Two-dimensional moving mirrors and the information loss problem

Dong-han Yeom

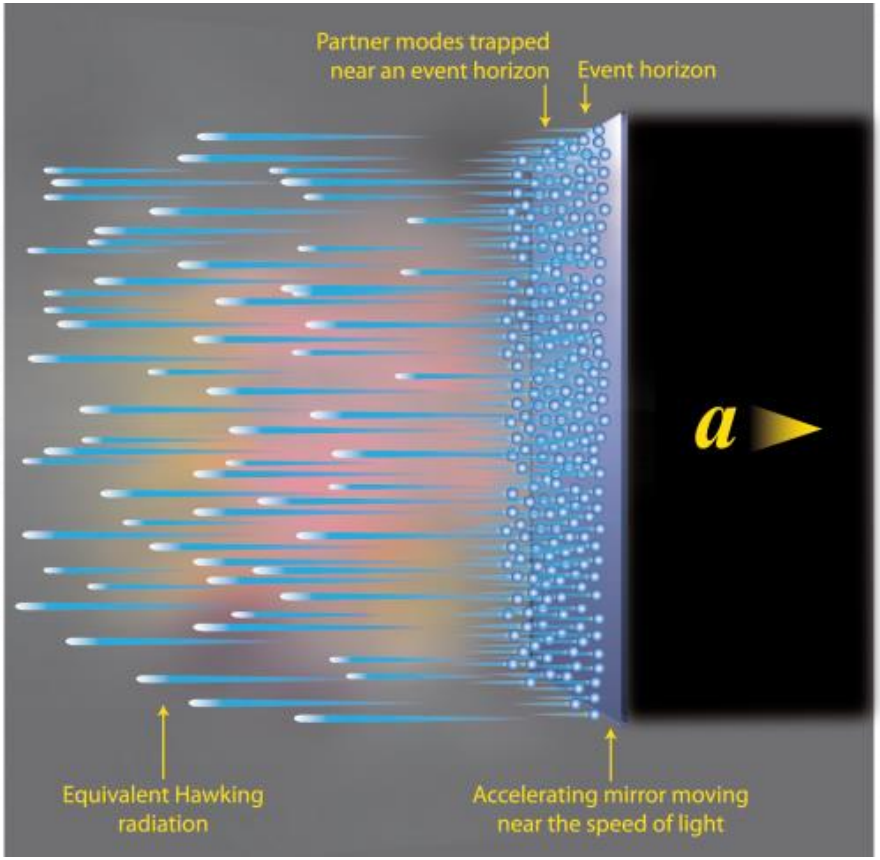
염동한

Asia Pacific Center for Theoretical Physics, POSTECH

How can we test Hawking radiation?

- ✓ Make a black hole? (by accelerator)
- ✓ Make a horizon? (acoustic black hole)
- ✓ **Make a mirror?**

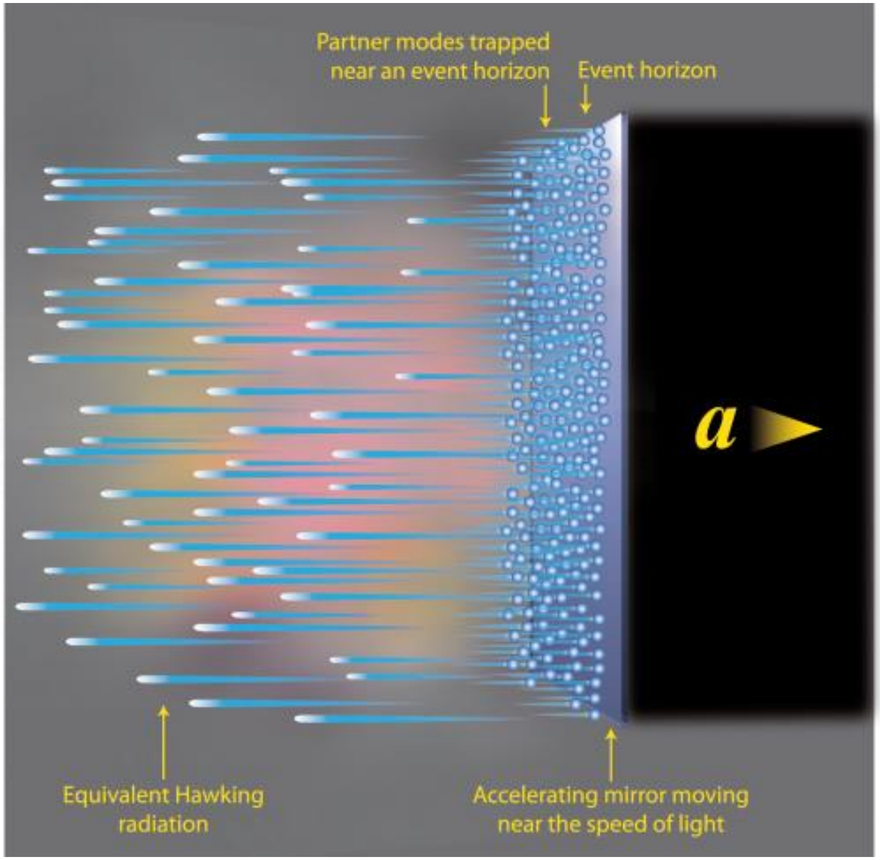
How can we test Hawking radiation?



Accelerating laser-plasma mirror

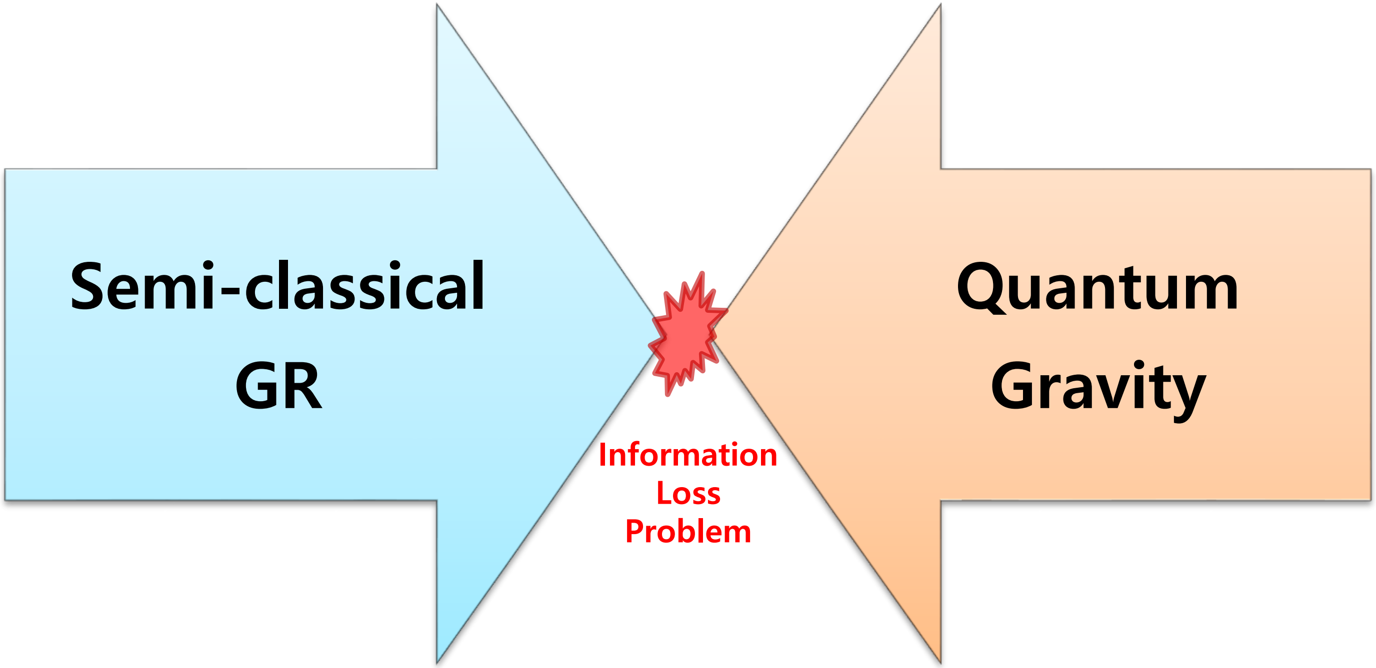
Chen and Mourou, 2017

How can we test Hawking radiation?

