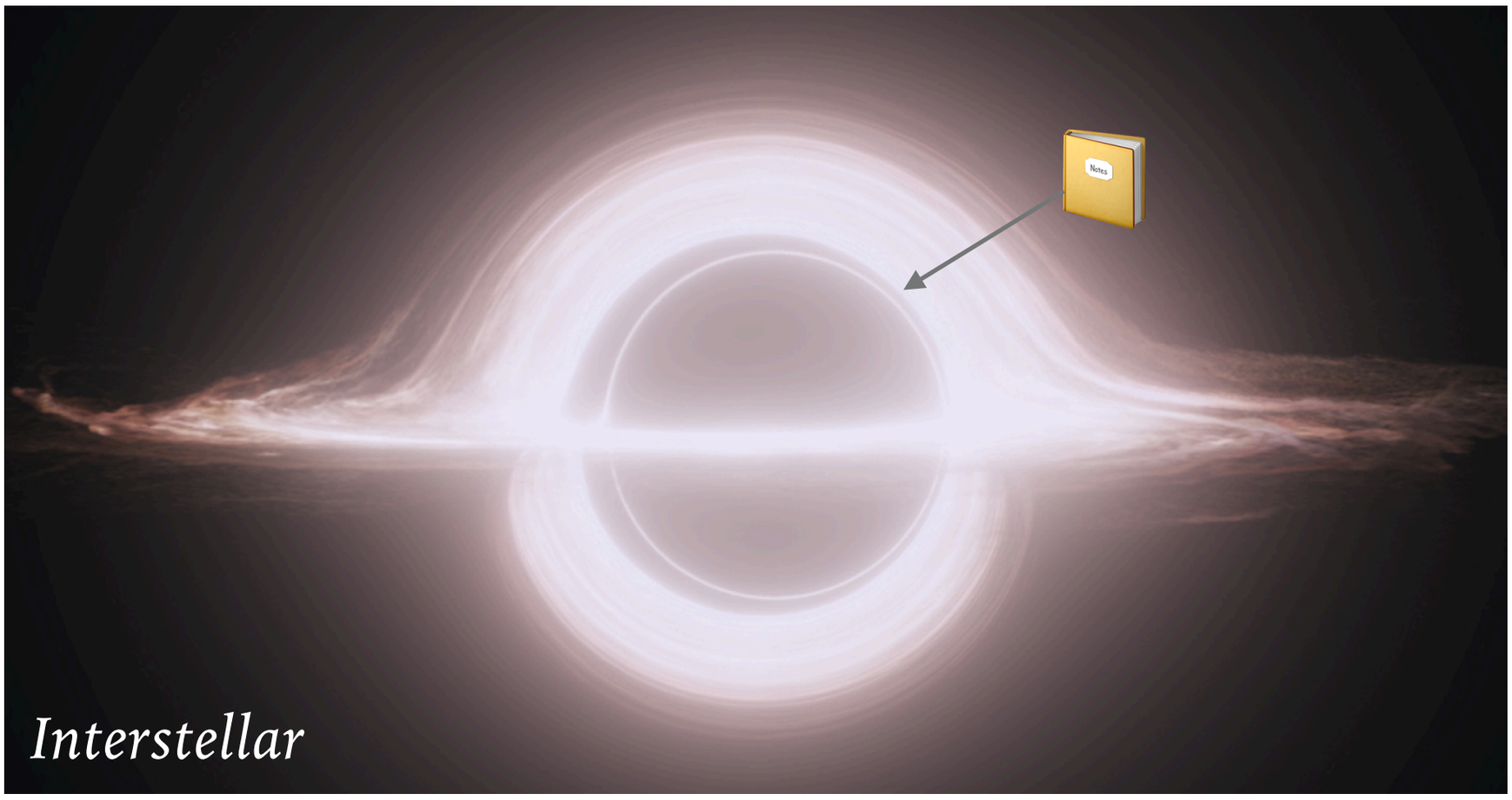

BLACK HOLE INFORMATION PARADOX

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