BLACK HOLES IN QUANTUM GRAVITY

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ASTROPHYSICAL BLACK HOLES

THE BLACK HOLES IN OUR UNIVERSE

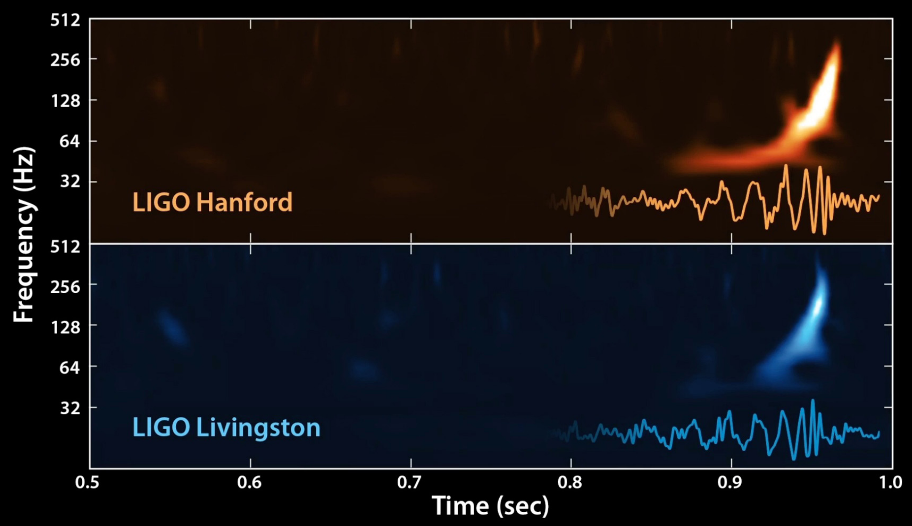
They spin fast as well!

They accrete matter, and supermassive black holes are at the center of most, if not all, galaxies

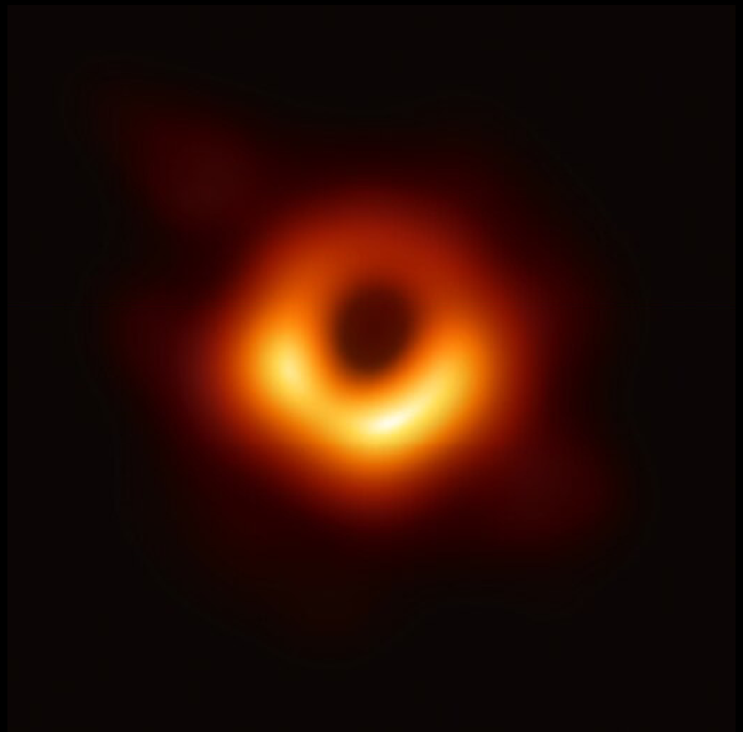
Black hole classifications

Class	Approx. mass	Approx. radius
Ultramassive black hole	10^9–10^{11} $M_\odot$	>1,000 AU
Supermassive black hole	10^6–10^9 $M_\odot$	0.001–400 AU
Intermediate-mass black hole	10^2–10^5 $M_\odot$	10^3 km ≈ R_{Earth}
Stellar black hole	2-150 $M_\odot$	30 km
Micro black hole	up to M_{Moon}	up to 0.1 mm

1 AU ~ 150 000 000 km; 1 $M_\odot \sim 2 \cdot 10^{30}$ kg



ASTROPHYSICAL BLACK HOLES: OBSERVATIONS



- We first detected gravitational waves on **September 14, 2015**, using the **Laser Interferometer Gravitational-Wave Observatory (LIGO)**. The discovery was announced on **February 11, 2016**, and marked a monumental achievement in physics.
- **GW150914:** The detected waves originated from the merger of two stellar-mass black holes approximately 1.3 billion light-years away.

- The first-ever image of a black hole was captured on **April 10, 2019**, by the **Event Horizon Telescope (EHT)** collaboration.
- This groundbreaking image revealed the supermassive black hole at the center of the galaxy **Messier 87 (M87)**, located about 55 million light-years away in the Virgo Cluster.

‘NOW’ THAT WE KNOW THEY EXIST, HOW CAN WE UNDERSTAND SUCH UNINTUITIVE OBJECTS?

(SEMI)-CLASSICAL BLACK HOLES

BLACK HOLES IN GENERAL RELATIVITY

- One of the main reasons why black holes are so interesting is their causal structure
- Their gravitational pull is so strong, that light—the fastest thing in the universe—is not able to escape their grip
- Creating a black hole pulls so much, that space and time start acting in a weird way, forming horizons and singularities

Can we build some intuition then?