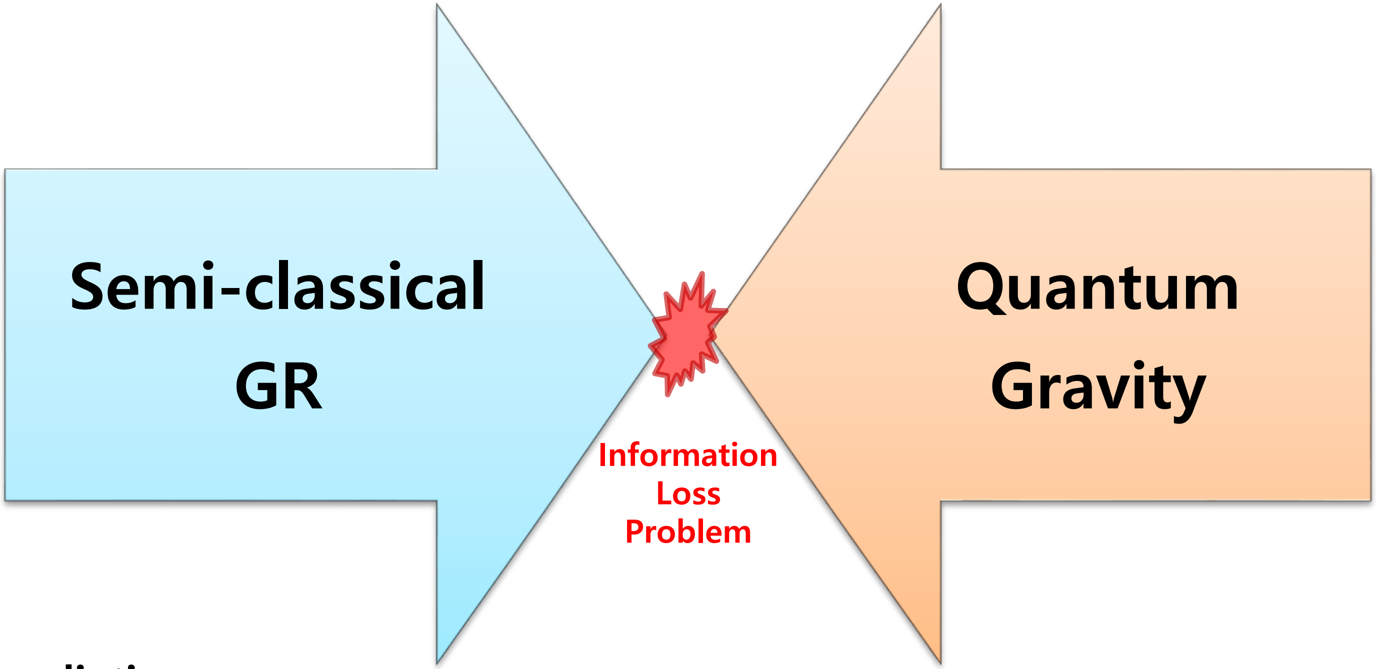


Then, what can we learn from the mirror about black holes?

Mirror (2D) and information loss problem



Mirror (2D) and information loss problem

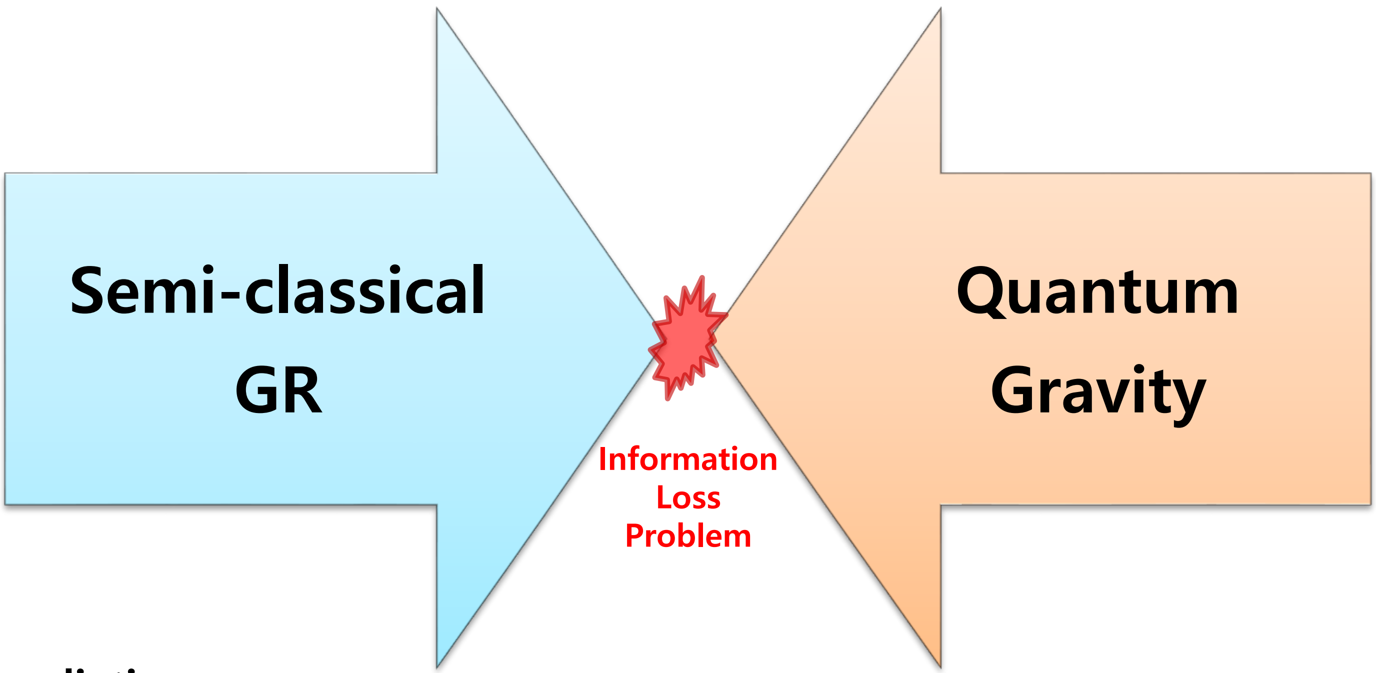


Thermal radiation

Fulling and Davies, 1976

Birrell and Davies, 1982

Mirror (2D) and information loss problem



Thermal radiation

Fulling and Davies, 1976

Birrell and Davies, 1982

Entanglement entropy

Holzhey, Larsen and Wilczek, 1994

Mirror (2D) and information loss problem

We know everything about a mirror!

Thermal radiation

Fulling and Davies, 1976

Birrell and Davies, 1982

Entanglement entropy

Holzhey, Larsen and Wilczek, 1994

Purpose of this presentation

 ~  ~ 

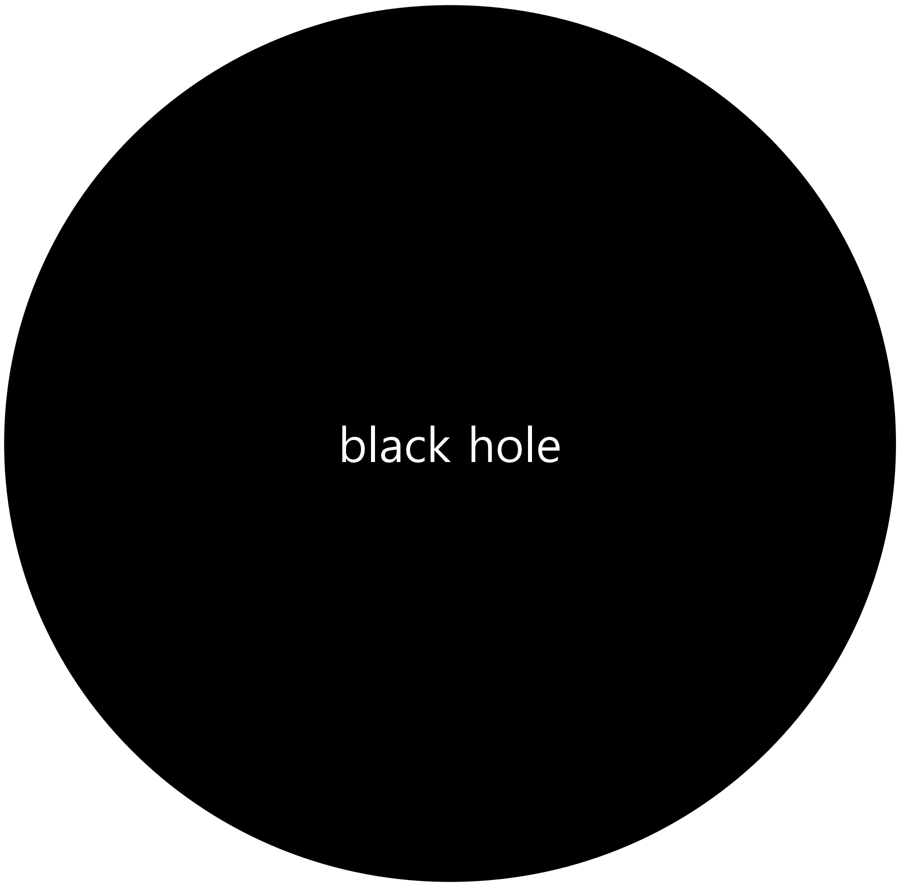
Mirror can mimic a black hole evaporation process.

