UV Physics and Hawking Radiation

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How robust is Hawking radiation?

Is effect theory valid for Hawking radiation?

Hawking radiation involves trans-Planckian modes ['t Hooft 85], but…

1. Not Lorentz invariant
2. Nice-slice argument $\Rightarrow$ effective theory is valid (?)
3. Robust even for modified (non-inv.) dispersion relations

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3. Robust even for modified (non-inv.) dispersion relations

$\exists$ Lorentz-invariant UV energy scale $\Rightarrow$ UV physics is needed.

A. UV cutoff $\Rightarrow$ Hawking radiation turned off. [PMH-Kawai 22]

B. non-renormalizable interactions dominate. [PMH-Kawai-Yokokura 21]

C. UV-IR effects [PMH-Kawai 22]

black hole formation

characteristic scale:

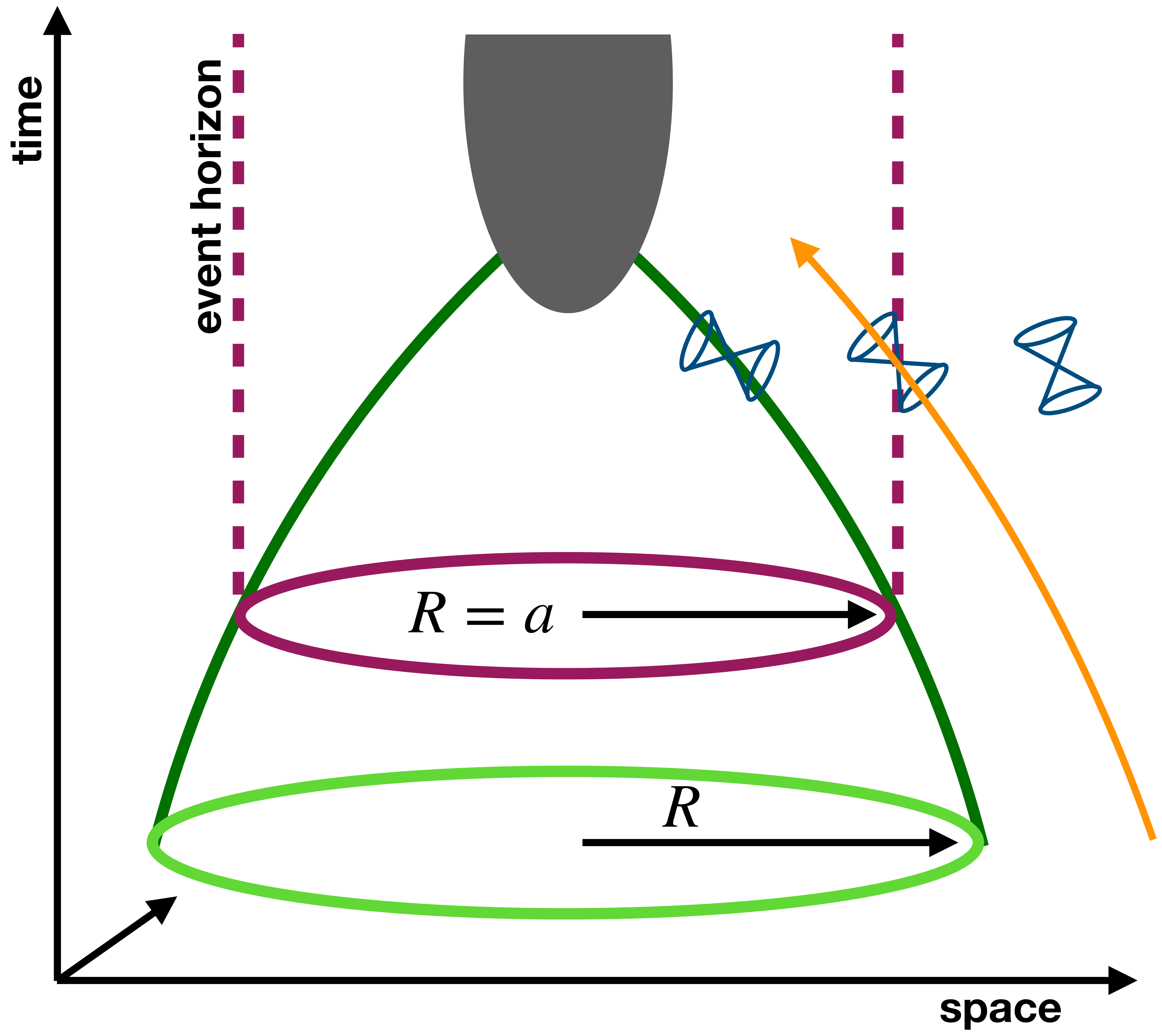
Schwarzschild radius (horizon)

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

$(c = 1, \quad \hbar = 1, \quad G_N = \ell_p^2 = 1/M_p^2)$

Estimates in powers of

$$(a/\ell_p)^n \quad \text{or} \quad (\ell_p/a)^n$$



Light-cone coordinates:

Distant observers:

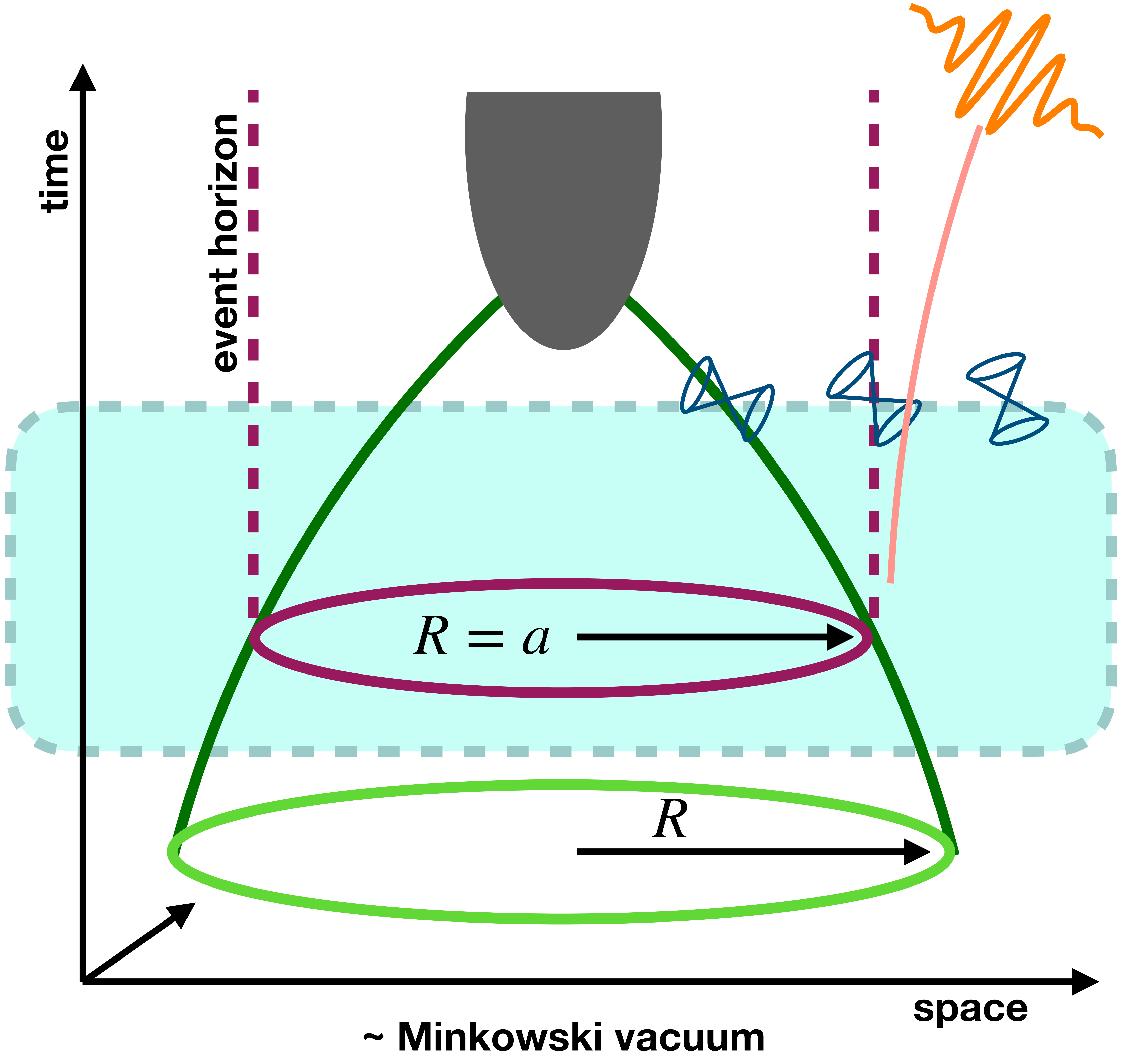
$$u = t - r, \qquad v = t + r$$

Freely falling observers:

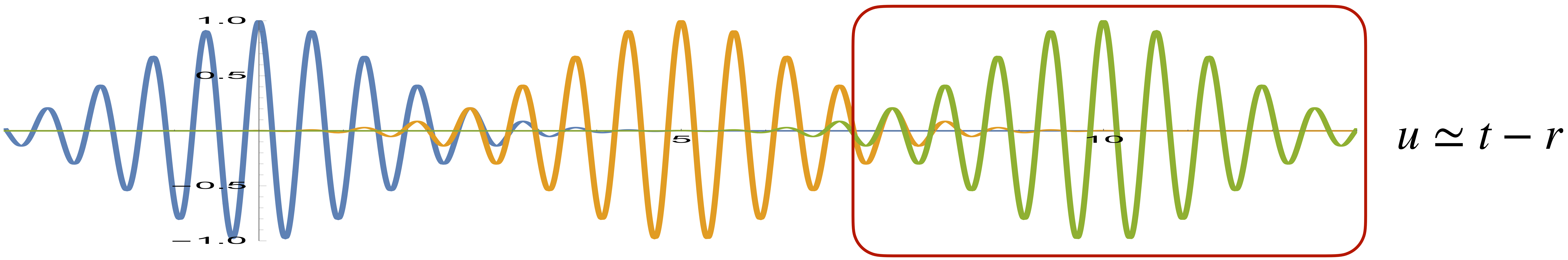
$$U = -2ae^{-u/2a}$$

$$\Rightarrow \quad \frac{dU}{du} = e^{-\frac{u}{2a}}$$

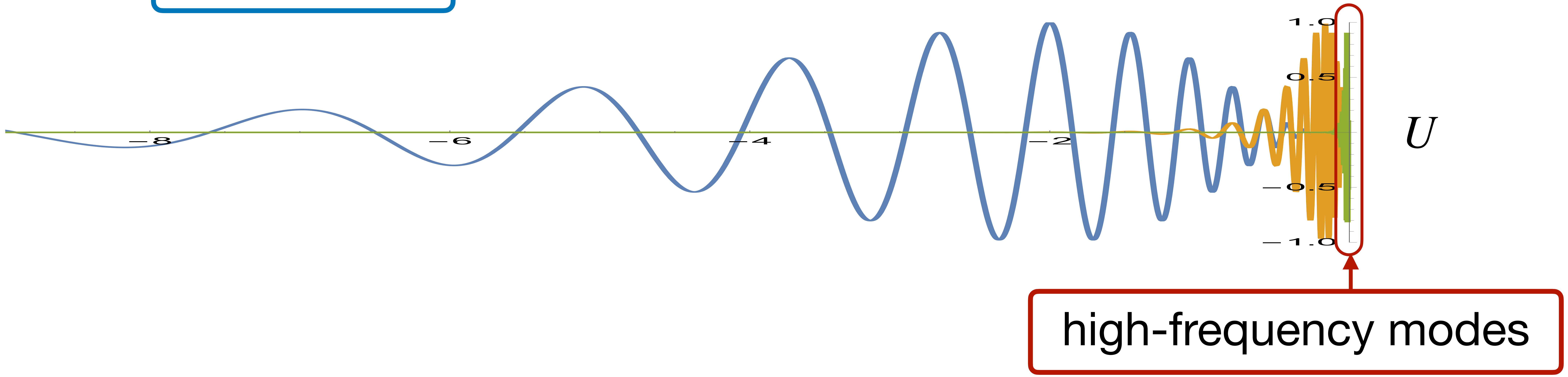
$U \in (-\infty, 0)$ for $u \in (-\infty, \infty)$



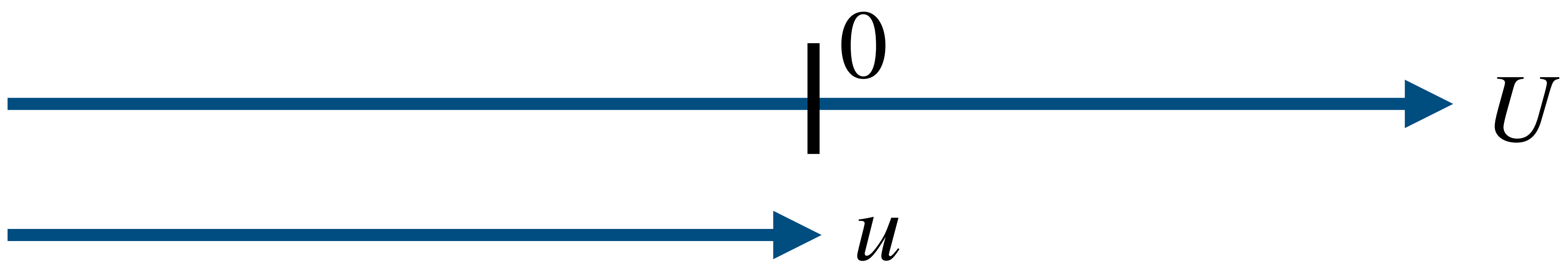
natural wave packet for distant observers (in u-coordinate)



Due to $\boxed{\dfrac{dU}{du} \simeq e^{-u/2a}}$, for freely falling observers (in U-coordinate)



Hawking radiation [Hawking 74]