HOW TO THINK ABOUT BLACK HOLES

There are some partial ways in which we can try to build intuition

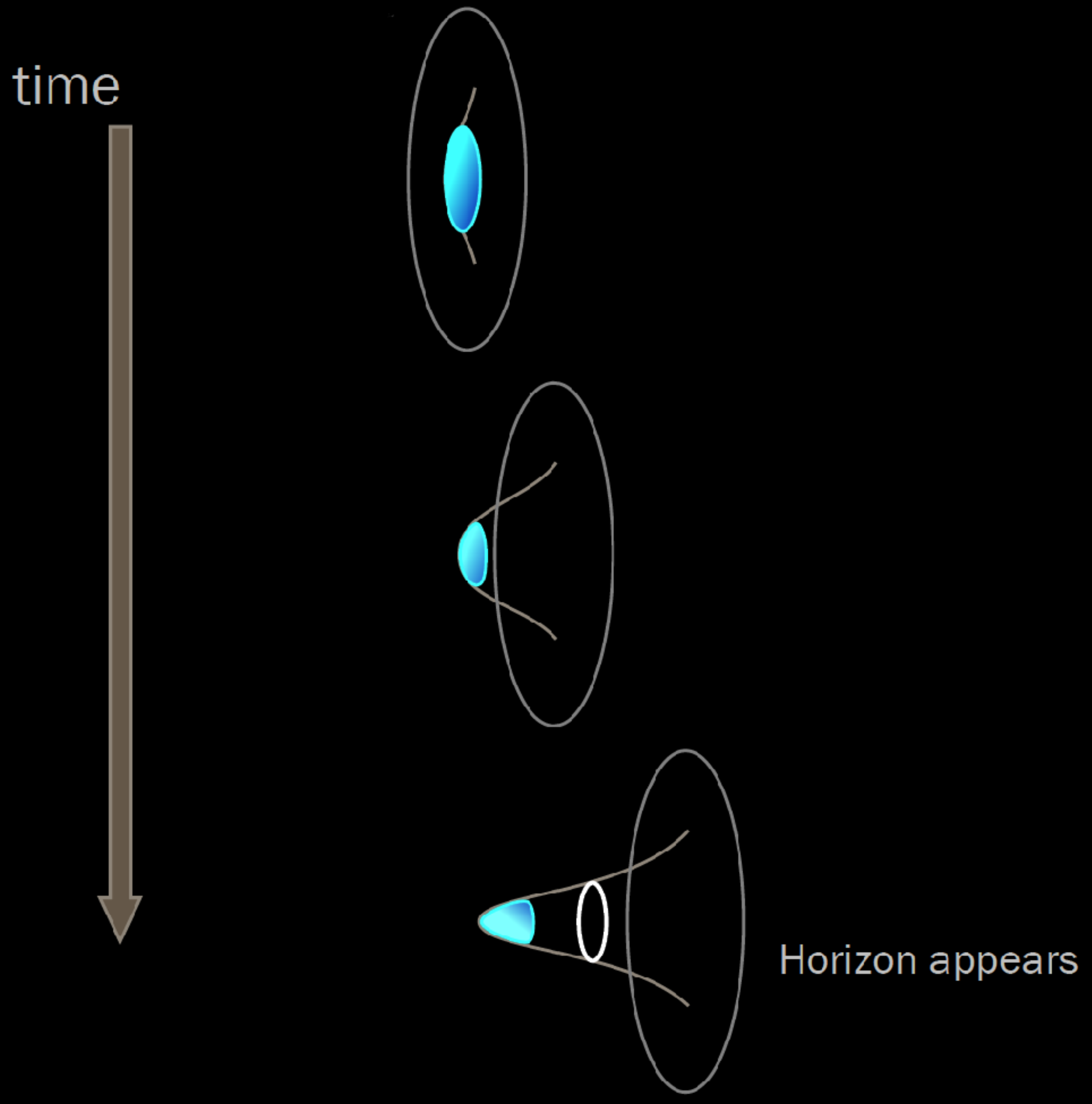
One can imagine having a waterfall, where the horizon would be the point of no return

[Lake Berryessa, Napa County, California.]

HOW TO THINK ABOUT BLACK HOLES

There are some partial ways in which we can try to build intuition

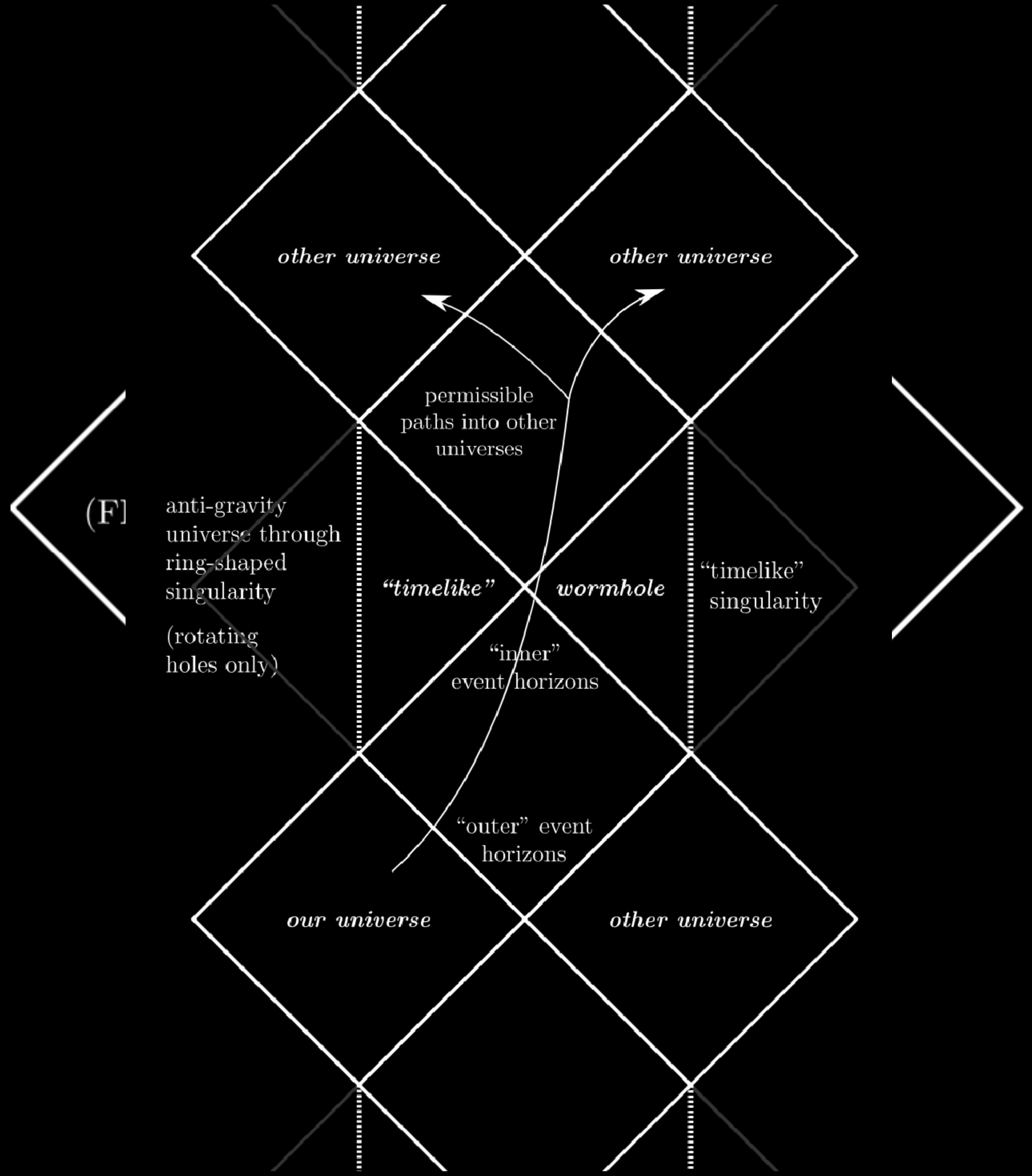
One can also draw pictures of a throat getting stretched in time