Hence, we can mimic/test a candidate resolution of the information loss paradox by adjusting the trajectory of the mirror.

Candidate resolutions of the information loss problem

Chen, Ong and DY, Phys.Rept. 603 (2015) 1-45

Black hole evaporation



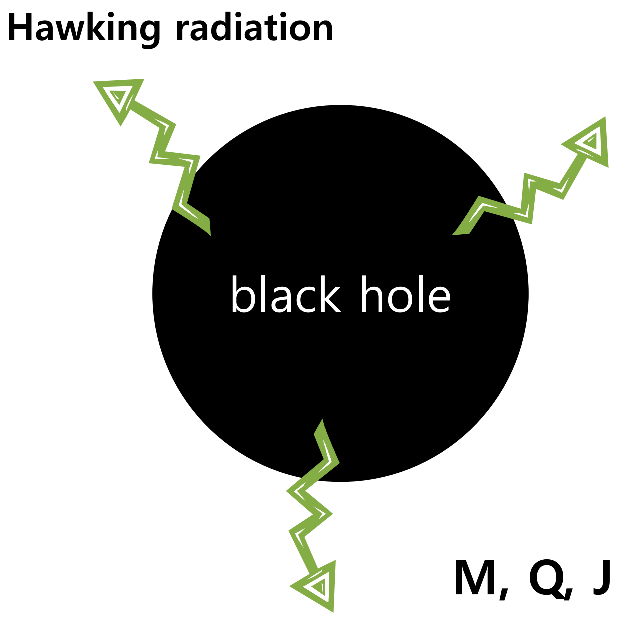
Black holes emit **thermal radiation**, and in the end, it will **disappear**.

$$\frac{dM}{dt} \propto -A\,T^4 \propto -\frac{1}{M^2}$$

The evaporation (mainly) depends on mass, charge, and angular momentum.

Then can we **recover** information, except mass, charge, and angular momentum?

Black hole evaporation



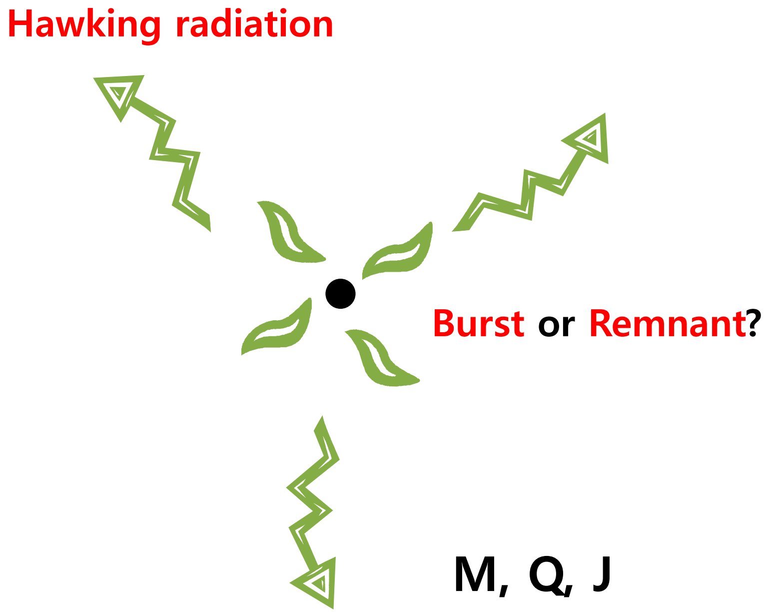
Black holes emit **thermal radiation**, and in the end, it will **disappear**.

$$\frac{dM}{dt} \propto -A\,T^4 \propto -\frac{1}{M^2}$$

The evaporation (mainly) depends on mass, charge, and angular momentum.

Then can we **recover** information, except mass, charge, and angular momentum?

Black hole evaporation



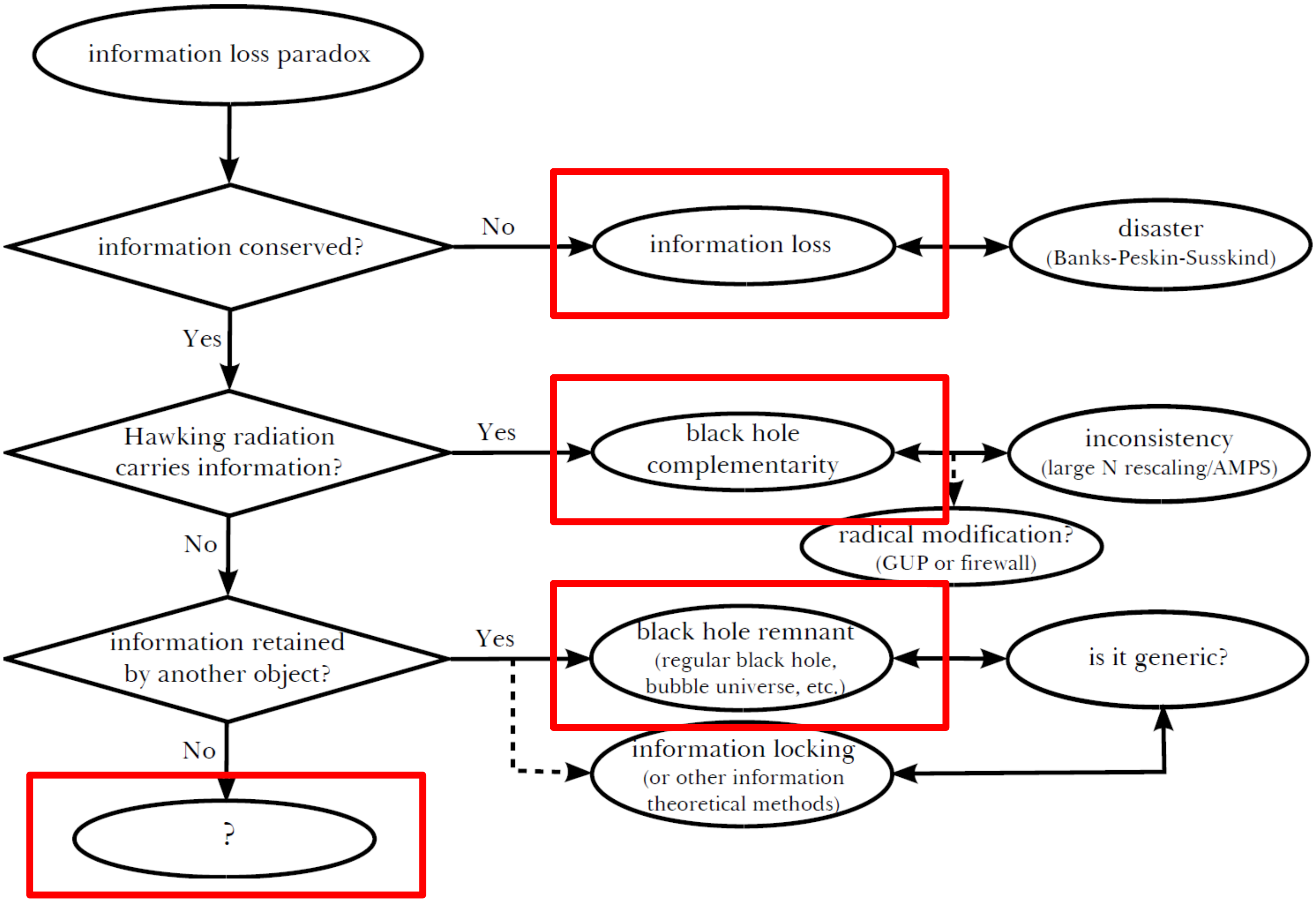
Black holes emit **thermal radiation**, and in the end, it will **disappear**.

$$\frac{dM}{dt} \propto -A\,T^4 \propto -\frac{1}{M^2}$$

The evaporation (mainly) depends on mass, charge, and angular momentum.