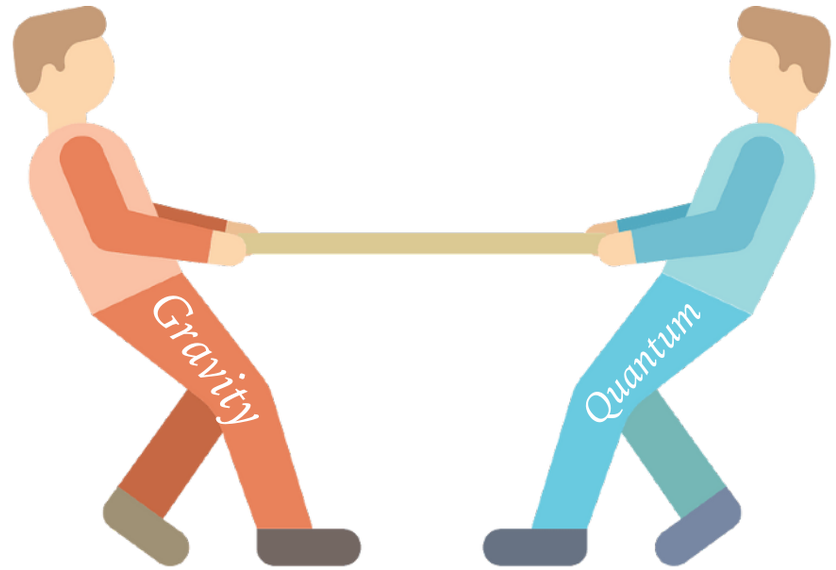
6/21/2023

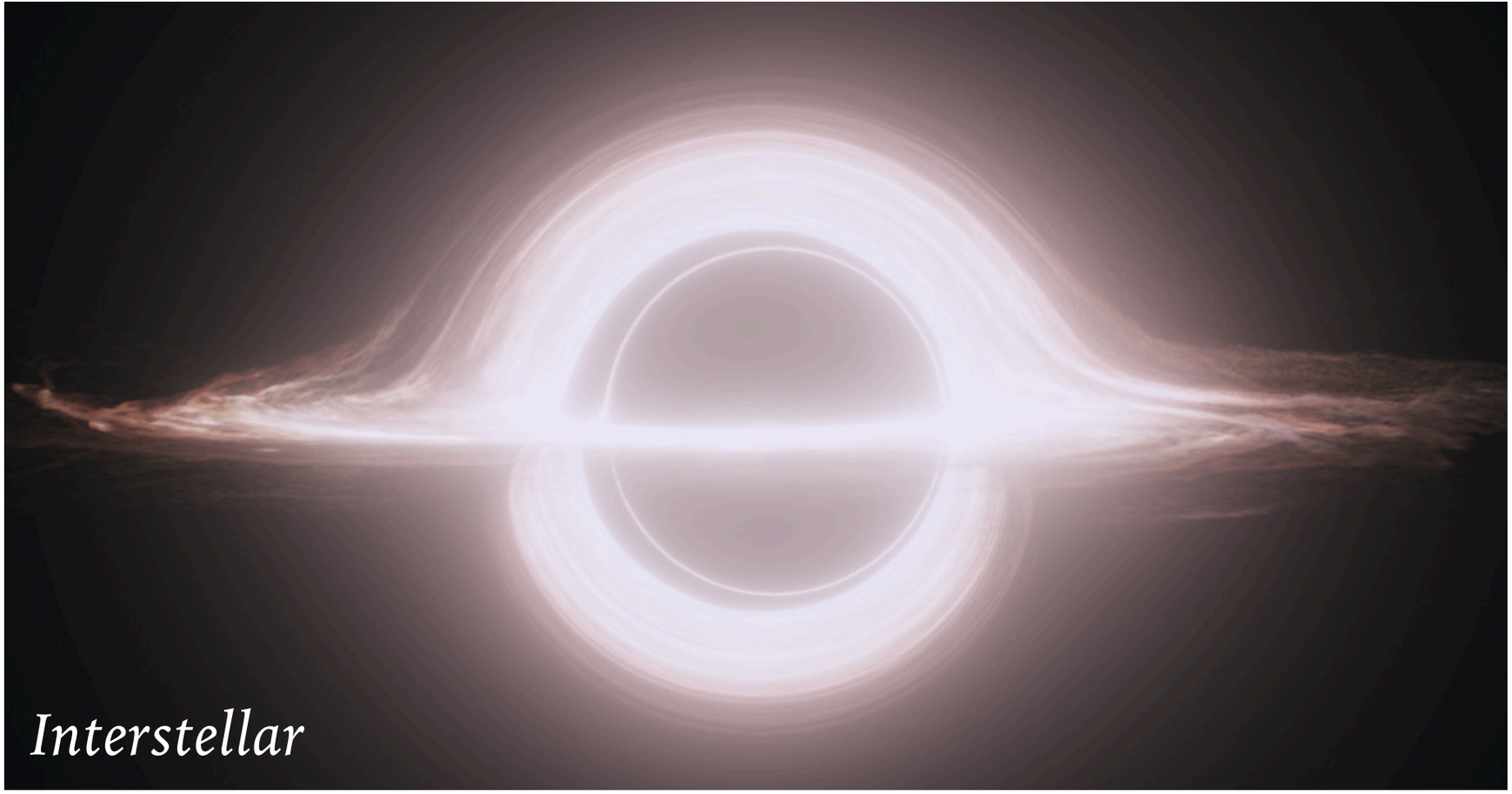
PARADOX BETWEEN GRAVITY, QUANTUM MECHANICS, AND THERMODYNAMICS