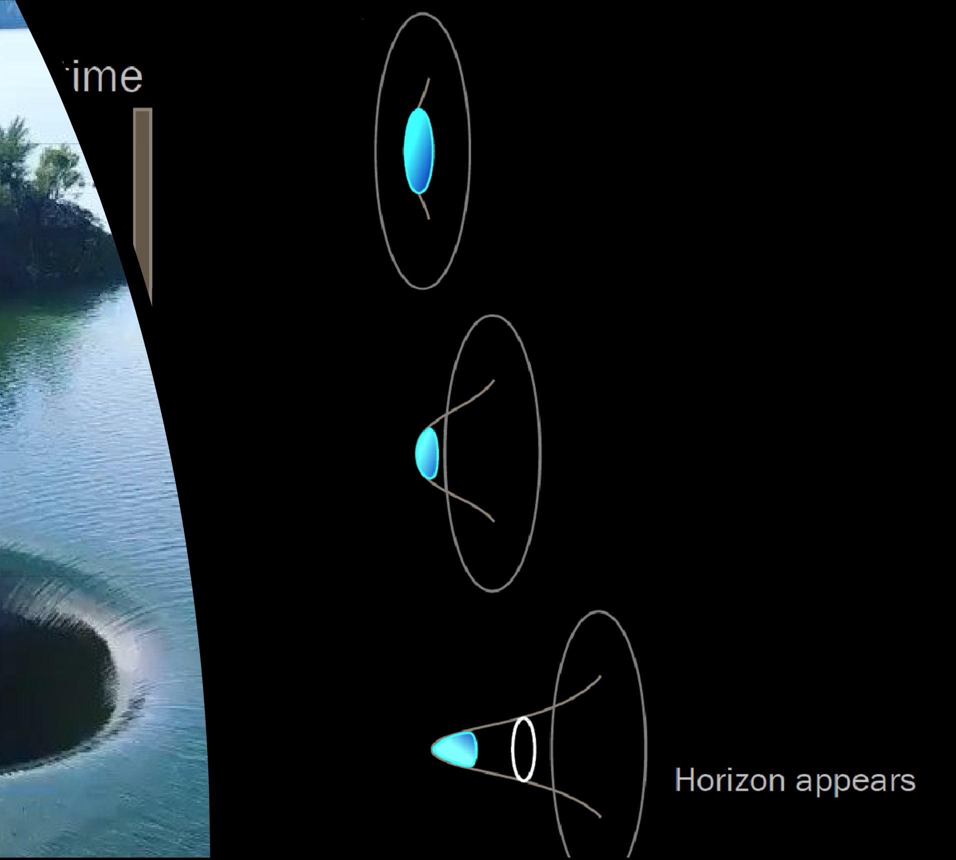
HOW TO THINK ABOUT BLACK HOLES

There are some partial ways in which we can try to build intuition

But our best way to understand them is through Penrose diagrams, which show the bare bones of the black hole a.k.a. its causal structure