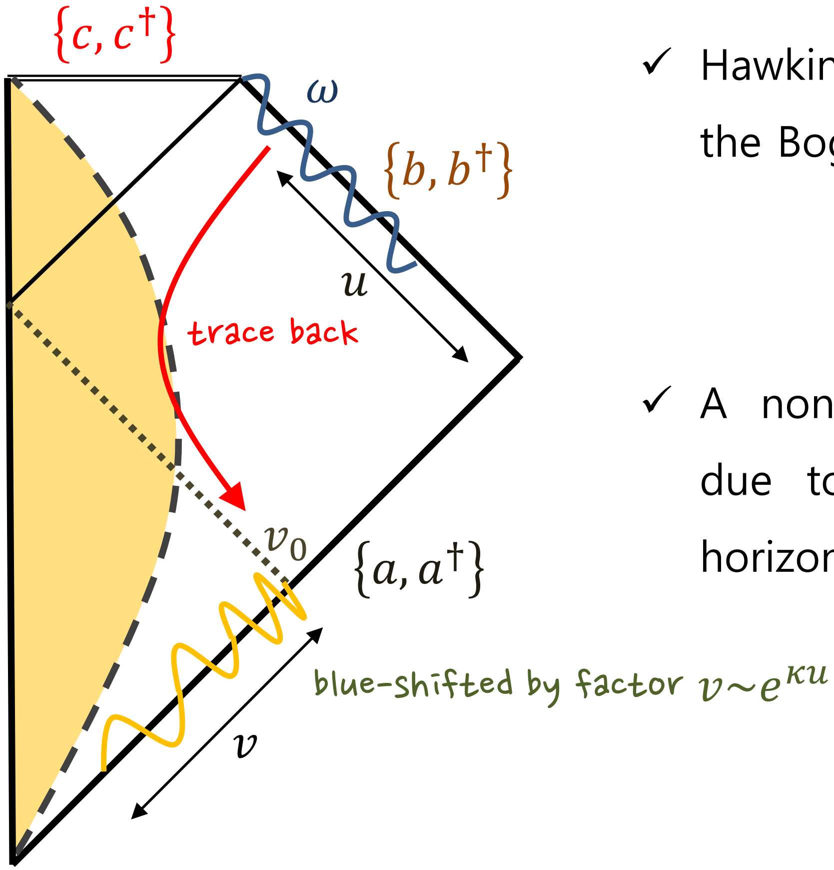
Then can we **recover** information, except mass, charge, and angular momentum?

Possible candidates



Theoretical basics of mirrors

Why there is radiation?



- ✓ Hawking radiation is theoretically estimated by using the Bogoliubov transformation.

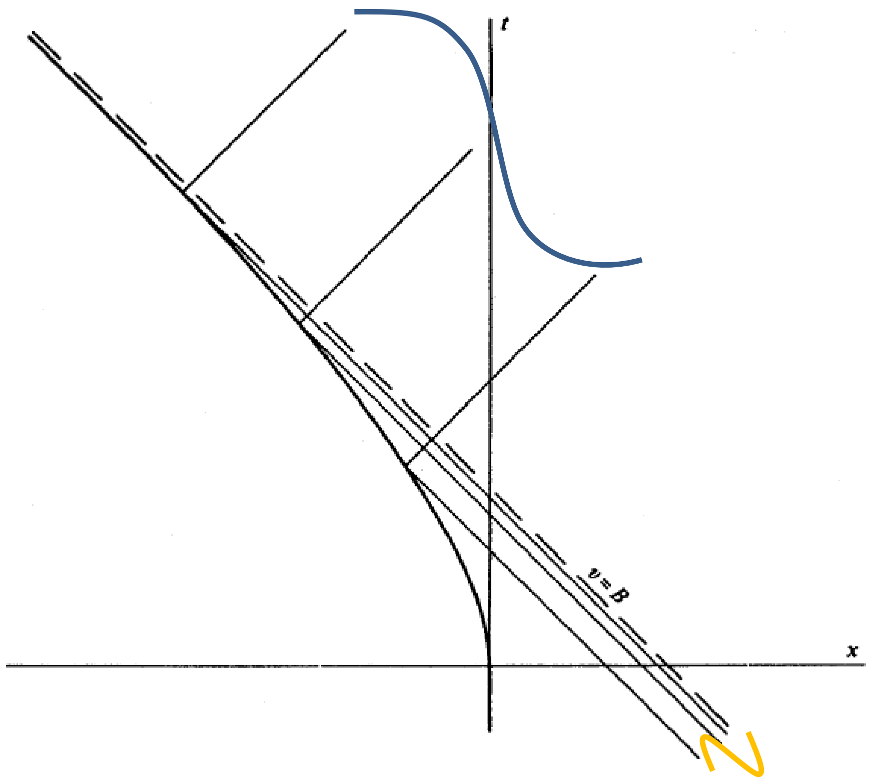
$$\langle n_\omega \rangle = \langle b_\omega^\dagger b_\omega \rangle = \sum_{\omega'} |\beta_{\omega\omega'}|^2$$

- ✓ A non-trivial Bogoliubov transformation is possible due to the **red-shift** of incoming modes by the horizon of a black hole.

$$p_\omega \sim e^{i\omega\kappa^{-1}\ln[(v_0 - v)/c]} \text{ (for } v > v_0\text{)}$$

$$= \sum_{\omega'} [\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} f^*_{\omega'}]$$

Red-shift by a mirror

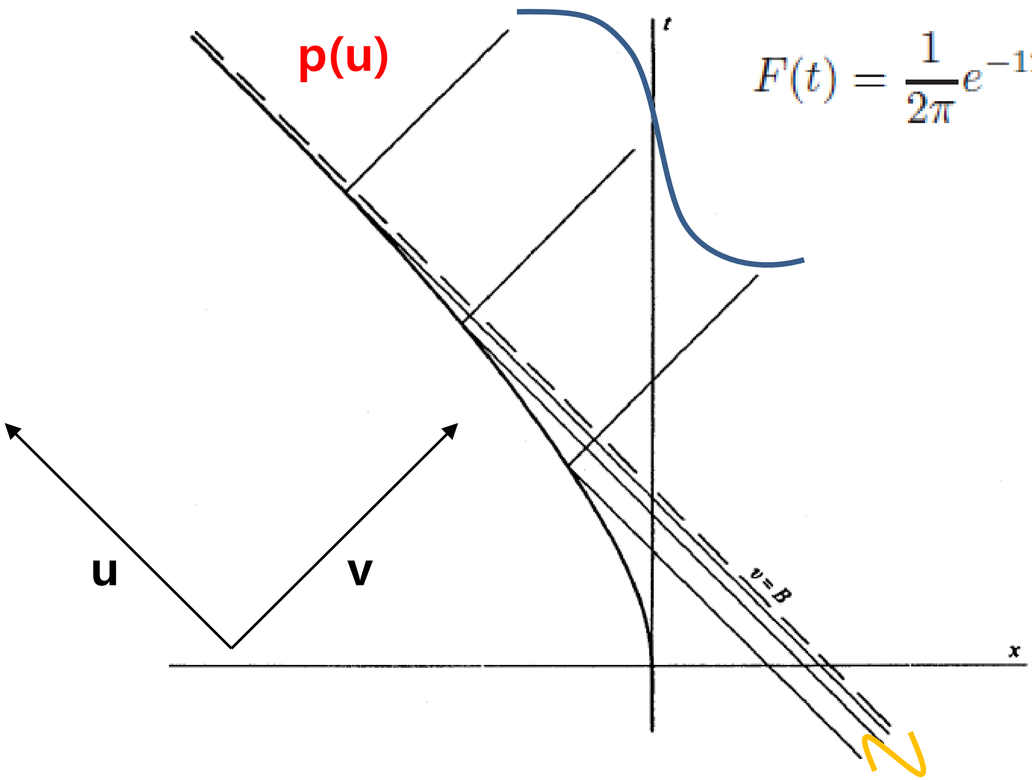


Fulling and Davies, 1976

Birrell and Davies, 1982

- ✓ **A moving mirror** is a surface of the reflecting boundary condition.
- ✓ If the mirror is moving with a constant acceleration, then it generates a thermal radiation.