- Thought experiments which combine all of the major pillars of physics
- Paradox tests which fundamental principles are valid
- Resolution could play key role in finding theory of quantum gravity

OUTLINE

- ➤Black Hole Properties (Entropy, Temperature, Radiation)
- ➤Why evaporation gives problems with quantum mechanics
- ➤Potential resolutions



BLACK HOLE PROPERTIES IN CLASSICAL GENERAL RELATIVITY

1) If you get too close to a black hole, you can't escape it

Since max speed is speed of light c, if you are closer than $R = 2\,GM/c^2 = 3km\ (M/M_{sun})$

you cannot escape (dimensional analysis using G, M, c)

2) Black holes evolve to very boring final states

They are characterized by 3 quantities, their mass M, charge Q, and angular momentum J

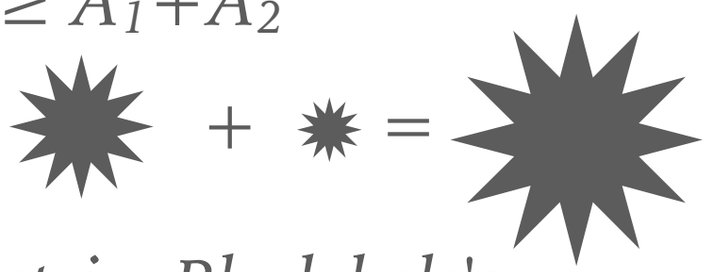
THOUGHT EXPERIMENTS

Wheeler: If black holes have no entropy, can lower entropy by throwing things into them, violating 2nd law of thermodynamics

Bekenstein: Thus black holes must have entropy!

Hawking: When black holes combine, the area of the event horizon always increases,

$A_{final} \geq A_1 + A_2$



Bekenstein: Black hole's entropy is proportional to it's area?

Aside: Area law can be tested by LIGO

HAWKING RADIATION

Hawking: Objects with entropy have a temperature, which requires them to radiate!

Hawking: In quantum theory, black holes do radiate!

$$S_{BH} = \frac{kc^3 A_{BH}}{4G\hbar}$$

$$T_{BH} = \frac{\hbar c^3}{8\pi GMk} = \left(\frac{M}{M_{sun}}\right) 10^{-8} K$$

Thus, black holes have underlying structure!