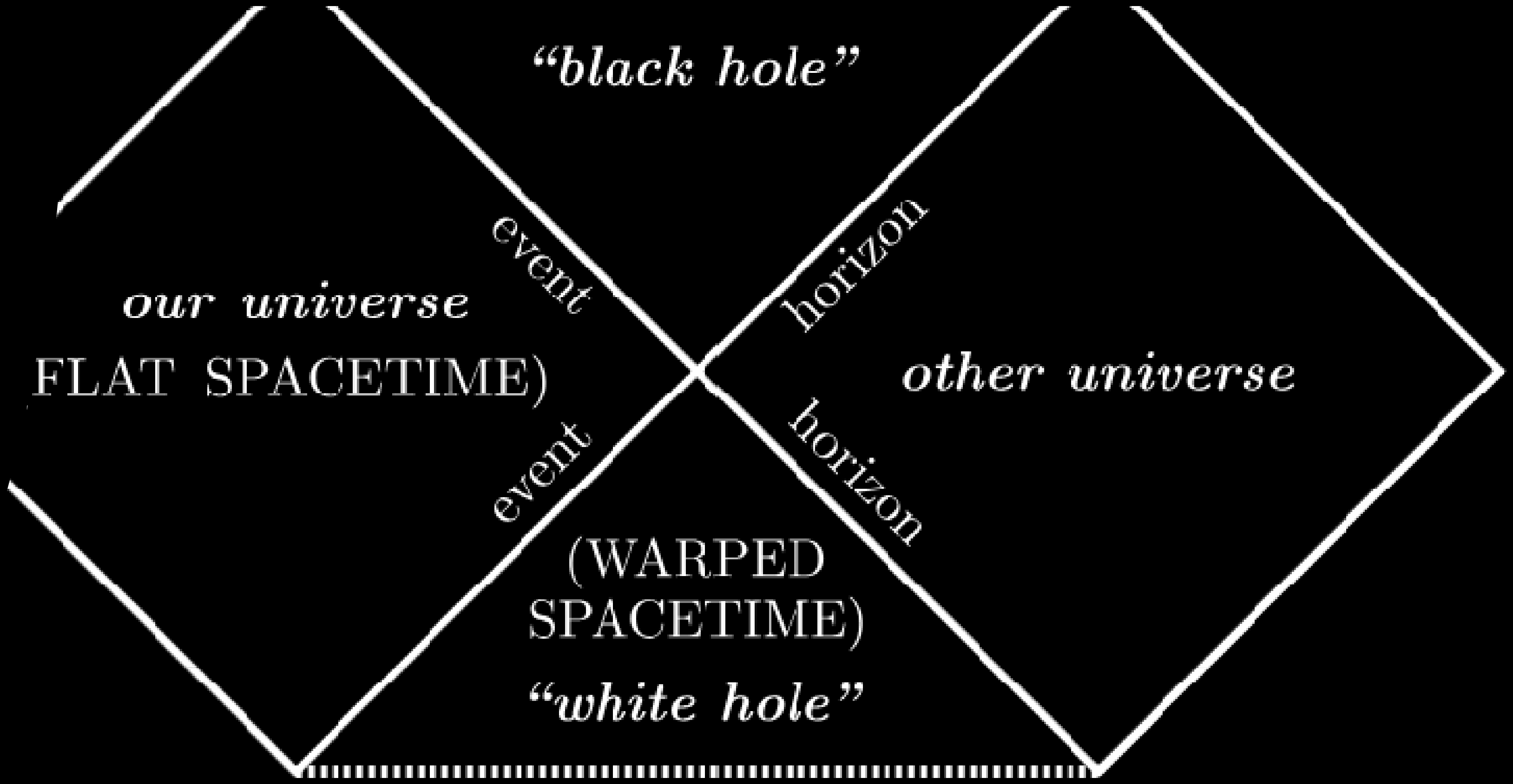


HOW TO THINK ABOUT BLACK HOLES

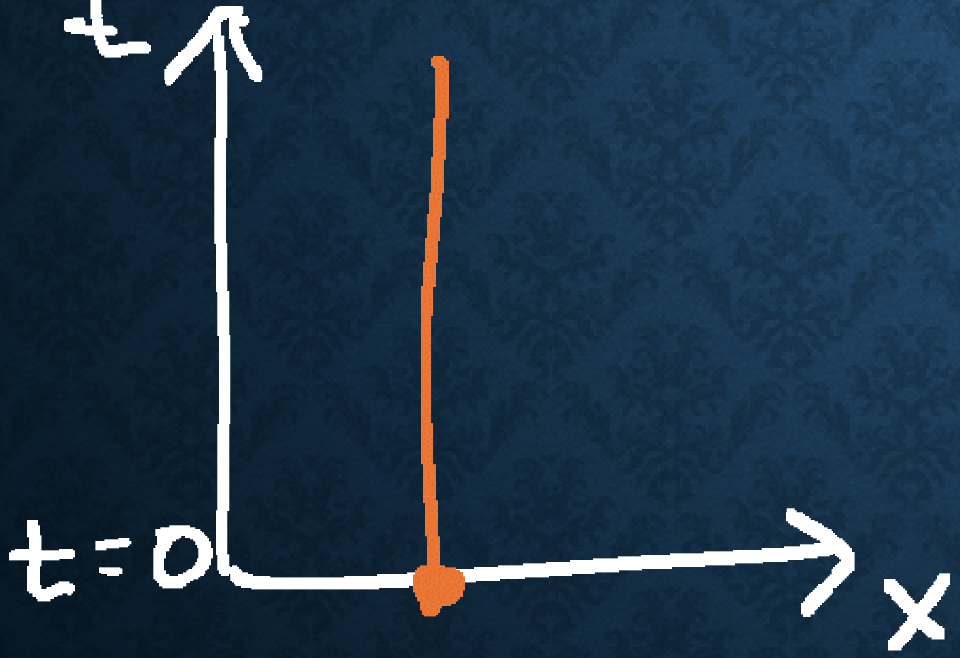


And it's really a combination of these various views that gives us a fuller understanding

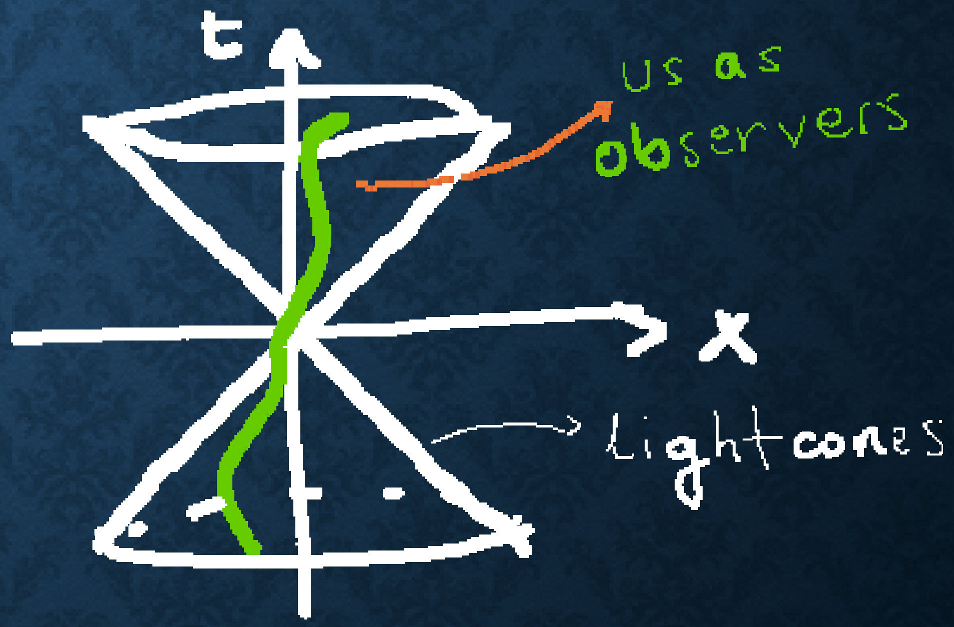
Penrose diagrams are the best since they contain most information, while the others give intuition