$$U \simeq -2ae^{-u/2a}$$

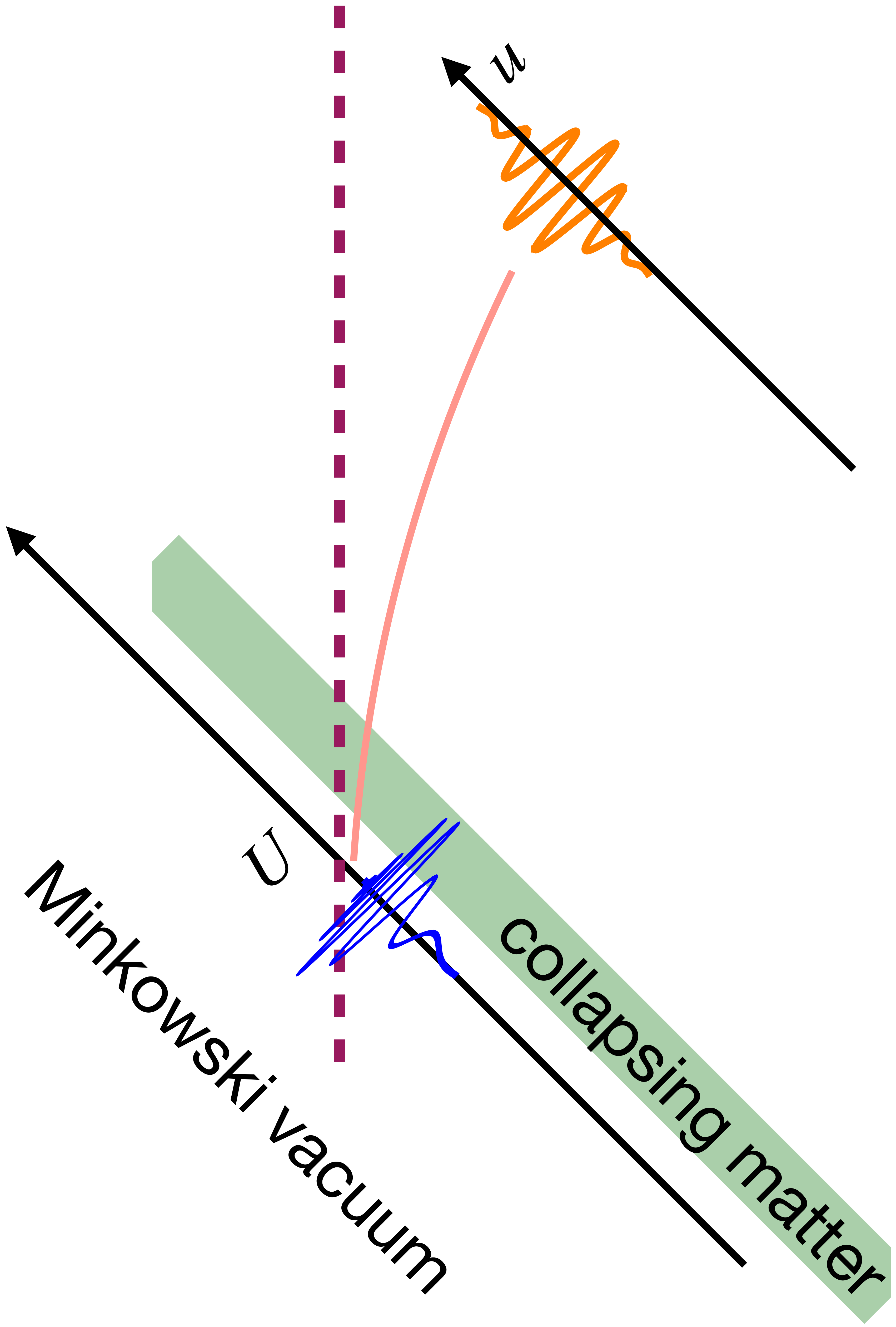
$$\Omega \sim \omega \frac{du}{dU} \simeq \frac{1}{a} e^{u/2a} \quad \text{for} \quad \omega \sim 1/a$$

(Ignore the interaction between outgoing modes and collapsing matter.)

$+$ modes in u

$\rightarrow$ both $+$ and $-$ modes in U

$\Rightarrow$ particle creation



information loss?

Decoupling theorem:

Quantum Gravity is not needed

unless there are **high-energy events.**

Nice-slice argument ⇒ no high-energy event.

Hawking: "**Effective theory** predicts information loss."

Q: Are there high-energy events?

literature review

- Hawking radiation [Hawking 76]
- “Sonic analog of black holes…” (analog gravity) [Unruh 95]
- “Hawking radiation without trans-Planckian frequencies” [Brout-Massar-Parentani-Spindel 95]
- “Hawking radiation and high-frequency dispersion” [Corley-Jacobson 96]
- “Hawking radiation and ultraviolet regulators” [Hambli-Burgess 96]
- “On the universality of the Hawking effect” [Unruh-Schutzhold 04]
- “Insensitivity of Hawking radiation to an invariant Planck-scale cutoff” [Agullo-Navarro-Salas-Olmo-Parker 09]

literature review

- microscopic states counted for BH entropy in string theory [Strominger-Vafa 96]
- BH complementarity? [Susskind-Thorlacius-Uglum 93]
- incompatibility of unitarity, locality, causality in **EFT** — paradox sharpened [Mathur 09, Braunstein-Pirandola-Zyczkowski 09, Almheiri-Marolf-Polchinski-Sully 12]
- quantum entanglement → geometry (AdS/CFT duality) [Maldacena 01, Ryu-Takayanagi 06, Van Raamsdonk 10]
- geometry and entropy intertwined via entanglement — generalized entropy, quantum extremal surface, entanglement wedge [Engelhardt-Wall 14]
- "Island" transferred to a subspace of radiation Hilbert space [Penington 19, Almheiri-Engelhardt-Marolf-Maxfield 19] *Mechanism? Non-local?* [Martinec 22]

nice-slice argument

[Polchinski 95]

The curvature $\sim \mathcal{O}(1/a)$.