Red-shift by a mirror



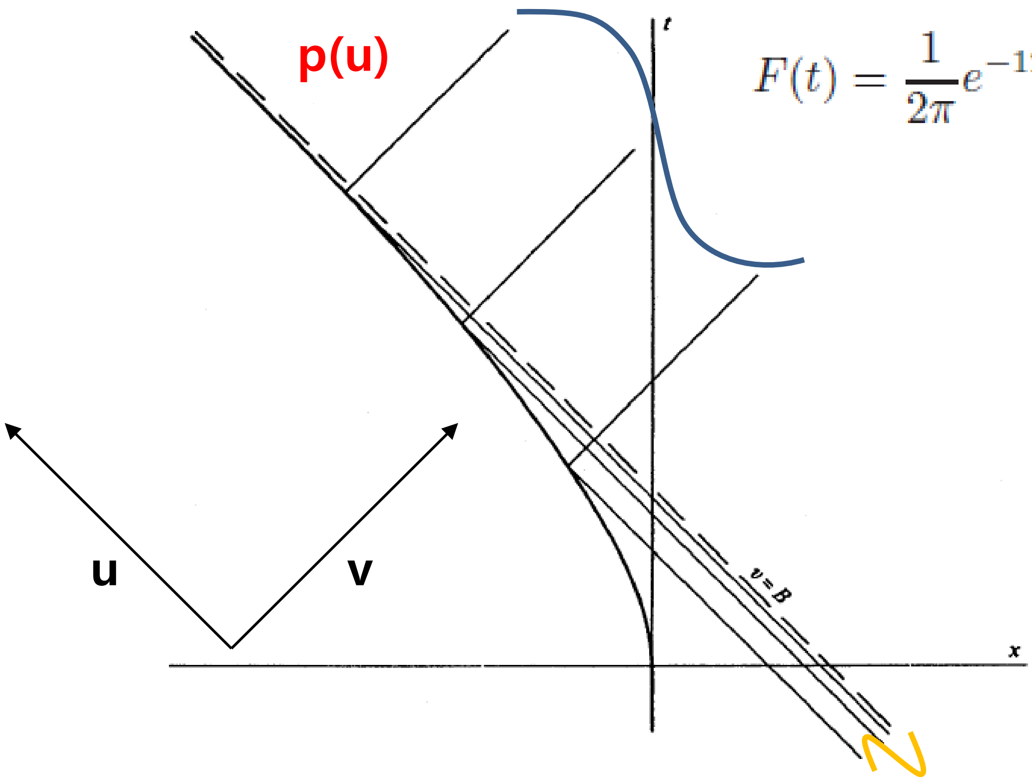
$$F(t) = \frac{1}{2\pi} e^{-12S} \left(6\dot{S}^2 \tanh 6S + \ddot{S} \right) \cosh^2 6S$$

$$S(t) = -\frac{1}{6} \tanh^{-1} \dot{x}(t)$$

Davies, Fulling and Unruh, 1976

- ✓ One can calculate the **out-going energy flux** as a function of the mirror trajectory (for 2D spacetime).

Is there information loss?



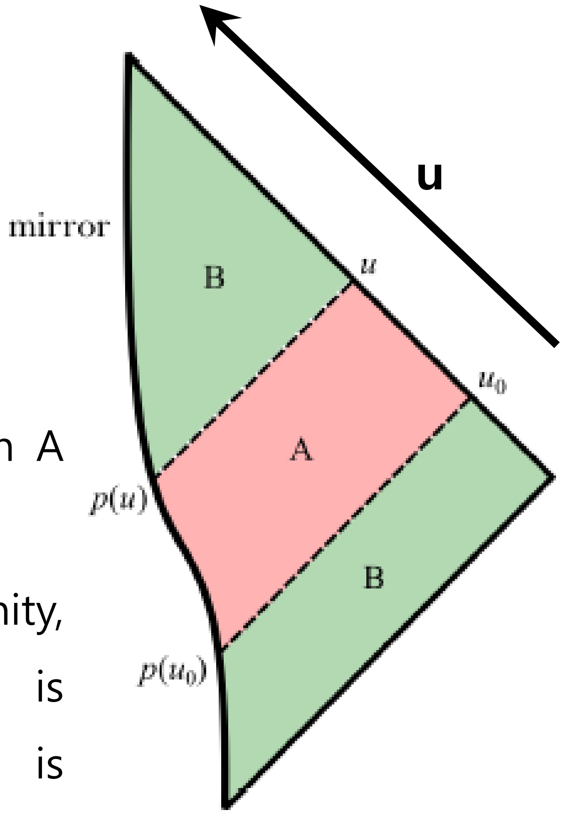
$$F(t) = \frac{1}{2\pi} e^{-12S} \left(6\dot{S}^2 \tanh 6S + \ddot{S} \right) \cosh^2 6S$$

$$S(t) = -\frac{1}{6} \tanh^{-1} \dot{x}(t)$$

Davies, Fulling and Unruh, 1976

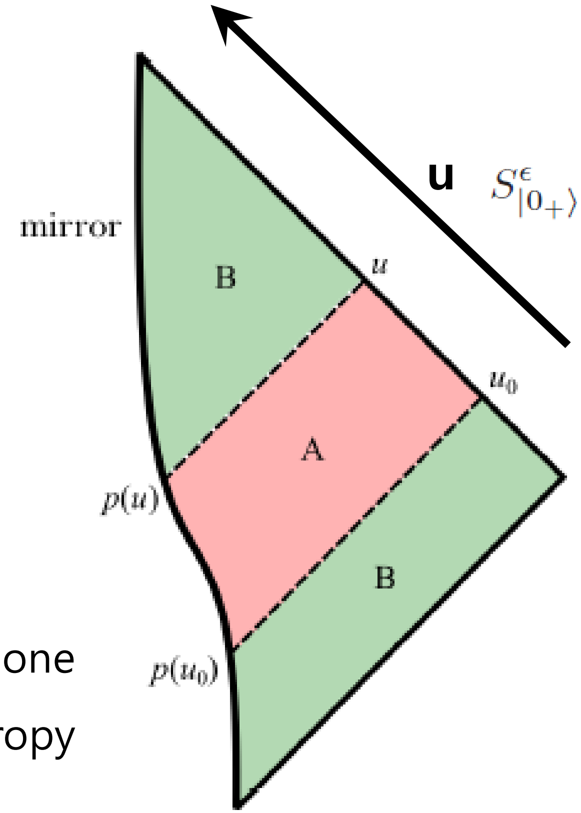
- ✓ Definitely, there should be no information loss in the mirror dynamics.
- ✓ Then what can we learn from the **entanglement entropy**?

Entanglement entropy



- ✓ The entanglement entropy is between A and B.
- ✓ If the first boundary is at the past infinity, then one can interpret that **A** is something **already** radiated and **B** is something **not yet** radiated.
- ✓ The boundary between A and B will be shifted as time goes on.

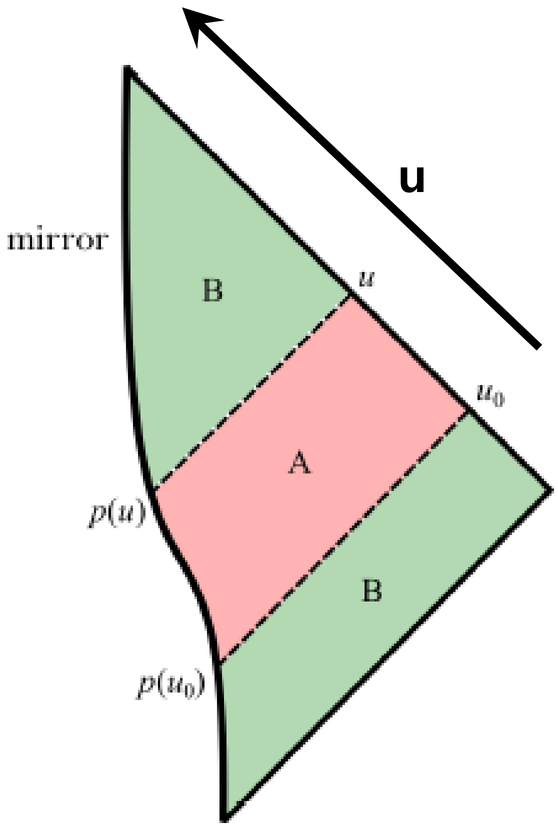
Entanglement entropy



$$S^{\epsilon}_{|0_+\rangle}(A) = \frac{c}{12}\log\frac{(u-u_0)^2}{\epsilon^2}$$

- ✓ In order to apply Page's argument, one can calculate the entanglement entropy as a function of u.
- ✓ In order to obtain a finite result, we need a **renormalization** of the cutoff ϵ**.**

Entanglement entropy formula



After a proper renormalization, we obtain the formula (Holzhey, Larsen and Wilczek, 1994; Bianchi and Smerlak, 2014).

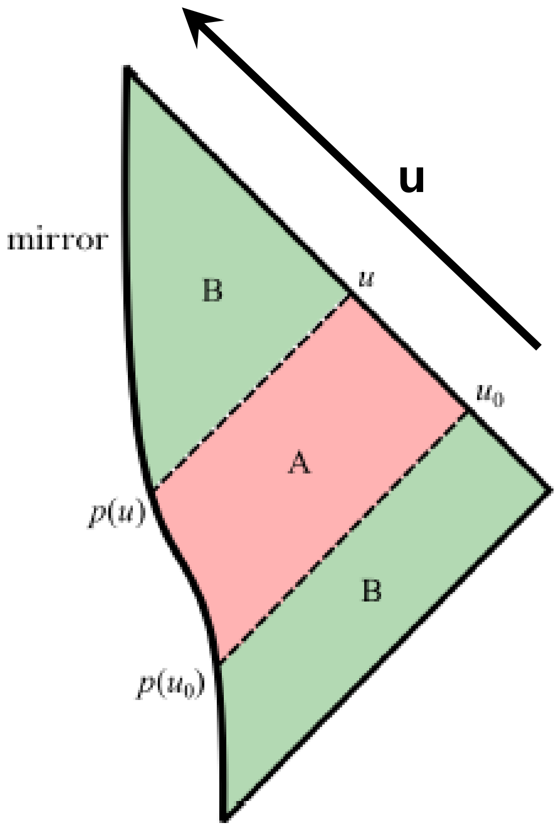
$$S(u) = -\frac{c}{12} \log \dot{p}(u)$$

There are several authors to test the consistency of this paper, e.g., Abdolrahimi and Page, 2015.