THE BASICS OF CAUSAL STRUCTURES



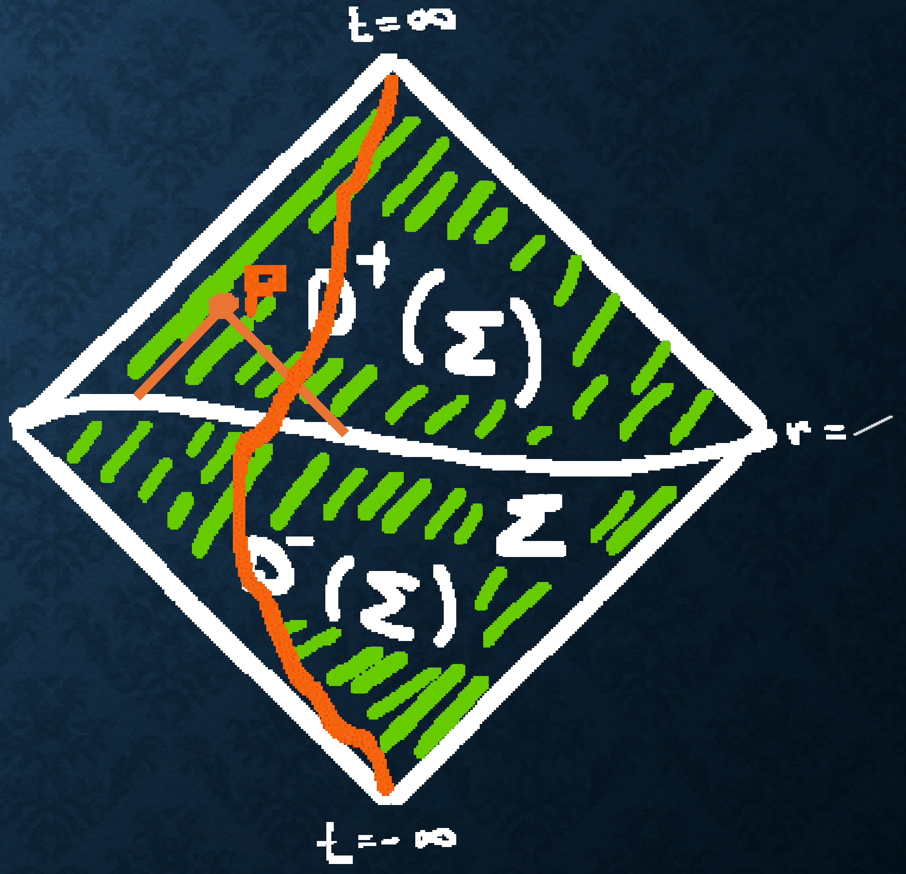
'Wasting time'



Bounded by the lightcone

THE BASICS OF CAUSAL STRUCTURES

- So, lightcones generally *limit the number of events that can influence us*
- We can also talk about a set of events that are entirely *determined* by another set of events—this is know as the **domain of dependence**

