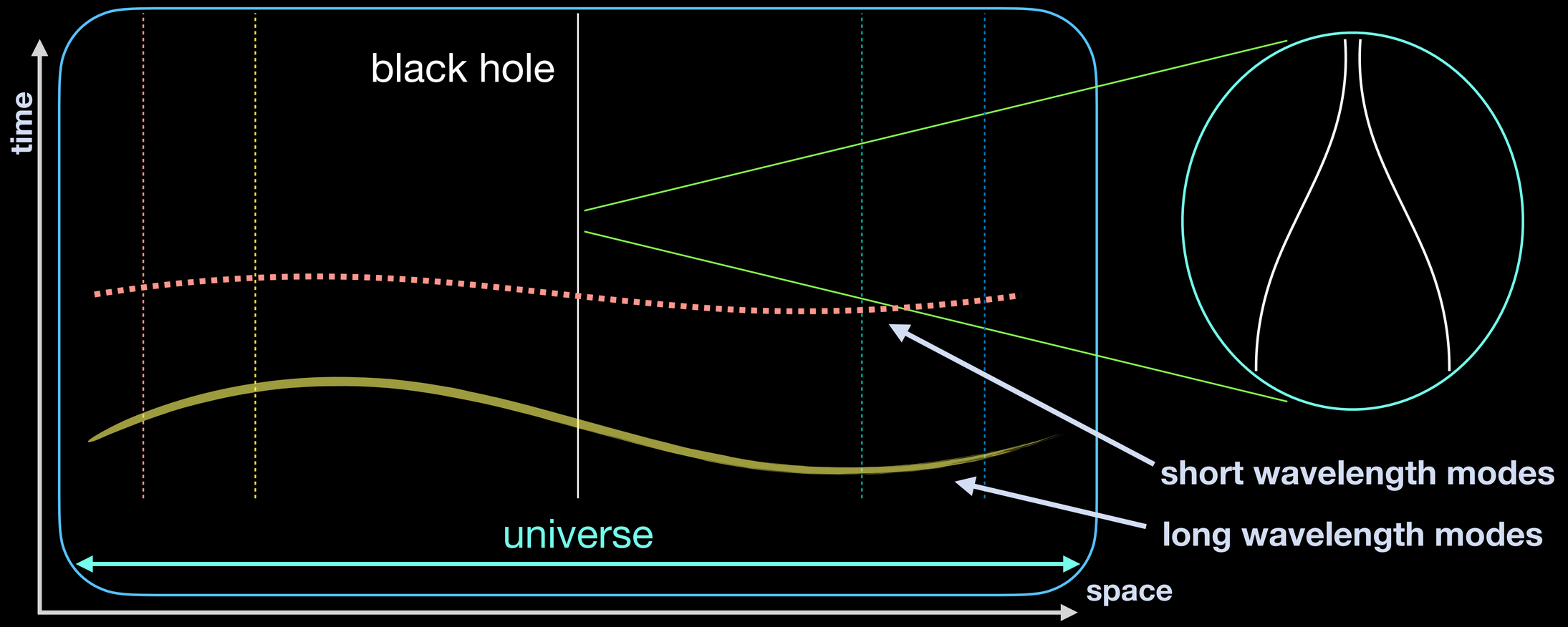
spacetime uncertainty $\Delta x \Delta t \gtrsim \ell_s^2$

generalized uncertainty relation $\Delta x \Delta p \gtrsim 1 + \ell_s^2 \Delta p^2$

$\to$ $\boxed{\Delta x \gtrsim \ell_s^2 \Delta p}$ (UV-IR connection)

Ex: For a solar mass black hole ($a \sim 3\,km$) for $\Delta x \sim$ universe.

$\rightarrow$ H.R. stops around $u \sim 5a\log(a/\ell_p) \sim 5\,ms$. (vs. 10^{64} yrs.)