Aside: What does black hole entropy count? In string theory, it is possible to get agreement w/ entropy

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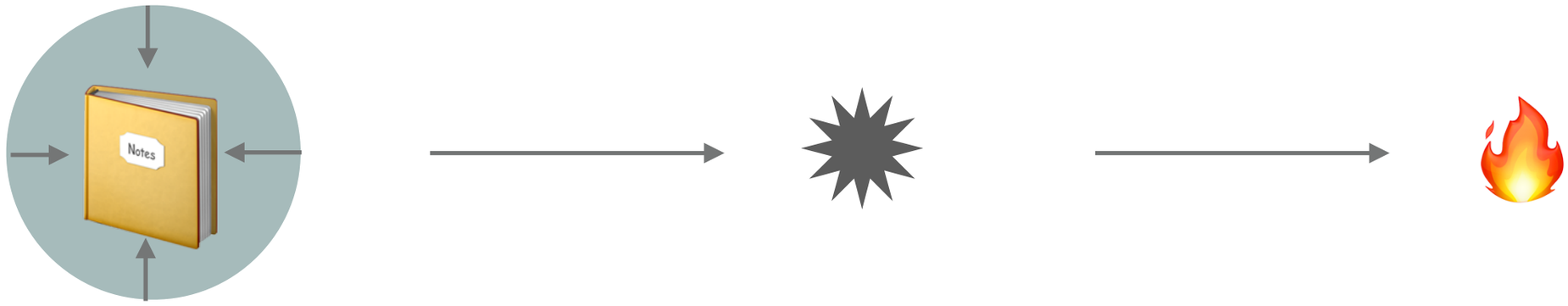
Q: After black hole evaporates are we just left with radiation?

Emitting this thermal radiation makes the black hole mass go down, which causes black holes to evaporate away in a time

$$t_{evaporation} = \left(\frac{M}{M_{sun}}\right)^3 10^{67} \text{ years}$$

QUANTUM INFORMATION

As Hawking noticed, if a quantum state evolves into a black hole and then evaporates into radiation, the predicted radiation has no information about what created the black hole



Unlike burning a book, the radiation doesn't depend on what book you burned and there is no leftover material to examine

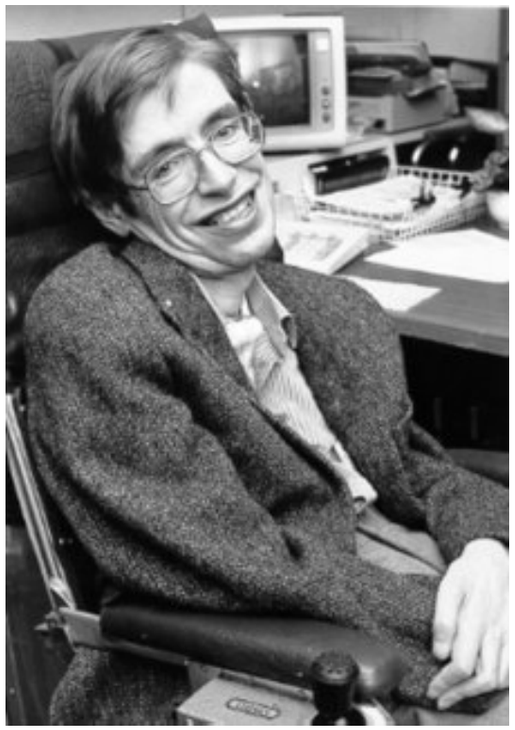
But this can't happen in quantum mechanics! It predicts evolution where you can always reconstruct the initial state. Alternatively, you can say that black hole evaporation causes information to be lost about the initial state whereas quantum evolution preserves information!

POTENTIAL RESOLUTIONS

- Info is preserved
  - Black holes do not completely evaporate, but leave a remnant which contains the information of initial state
    - Something is wrong in Hawking's calculation and the information leaks out with the radiation
- Information can be destroyed
  - Quantum mechanics does not apply to black hole evolution and information is violated

INFORMATION PARADOX AND BET

Kip Thorne



Stephen Hawking

John Preskill

Quantum mechanics needs to be modified!

Black hole dynamics must be modified!