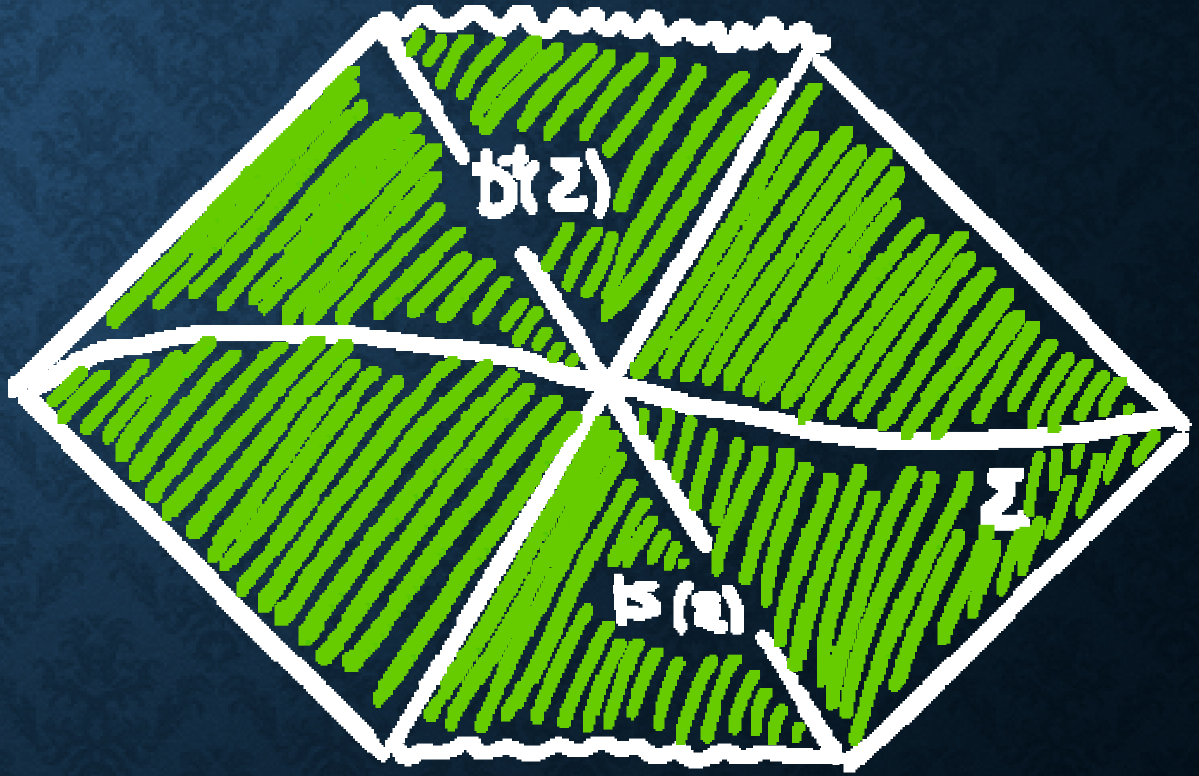


Minkowski spacetime

SCHWARZSCHILD BLACK HOLE

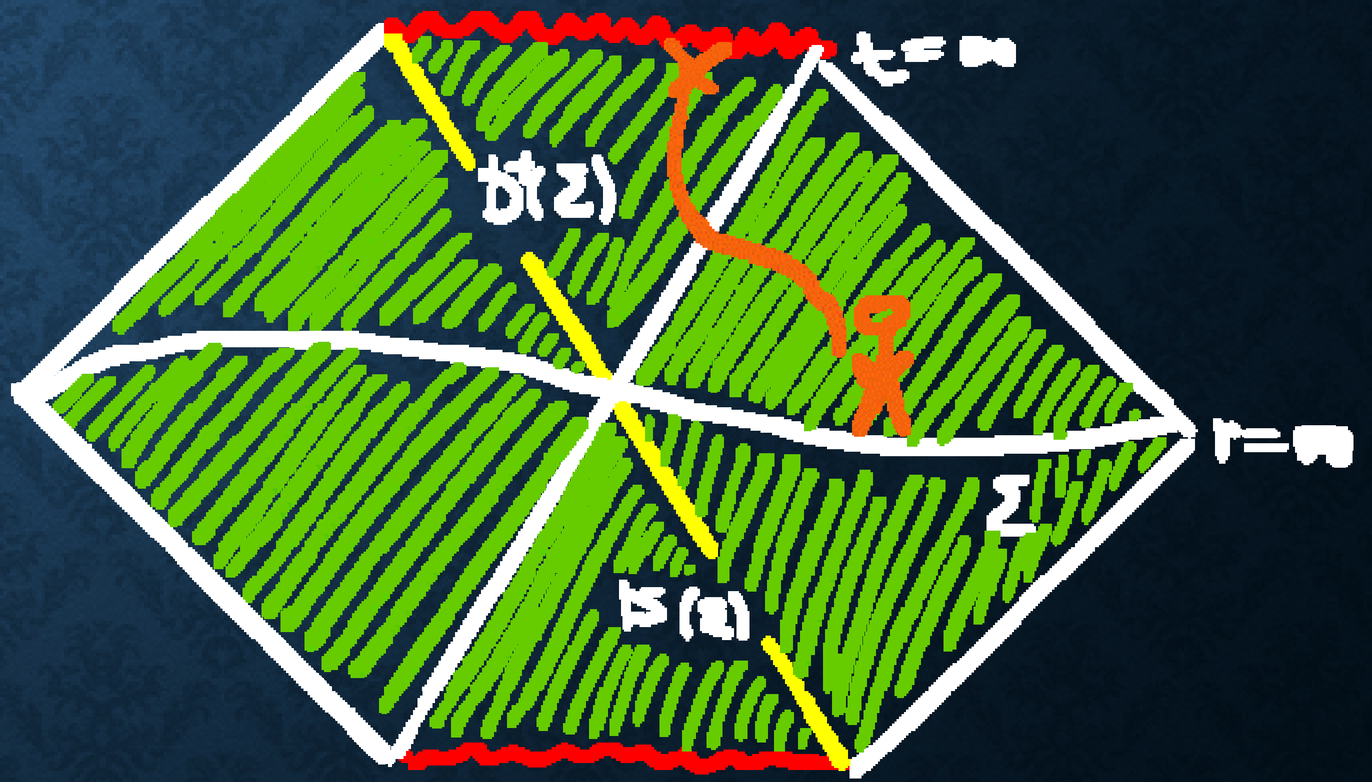
We can now look at the simplest black hole—the first black hole solution found by Schwarzschild several weeks after Einstein's GR publication!

This black hole does not have any charge, nor does it rotate—unlike the ones in our Universe



SCHWARZSCHILD BLACK HOLE

The wiggly line is the singularity, and there is also the event horizon



Note that the singularity is 'spacelike'—the singularity is **an event in time**, spread over space! It is NOT an object

(that would be a 'timelike' singularity)

BLACK HOLE FROM COLLAPSE

This was the maximally extended solution, also known as the eternal black hole

To form a black hole from collapse, we need some matter that will undergo such a collapse process

The resulting Penrose diagram is that of the **Oppenheimer-Snyder black hole**

BLACK HOLES IN GENERAL RELATIVITY

- So far, we discussed only the causal skeleton of the black hole
- But black holes are more than just their skeleton: they are physical objects that should obey physical laws
- For one, we can determine what is the mass, the spin and the charge of a black hole from asymptotic observations

- But that's more or less it: black holes don't have much 'hair'

BLACK HOLES AND INFORMATION

But this is intriguing: we made this black hole from a collapse of matter that carried *much more information* than just M, J and Q

So where did all this information about the quantum state of the star go?