Generalized Uncertainty Principle (GUP)

$$\Delta x \Delta p \gtrsim 1 + \ell_p^2 \Delta p^2$$

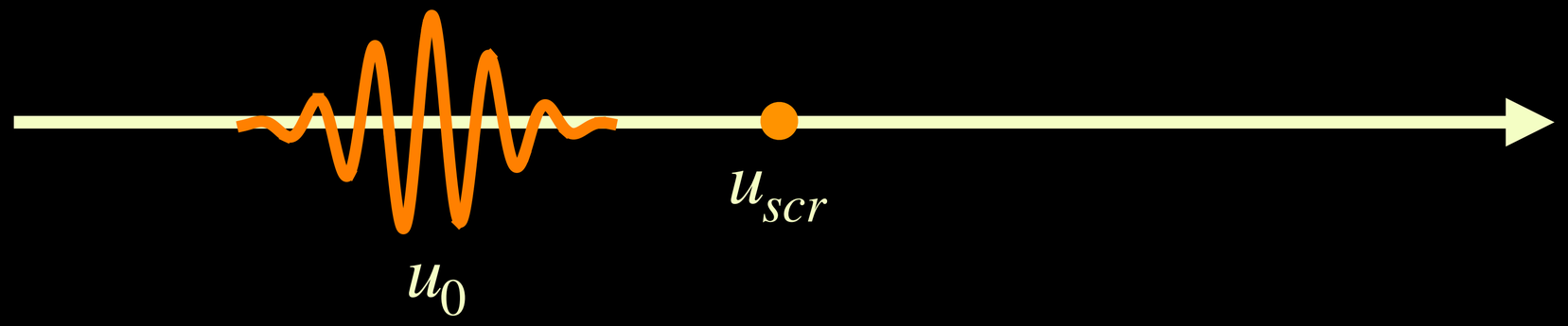
[Amati-Ciafaloni-Veneziano 87, 89] [Konishi-Paffuti-Provero 90]

$\Rightarrow$ minimal length $\Delta x \gtrsim 2\ell_p$

$\Delta p \gg \ell_p^{-1} \quad \Rightarrow \quad \Delta x \gtrsim \ell_p^2 \Delta p$

Robustness of HR with GUP noted repeatedly in many works.

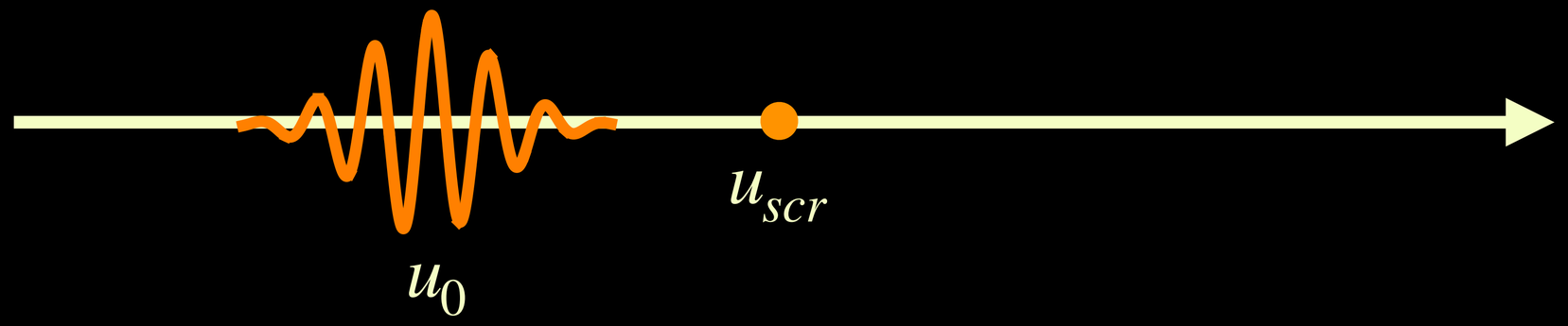
[0506110, 1212.6591, 1410.4115, 1410.5065, 1501.03256, 1501.06025, 1602.04304, 1704.03536, 1709.00637, 1903.01382, 2112.13573, 2306.03077].