Adiabatic theorem $\Rightarrow$

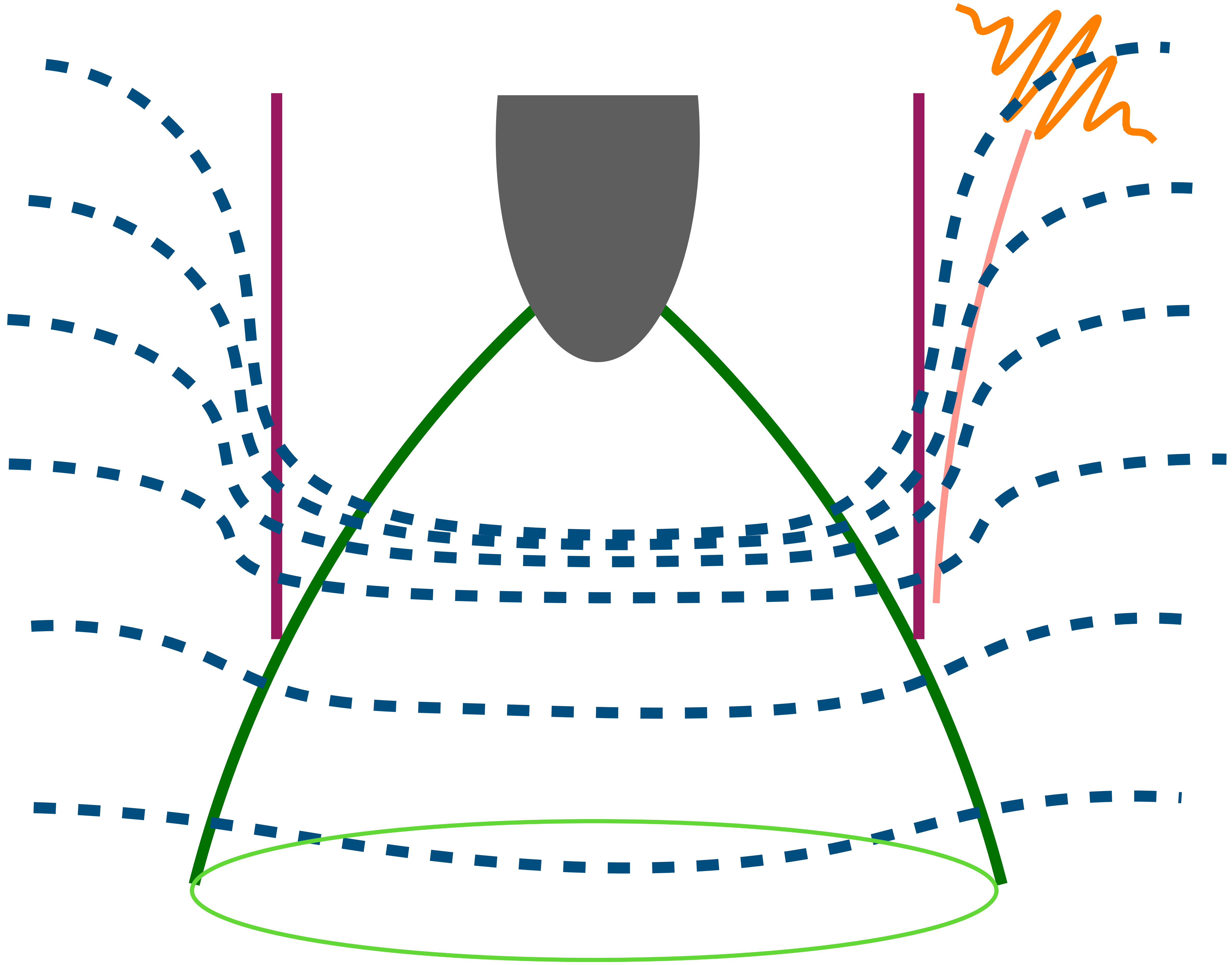
If the initial state is vacuum,

excitations of energies $\lesssim \mathcal{O}(1/a)$

from time evolution.

$\Rightarrow$ Effective theory remains valid.