In 2004, Hawking conceded the bet (Thorne did not) and awarded Preskill a baseball encyclopedia

HINTS FOR "SOMETHING IS WRONG IN HAWKING'S CALCULATION AND THE INFORMATION LEAKS OUT WITH THE RADIATION"

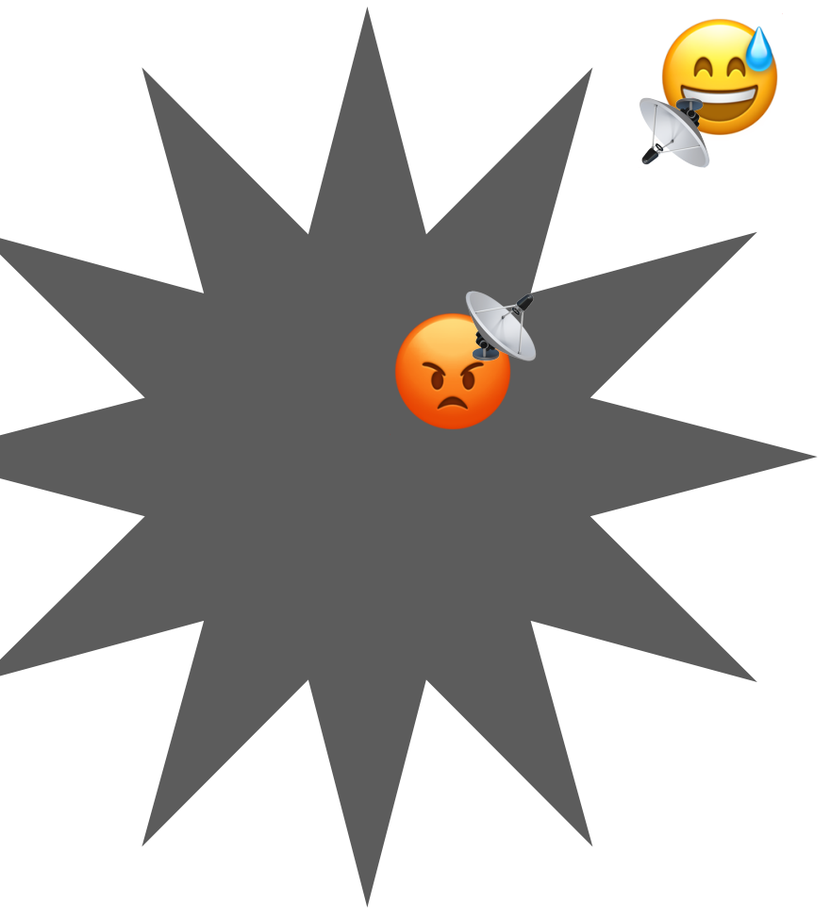
String Theory and the AdS/CFT correspondence

Theory with gravity (AdS = Anti-de Sitter space) is equivalent to a quantum theory (CFT = conformal field theory)

CFTs preserve information, so the black holes must preserve information

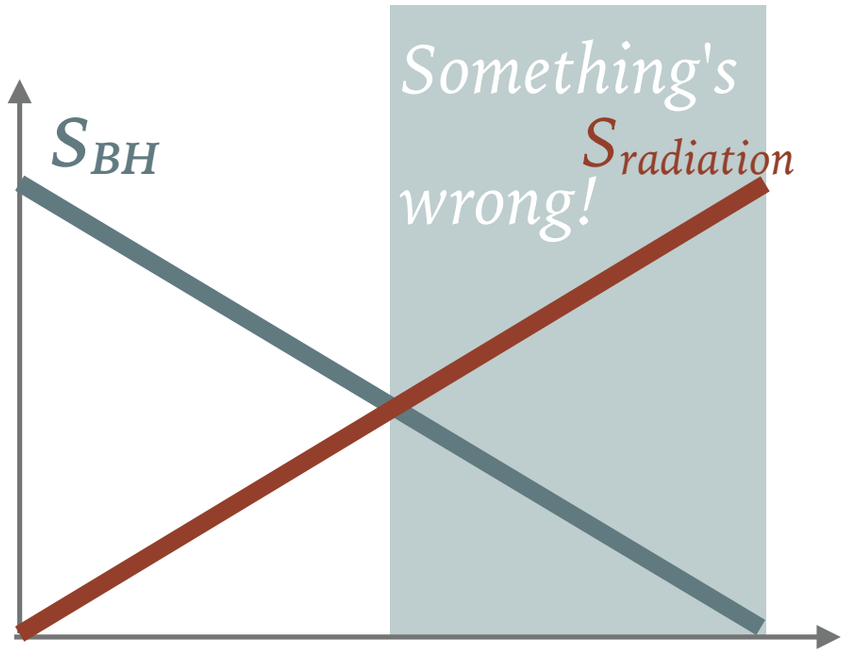
Moreover, CFTs do not have candidates for black hole remnants, thus it strongly suggests that the information gets out in the radiation, but does not say how