Hawking radiation = the VEV of the number operator for this wave packet:

$$\langle 0 \mid b_\Psi^\dagger b_\Psi \mid 0 \rangle \simeq \frac{1}{2} \frac{\omega_0}{e^{4\pi a \omega_0} - 1} \int_{-\infty}^{u_{scr}} du \left| \Psi_{(\omega_0, u_0)}(u) \right|^2$$

$$u_{scr} = 4a \log(a/\ell_p)$$



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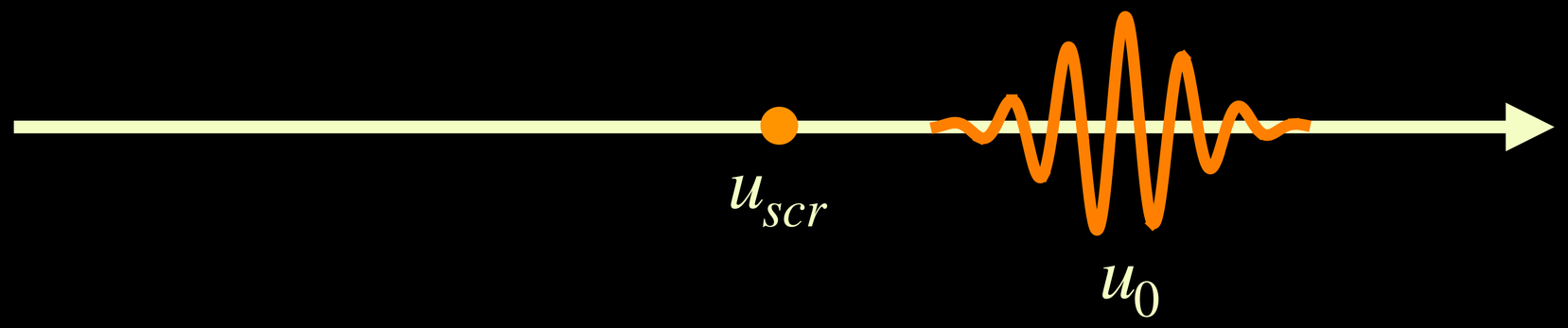
Hawking temperature is the same.



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$\longrightarrow 0$ when $u_0 \gg u_{scr} \equiv 2a \log(a/\ell_p)$ (scrambling time).

At late times, the wave packet has a large Δp, GUP implies a large Δx.

When Δx is much larger than a, it does not contribute to Hawking radiation.

[Chau-PMH-Kawai-Shao-Wang 23]

other examples

- String Field Theory [PMH-Imamura-Kawai-Shao 23][Chang-PMH-Lee-Shao 24]

  $\rightarrow \quad \Delta U \Delta V \gtrsim \ell_E^2$

  ~ spacetime uncertainty relation [Yoneya]

- Noncommutative Geometry [Ho-Shao-Yoda, WIP]

  ⋮

Geometry is scale dependent.

No horizon in UV limit. (vs. fuzzball)

comments

- Entanglement Island proposal [Almheiri-Engelhardt-Marolf-Maxfield 19, Penington 19]
  nonlocal but low-energy effective description (lower dimensions)

  UV description for $D \geq 4$?
- AdS/CFT duality compatibility

Applications:

- Primordial black holes as dark matter candidates. [Che-Yu's talk]
- Trans-Planckian Censorship Conjecture
  [Blamart-Laliberte-Brandenberger 23][Brandenberger-PMH-Kawai-Shao 24]

conclusion

LEET breaks down at scrambling time for Hawking radiation.

Alternative proposal

- Spacetime uncertainty turns off Hawking radiation at scrambling time.
- Black holes are essentially classical.
- Hawking temperature not modified → same BH entropy, etc.
- Spacetime uncertainty blurs the horizon.

  → Other channels of informative radiation (cf. fuzzball)

Thank you!