Decoupling theorem



nice-slice argument

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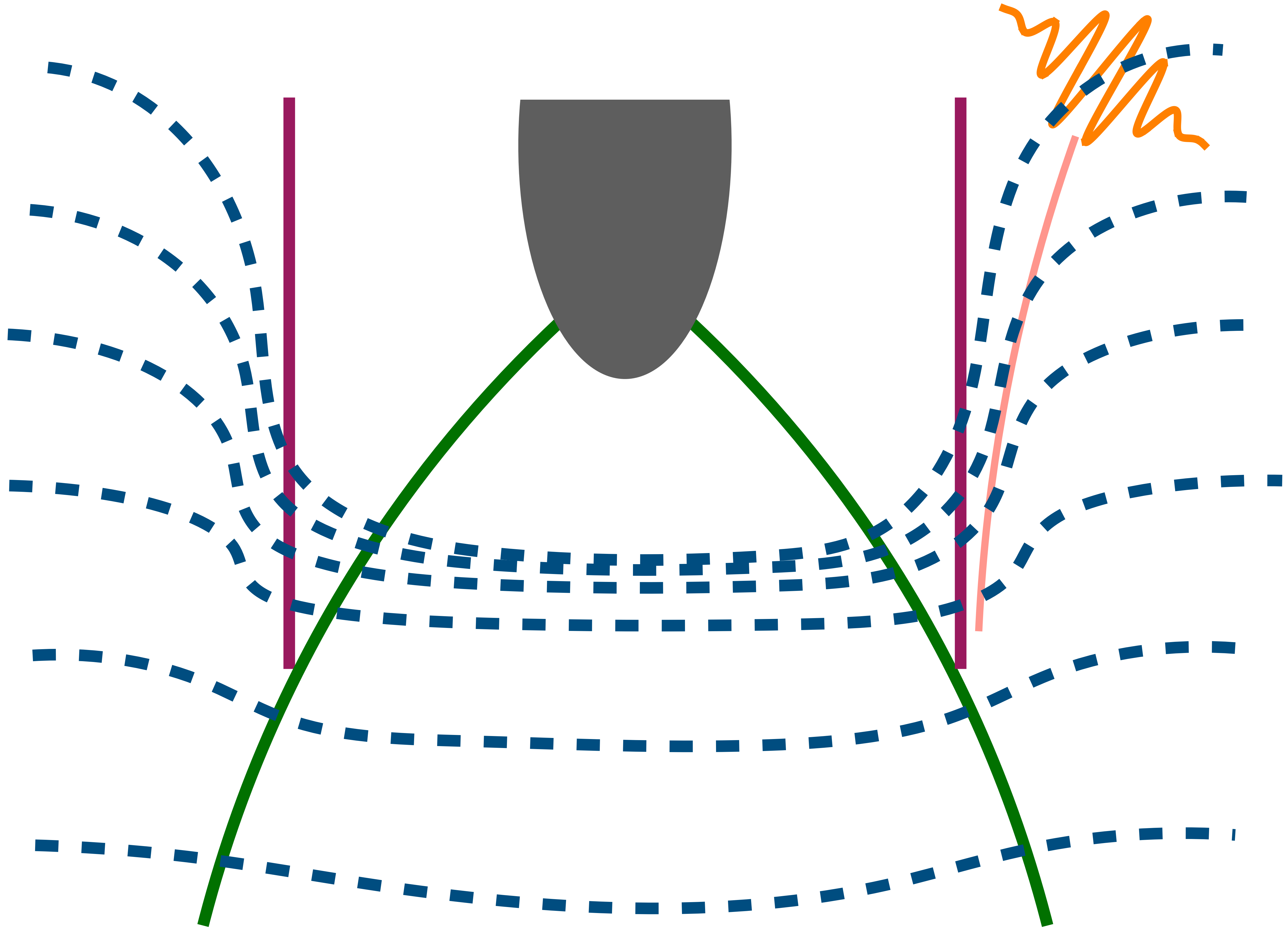
Decoupling theorem $\leftarrow$ **loophole**



Effective theory breaks down for trans-Planckian observations.

Lorentz-invariant UV cutoff

[PMH-Kawai 22]

$\exists$ Lorentz-invariant high-energy scale:

Large c.o.m. energy btwn bckgrd and outgoing quant. fluctuations

$\rightarrow$ UV physics (QG) is relevant for outgoing quant. fluctuations.

If UV cutoff $M_p^2 \geq P_U P_V' \sim \Omega \cdot 1/a$ $\quad\Rightarrow\quad$ $\boxed{\Omega \leq M_p^2 a}$

Nice-slice argument still holds: no high-energy event in effective theory.

UV theory needed for Hawking particles as “Wheeler’s delayed choice”.

trans-Planckian problem revisited

Particles of energies $\omega \sim 1/a$ at large distances have arbitrarily larger energies at the horizon at large u:

$$\Omega \sim \omega \frac{du}{dU} \simeq \frac{1}{a} e^{u/2a}$$

$\left(\ell_p = \text{Planck length} = 1/M_p \right)$

$\left(\ell_p \sim 10^{-35} m, \quad a_\odot \sim 3000 m \right)$

At the **scrambling time** $u \sim na \log(a^2/\ell_p^2),$

it is **trans-Planckian** for $n > 2$: $\Omega \sim \left(\frac{a}{\ell_p} \right)^{n-1} M_p \gg M_p^2 a$

UV cutoff turns off HR

[PMH-Kawai 22]

$$\mathcal{N}_{(\omega_0,u_0)} \equiv b^\dagger_{(\omega_0,u_0)} b_{(\omega_0,u_0)}$$

$$\langle 0 | \mathcal{N}_{(\omega_0,u_0)} | 0 \rangle \simeq \frac{1}{e^{4\pi a \omega_0} - 1} \left(\int_{-\infty}^{2a \log(2a\,\Omega_\Lambda)} du\, \rho_{(\omega_0,u_0)} \right)$$

$$\rho_{(\omega_0,u_0)} \equiv \psi^*_{(\omega_0,u_0)} \left(i \frac{\partial}{\partial u} \psi_{(\omega_0,u_0)} \right) - \psi_{(\omega_0,u_0)} \left(i \frac{\partial}{\partial u} \psi^*_{(\omega_0,u_0)} \right)$$

The particle number $\to 0$ when $u_0 \gg 2a \log(2a\Omega_\Lambda)$

Minimal length in QG ⇒ Hawking radiation turned off after scrambling time.

This is the simplest way to resolve the information loss paradox.

comments

Models of Quantum Gravity often have minimal lengths $\Rightarrow$ UV cutoff

$\Rightarrow$ Hawking radiation turned off after scrambling time.

If no UV cutoff:

- Large particle number in Hawking radiation

  due to higher-derivative (non-renormalizable) interactions.