DETAILED ISSUES



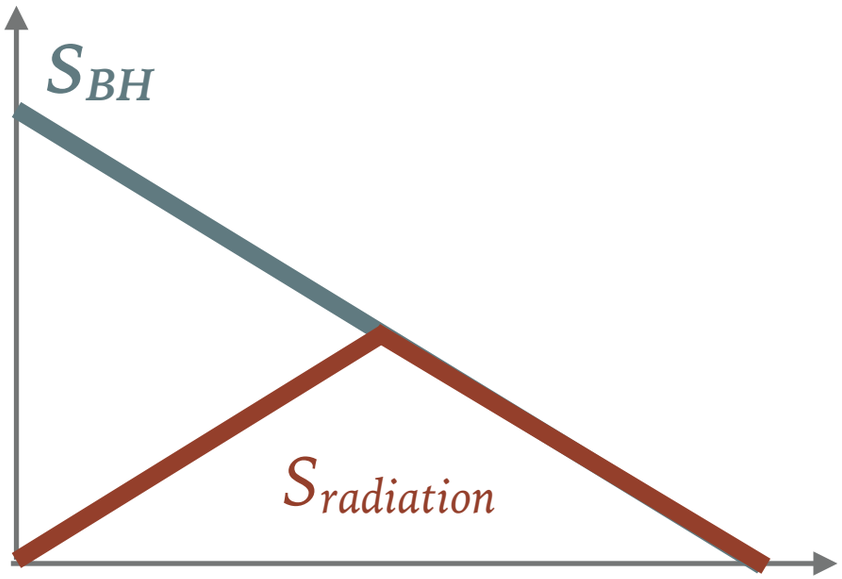
Take a quantum state that collapses to a black hole and imagine a scientist inside the event horizon and a scientist outside of it measuring as the black hole evaporates

Because the whole system is a quantum state, quantum mechanics predicts that the entropy outside is the same as the entropy inside $S_{radiation} = S_{out} = S_{in} \leq S_{BH}$



Don Page: Something must go wrong with Hawking's calculation much earlier, when black hole is still very large. May not need quantum gravity?

CALCULATING PAGE CURVE



Page argument made many think that something drastic has to happen (e.g. firewalls)

However, recently two groups (Penington and Almheiri, Engelhardt, Marolf, and Maxfield) have used a variety of tricks to compute the entropy outside and find that the entropy goes down precisely when it needs to!

Not fully accepted yet, but if true, it strongly suggests that black holes preserve information. Disappointingly, it doesn't precisely say how the information is preserved and it also doesn't require quantized gravity

CONCLUSIONS

- Information paradox has been a very productive thought experiment playground to explore fundamental issues combining gravity, quantum mechanics, and thermodynamics
- Long history which may be close to resolution

THANK YOU!


YOUR THEORY
OF A DOUGHNUT-SHAPED UNIVERSE
IS INTRIGUING, HOMER.

REFERENCES

- https://www.quantamagazine.org/the-most-famous-paradox-in-physics-nears-its-end-20201029/

PROBLEMS FOR YOUR STUDENTS

- **Black Hole Event Horizon radius:** i) Find combination G^n M^m c^r of Newton's Gravitational constant G, Mass M, and speed of light c that has units of length or ii) Find distance R, where escape velocity is speed of light c. (Ans: $R = 2GM/c^2$) Use the result to find radius of solar mass black hole. (Ans: 3 km)

- **Planck length, time (where quantum gravity is important):** Find combination of Newton's Gravitational constant G, Planck's constant h, and speed of light c that has units of i) length (Ans: $(Gh/c^3)^{1/2} \sim 10^{-35}$ m) and ii) time (Ans: $(Gh/c^5)^{1/2} \sim 10^{-43}$ s)