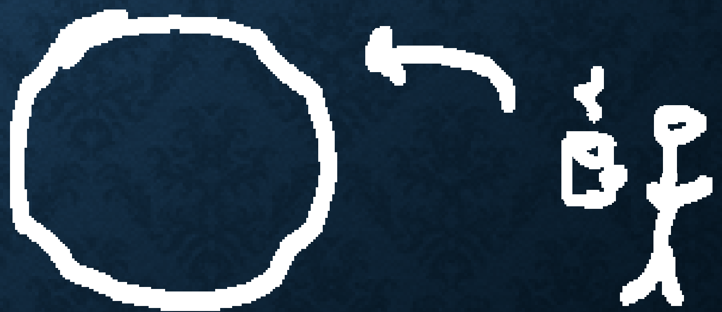
Well, perhaps it is all inside the black hole and we shouldn't worry about it too much

Bekenstein '72

BEKENSTEIN AND A CUP OF TEA

- Luckily, Bekenstein and his advisor Wheeler, did worry about this and the information content of a black hole
- They came up with a thought experiment that still stands the test of time
- Namely, they thought about what would happen to the **entropy of a cup of tea** as it is thrown inside the black hole

$$S_{universe} = S_{cup} + S_{bob}$$



BEKENSTEIN AND A CUP OF TEA

Well, the entropy of the entire universe outside the black hole would go down, but the entropy of the tea will be preserved inside the black hole, so if we “include” the inside of the black hole, it seems that the second law of thermodynamics would be fine

$$S_{universe} = S_{B.b} \quad \times$$

Need to include S_{cup} from inside the black hole!

BEKENSTEIN AND A CUP OF TEA

However, Bekenstein was adamant about *not taking this stance*! In his view, if we cannot **verify** that the second law of thermodynamics is correct, then we lose all falsifiability

(imagine a tiny black hole forming in your experiment---how would you know that the second law holds?)

BEKENSTEIN'S INSIGHT

- In order to fix the problem with the second law, Bekenstein conjectured that the black hole itself must have some sort of an entropy
- Based on some theorems about the geometric properties of black holes, he finally wrote down the proposal for the black hole entropy

$$S = \frac{Area}{4G\hbar}$$

This is still the only formula we have in quantum gravity

Hawking ‘74

HAWKING’S INSIGHT

- Hawking almost immediately reacted to Bekenstein’s paper, thinking that this is an absurd proposal!
- For if an object has a mass and entropy, then by the first law, it must also have a temperature
- And therefore, the black hole must radiate
- But how can it radiate if not even light can escape it? Absurd!

HAWKING'S INSIGHT

$$T_H = \frac{\hbar c^3}{8\pi k_B G M} = 6 \times 10^{-8} \frac{M_\odot}{M}\,\mathrm{K}$$

$$S_{BH} = \frac{c^3}{\hbar G}\frac{\mathcal{A}_H}{4} \simeq 10^{76}\left(\frac{M}{M_\odot}\right)^2$$

$$M \sim 10^{6-9} M_\odot$$

- Yet, through a detailed calculation of quantum fields in the presence of a black hole, Hawking famously showed that **black holes indeed do radiate at a very low temperature**
- So, for a solar-mass black hole, this is around 10^(-7) K --- much lower than the CMB (~ 3 K)
- But we shouldn't be surprised by its smallness: there's an ħ in it – it is a quantum effect!
- Similarly, the entropy of a single supermassive black hole is *huge*: more than all the matter and radiation of the universe (~ 10^(87))

A PARADOX

- Hawking also calculated the spectrum of the radiation and found it to be thermal
- Thermal means that it doesn't carry any information about the quantum state of the matter that collapsed to form the black hole
- But now we can no longer say that that information is just inside the black hole because the black hole will evaporate and eventually disappear

- So, now it really seems like we have a puzzle: all of our information will disappear with the black hole! But this is not allowed by quantum mechanics which asserts that we must have conservation of information

This is known as the **black hole information paradox**

A PARADOX

- Of course, such a bold statement did not go unchecked: people redid Hawking's calculation, but alas they found the same result
- People also came up with different ways of phrasing the paradox:
- 1) The Page curve does not follow unitarity
- 2) The 2-point function of fields does not follow that of quantum field theory at late times
- 3) The Hilbert space of the black hole interior does not have a finite dimension
- …

A PARADOX AND ITS PARTIAL RESOLUTION

- For nearly 50 years, the paradox was there and all the proposed resolutions were always unsatisfactory in some sense
- To give a flavor of the proposed resolutions:
- 1) Remnants --- but they'd be seen in LHC!
- 2) Firewalls --- but we lose the equivalence principle!
- 3) Fuzzballs --- but there's not enough of them for S!
- 4) Black hole complementarity --- but we lose locality!

A PARADOX AND ITS PARTIAL RESOLUTION

However, recently we had a small breakthrough!

All of the proposed resolutions were just results of people's imaginations (and some small calculations)

However, in 2019, using the tools from AdS/CFT and utilizing the Euclidean path integral, we managed to resolve 'the first phrasing of the paradox': the Page curve

A PARADOX AND ITS PARTIAL RESOLUTION

The calculation of the Page curve requires a rigorous way of calculating the quantum entropy of the radiation and the black hole during evaporation

One can prove that if the curve follows Page's result, then the evaporation process is unitary

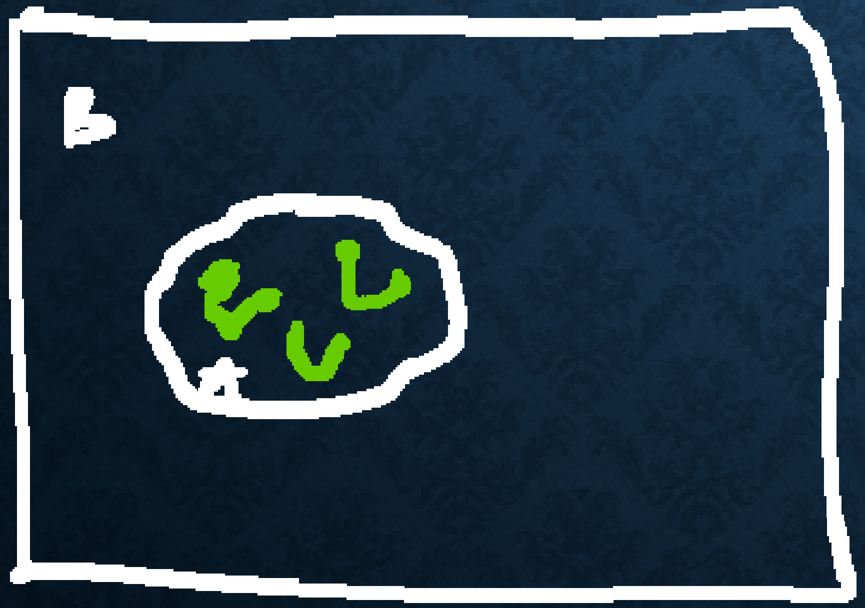
This result also points in the direction of **black hole complementarity**, but further research is necessary to truly tell