- HR becomes sensitive to the IR cutoff.

higher-derivative interactions

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

Example:

$$g^{\mu_1\nu_1}\dots g^{\mu_{2n}\nu_{2n}} \left(\nabla_{\mu_1}\cdots\nabla_{\mu_n}\phi_1\right)\left(\nabla_{\mu_{n+1}}\cdots\nabla_{\mu_{2n}}\phi_1\right)\left(\nabla_{\nu_1}\cdots\nabla_{\nu_n}\phi_2\right)\left(\nabla_{\nu_{n+1}}\cdots\nabla_{\nu_{2n}}\phi_2\right)$$

$$\longrightarrow \quad \left(g^{uv}\right)^{2n} \left(\nabla_u^n\phi_1\right)^2 \left(\nabla_v^n\phi_2\right)^2$$

$$\longrightarrow \quad E^2 \sim g^{uv} p_u^{(1)} p_v^{(2)} \sim p_U^{(1)} p_V^{(2)} \propto \Omega$$

$$\longrightarrow \quad \mathscr{A} \propto \frac{\Omega^n}{M_p^n}$$

$$\left(1 - \frac{a}{r}\right)^{-1}$$

blue-shifted for given ω

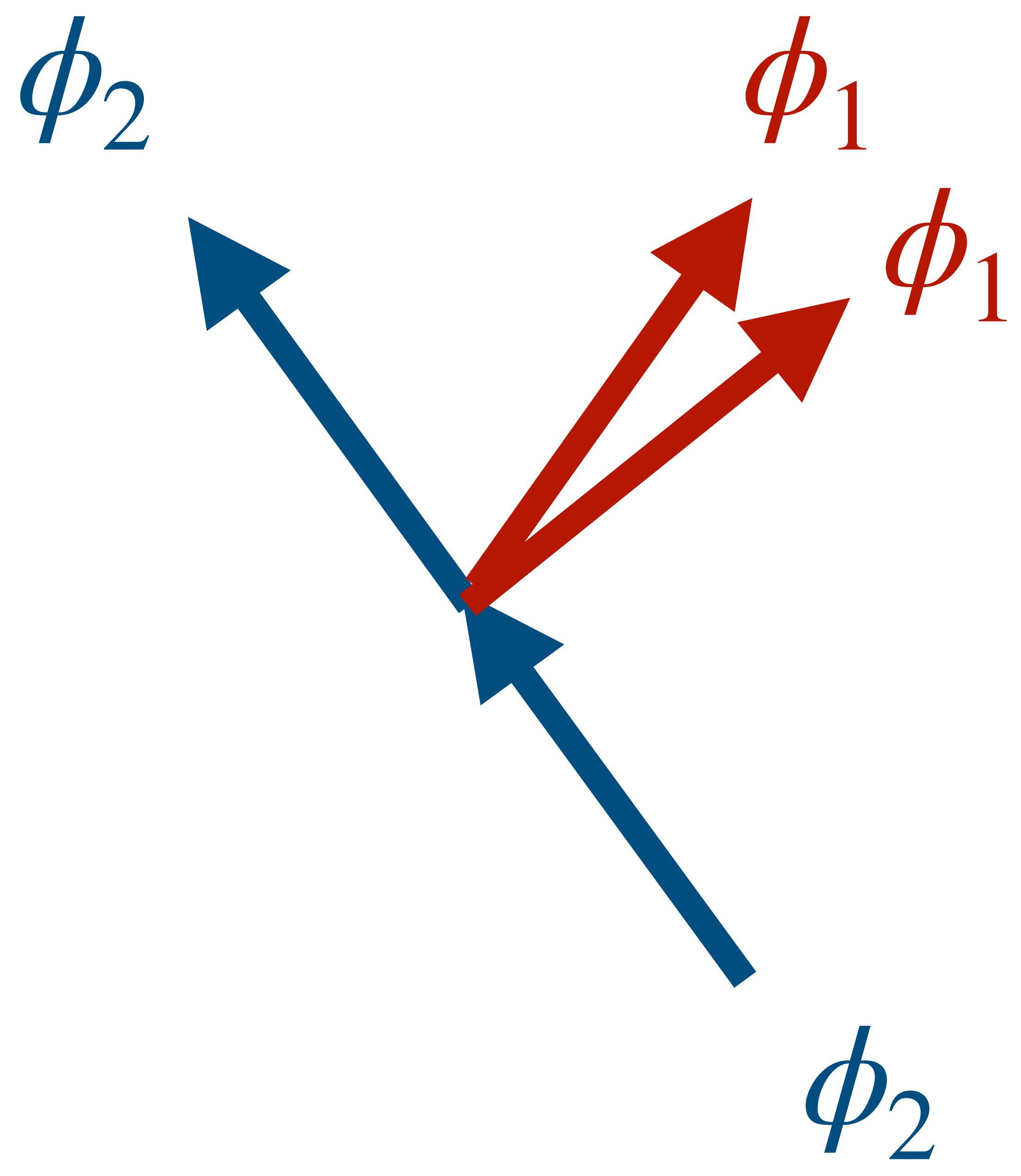
large amplitude of particle creation

[PMH-Yokokura 20, PMH 20, PMH-Kawai-Yokokura 21, PMH-Kawai 22]

For $p_u = \omega \sim 1/a$

$$\mathscr{A} \sim \left(\frac{\ell_p^2}{a^2}\right)^m e^{ku/2a} \quad \text{for some} \quad m, k > 0$$

$\Rightarrow \quad \mathscr{A} \gtrsim \mathcal{O}(1)$ at $u \gtrsim \mathcal{O}\left(a \log\left(a^2/\ell_p^2\right)\right)$



$\Rightarrow$ Higher-derivative interactions $\rightarrow$ higher exponential contributions.