Entropy evolution of moving mirrors and the information loss problem

Chen and DY, Phys.Rev. D96 (2017) no.2, 025016

Mirror trajectories



Using this formula, we can test several candidates of trajectories.

$$\begin{aligned} \frac{dS(t)}{dt} &= A \sin^2 \pi \frac{t}{t_{\mathrm{P}}} & 0 \le t < t_{\mathrm{P}}, \\ &= -A \frac{t_{\mathrm{P}}}{t_{\mathrm{f}} - t_{\mathrm{P}}} \sin^2 \pi \frac{t - t_{\mathrm{P}}}{t_{\mathrm{f}} - t_{\mathrm{P}}} & t_{\mathrm{P}} \le t < t_{\mathrm{f}}, \end{aligned}$$

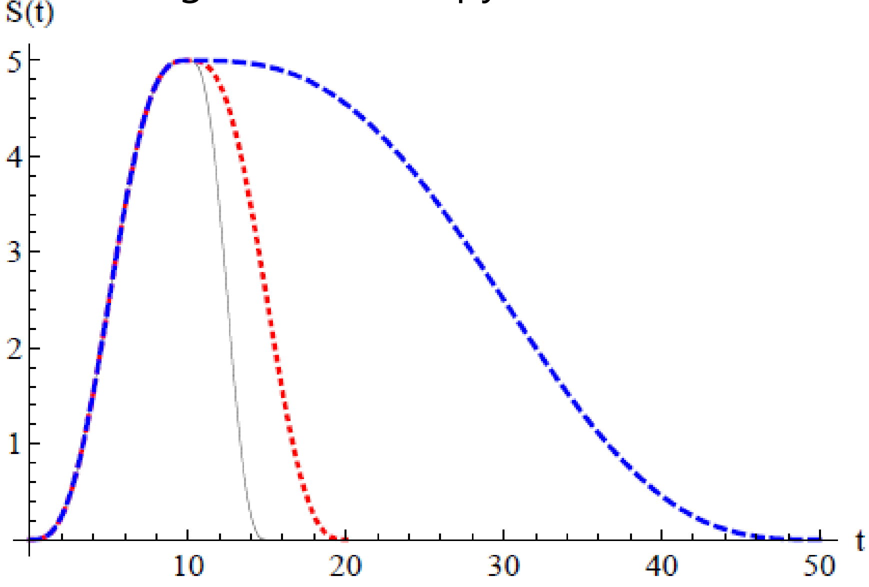
– Suddenly stopping mirror: $t_{\mathrm{f}} = 15$,

– Slowly stopping mirror: $t_{\mathrm{f}} = 20$,

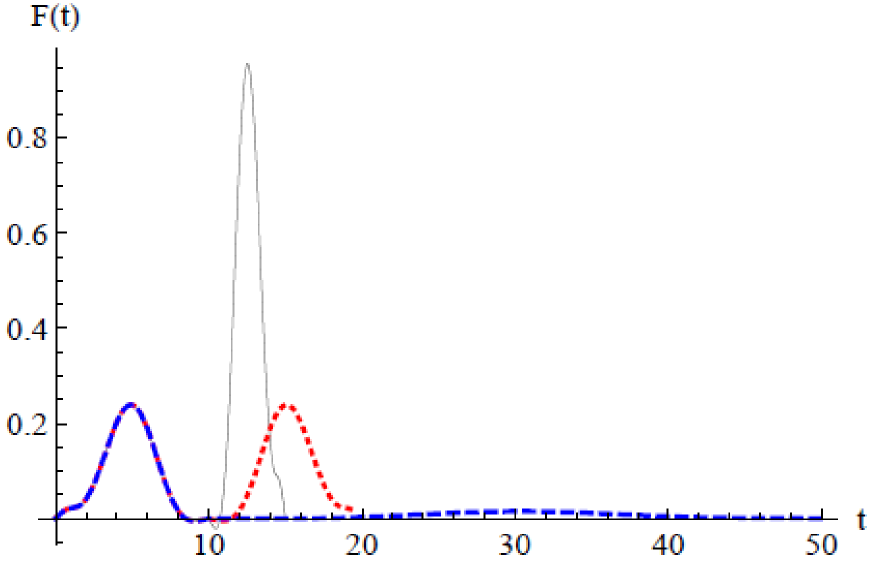
– Long propagating mirror: $t_{\mathrm{f}} = 50$.

Test of scenarios

Entanglement entropy

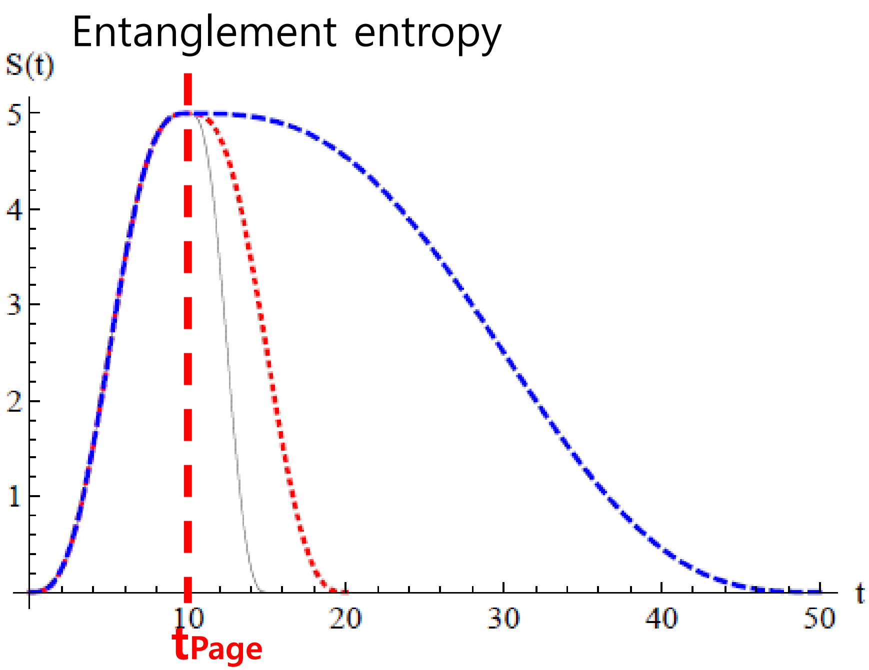


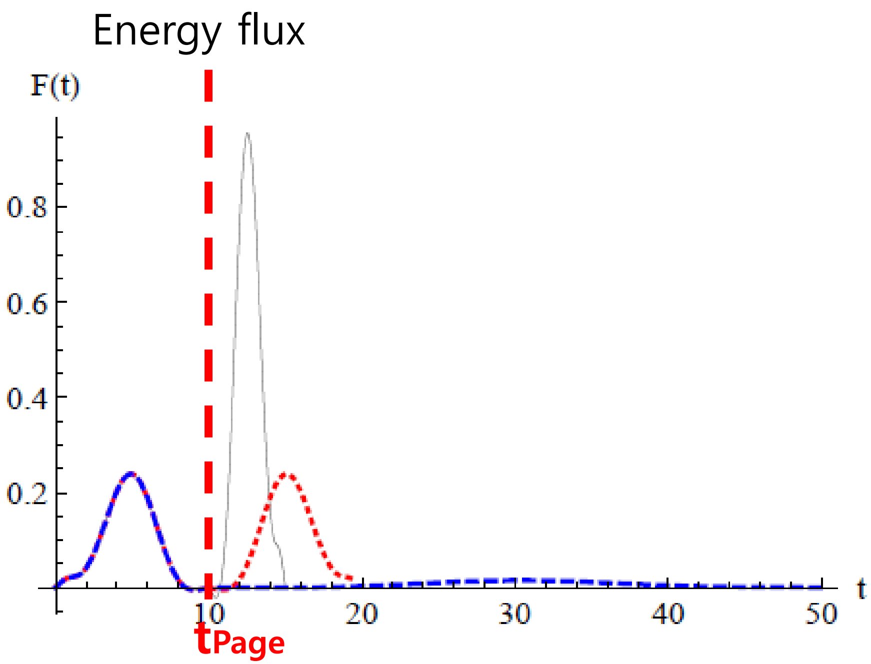
Energy flux



- ✓ Black: Suddenly stopping mirror
- ✓ Red: Slowly stopping mirror
- ✓ Blue: Long propagating mirror

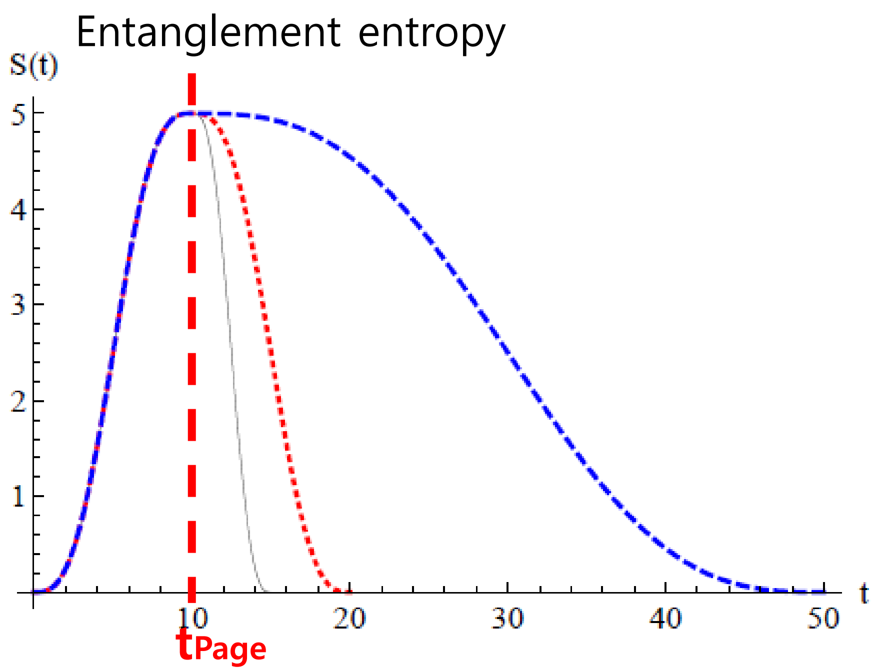
Test of scenarios

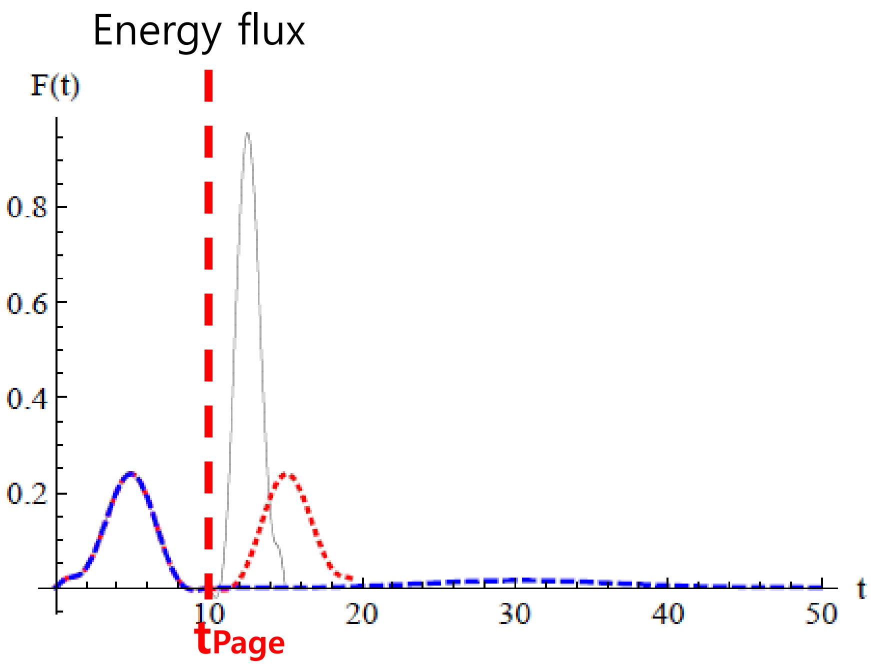




- ✓ Black: Suddenly stopping mirror
- ✓ Red: Slowly stopping mirror
- ✓ Blue: Long propagating mirror

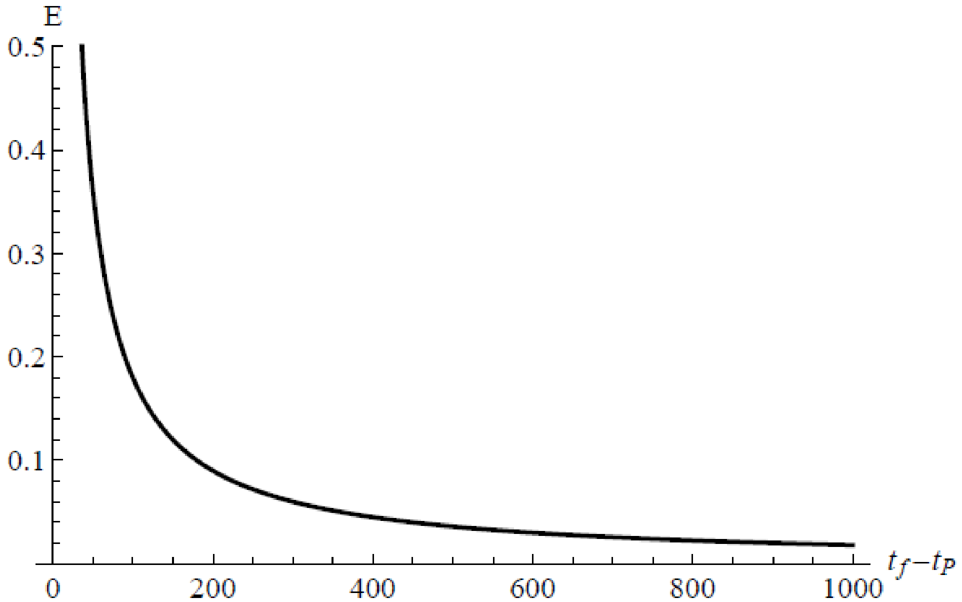
Test of scenarios





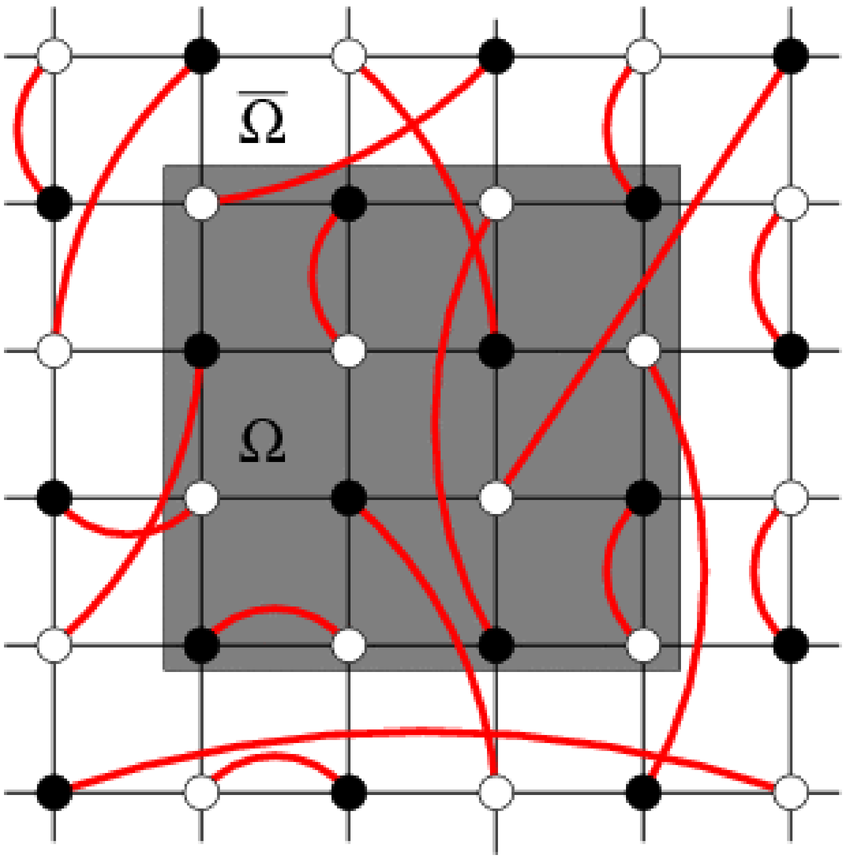
✓ For a suddenly stopping mirror, there is a large amount of energy emission. In general it is too large and hence it cannot mimic the last burst of a black hole.