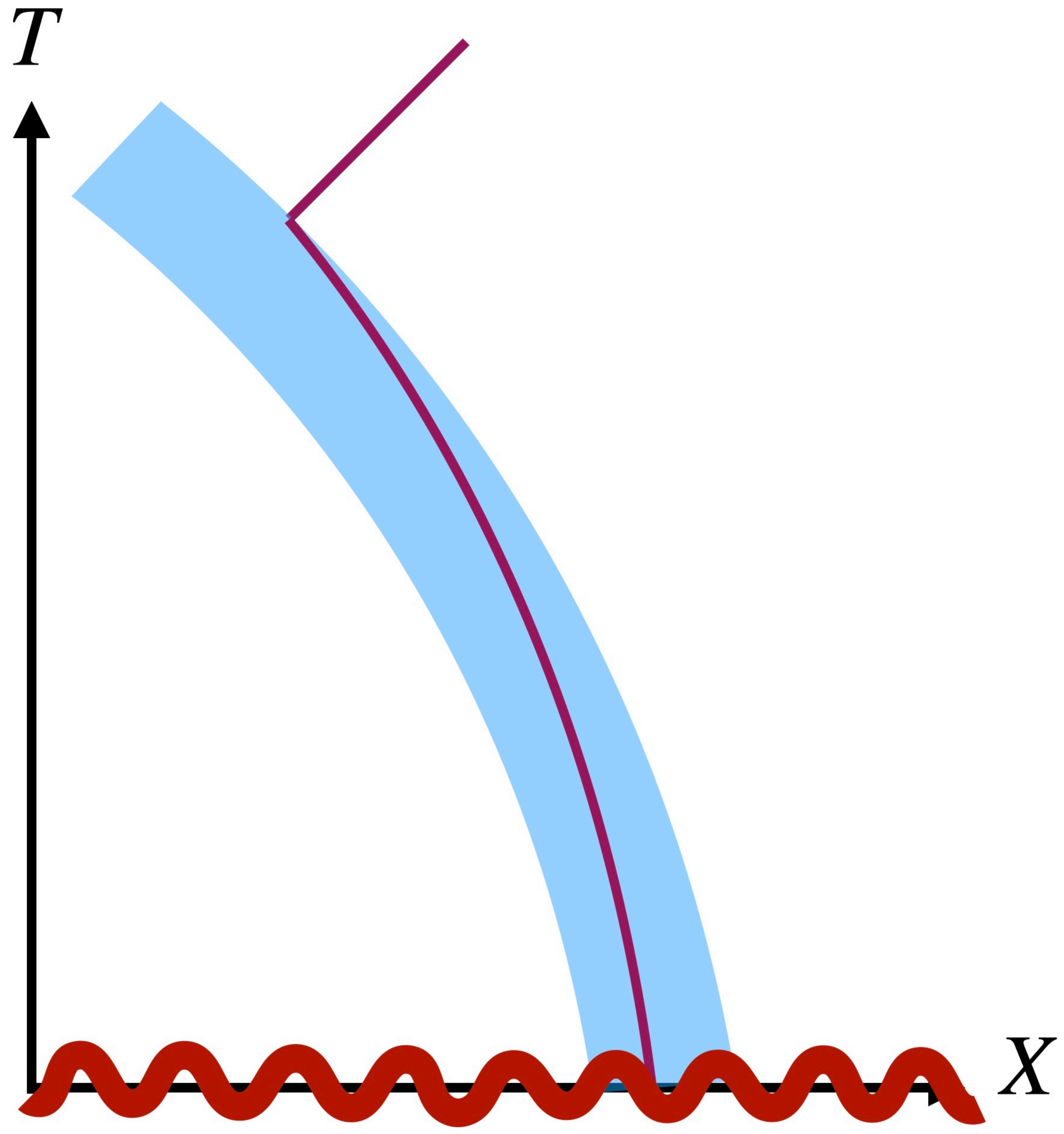
$\rightarrow$ ***Hawking radiation is not a reliable prediction of effective theory.***

UV-IR connection

[PMH-Kawai 22]

- Higher-derivative interactions.
- If not superluminal, high-energy modes are trapped inside the collapsing matter.
- Example:

  For a black hole of the solar mass, at 10 times the scrambling time, the time duration inside the collapsing shell is 10^{1000} × age of universe for $k = 2$.



conclusion

Hawking radiation is sensitive to UV physics.

It is not a valid prediction of effective theory.

A UV cutoff kills Hawking radiation after scrambling time.

Non-renormalizable interactions are important.

No firewall. $\leftarrow$ Different physics for different observers!

$\rightarrow$ It will be very interesting to study Hawking radiation in a QFT on various quantum spaces.

Thank you!