Test of scenarios

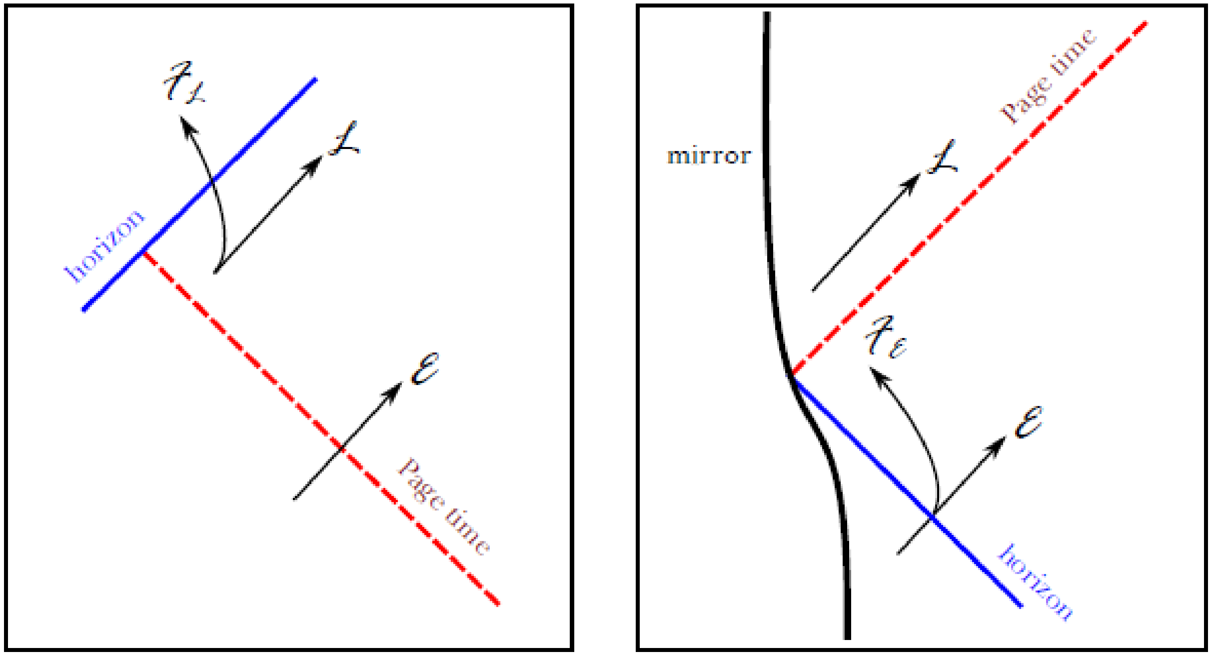


- ✓ For a mirror with very long lifetime, the emitted energy can be arbitrarily small.
- ✓ This mimics the possibility of correlation between vacuum and radiation or the remnant scenario.

Monogamy of entanglement

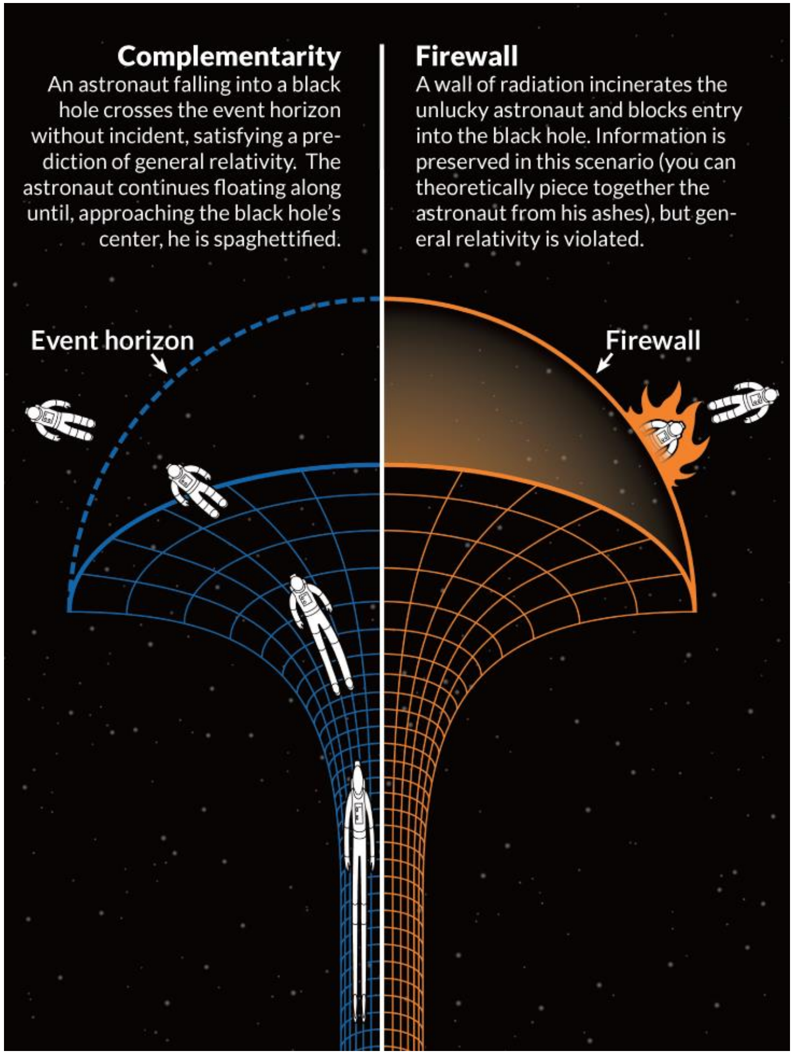


Consistency test: AMPS thought experiments

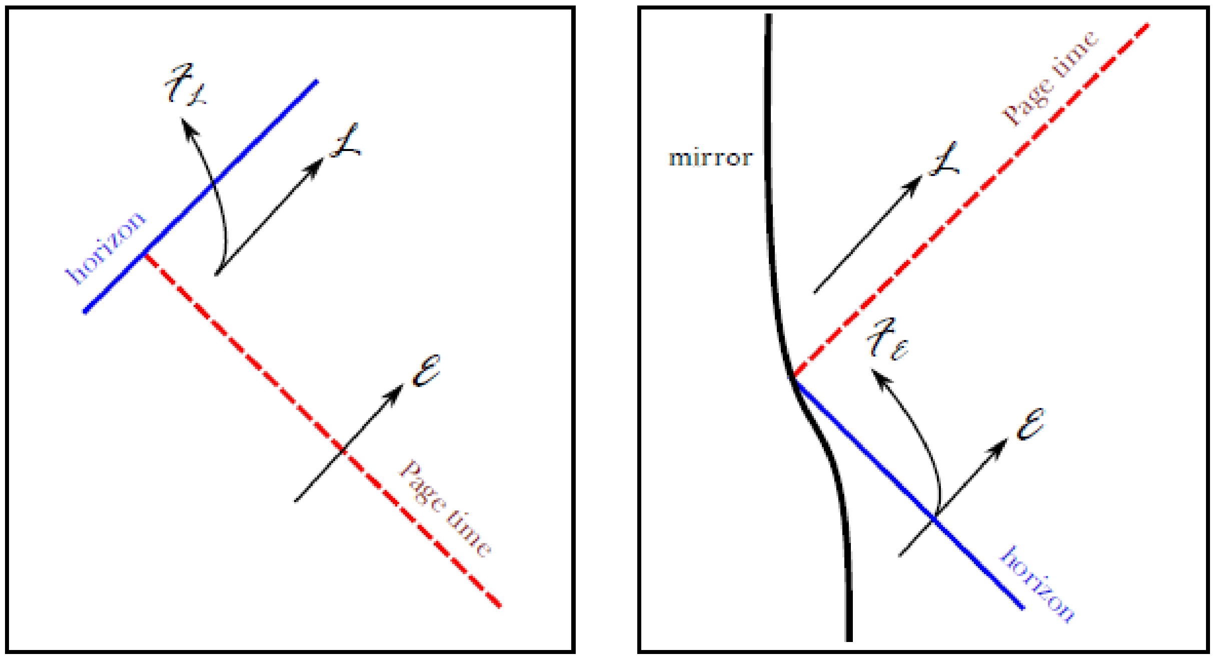


- ✓ Due to the monogamy of entanglements, there should be an effect that break one link.
- ✓ For a black hole case, this is called by (hypothetical) the **firewall**.

Complementarity vs. Firewall



Consistency test: AMPS thought experiments



- ✓ Due to the monogamy of entanglements, there should be an effect that break one link.
- ✓ For a black hole case, this is called by (hypothetical) the **firewall**.
- ✓ There should be a violent effect from a **mirror**: a **firewall-like emission**?

Future perspectives

Future perspectives

✓ We need to theoretically generalize for

1) 4-dimensional
2) finite-sized
3) non-constantly accelerating
4) non-perfectly reflecting moving mirrors
5) in a noisy background.

Future perspectives

- ✓ The entanglement entropy for 4D moving mirrors is a challenging issue.
- ✓ The way to measure the entanglement entropy between the mirror and the radiation is also a difficult problem.