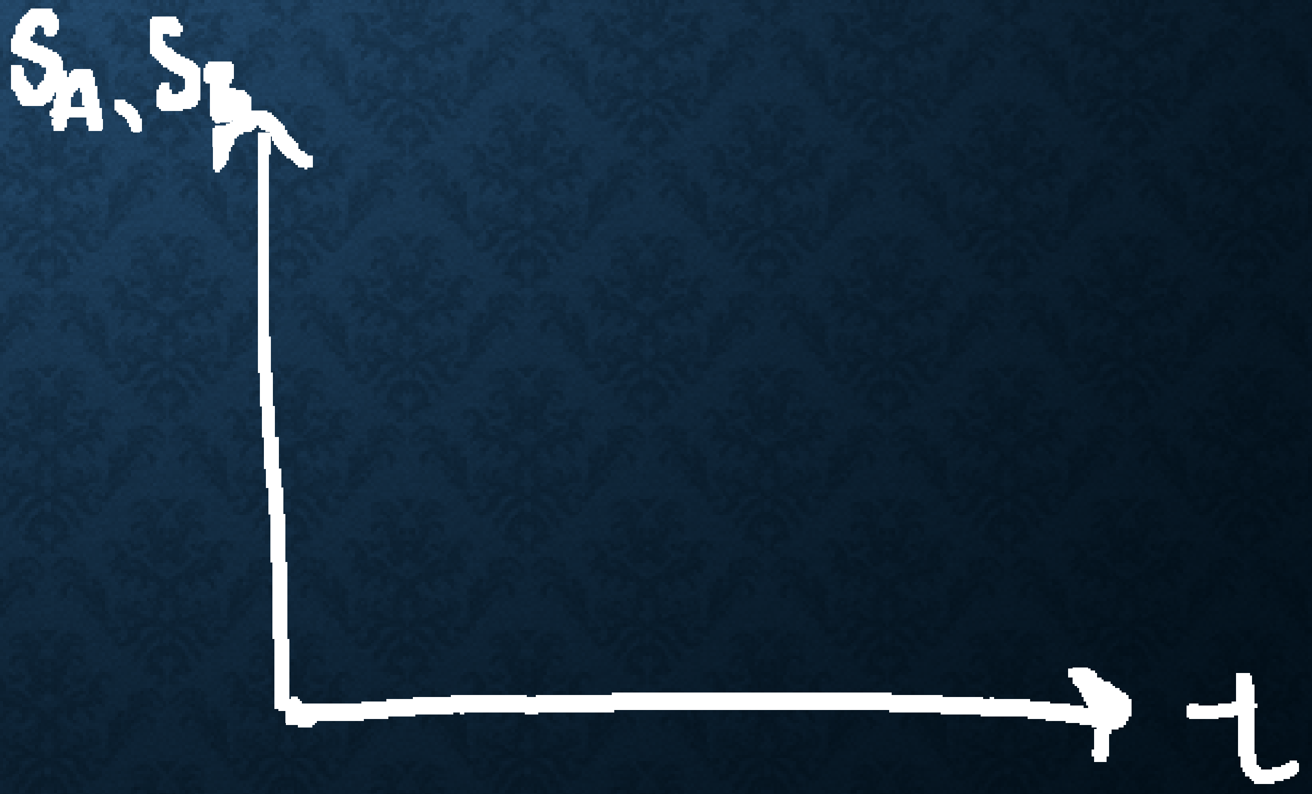
Page ‘93

A PARADOX AND ITS PARTIAL RESOLUTION

- So, what is this Page curve about?
- The Page curve tells us about the way the information is preserved when we let two systems interact

$t = 0$





A PARADOX AND ITS PARTIAL RESOLUTION

- So what is this Page curve about?
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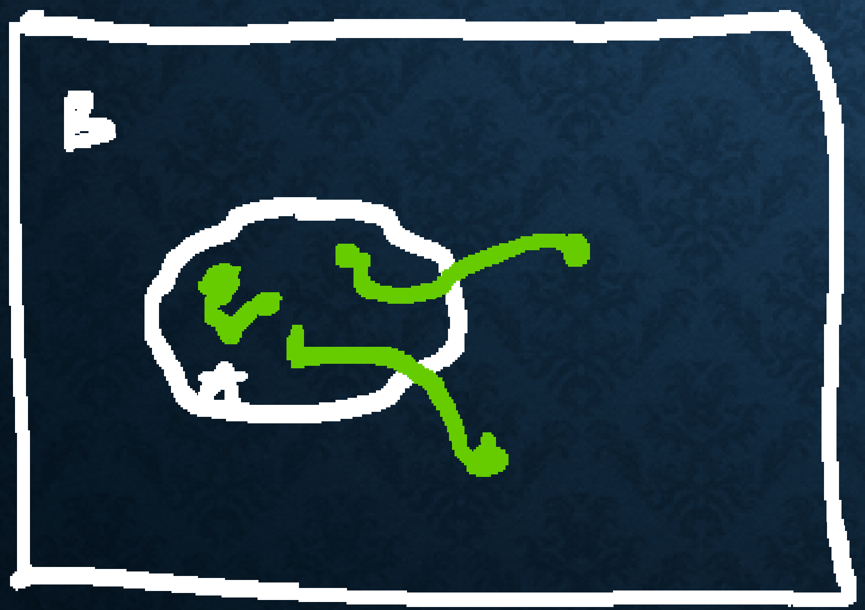
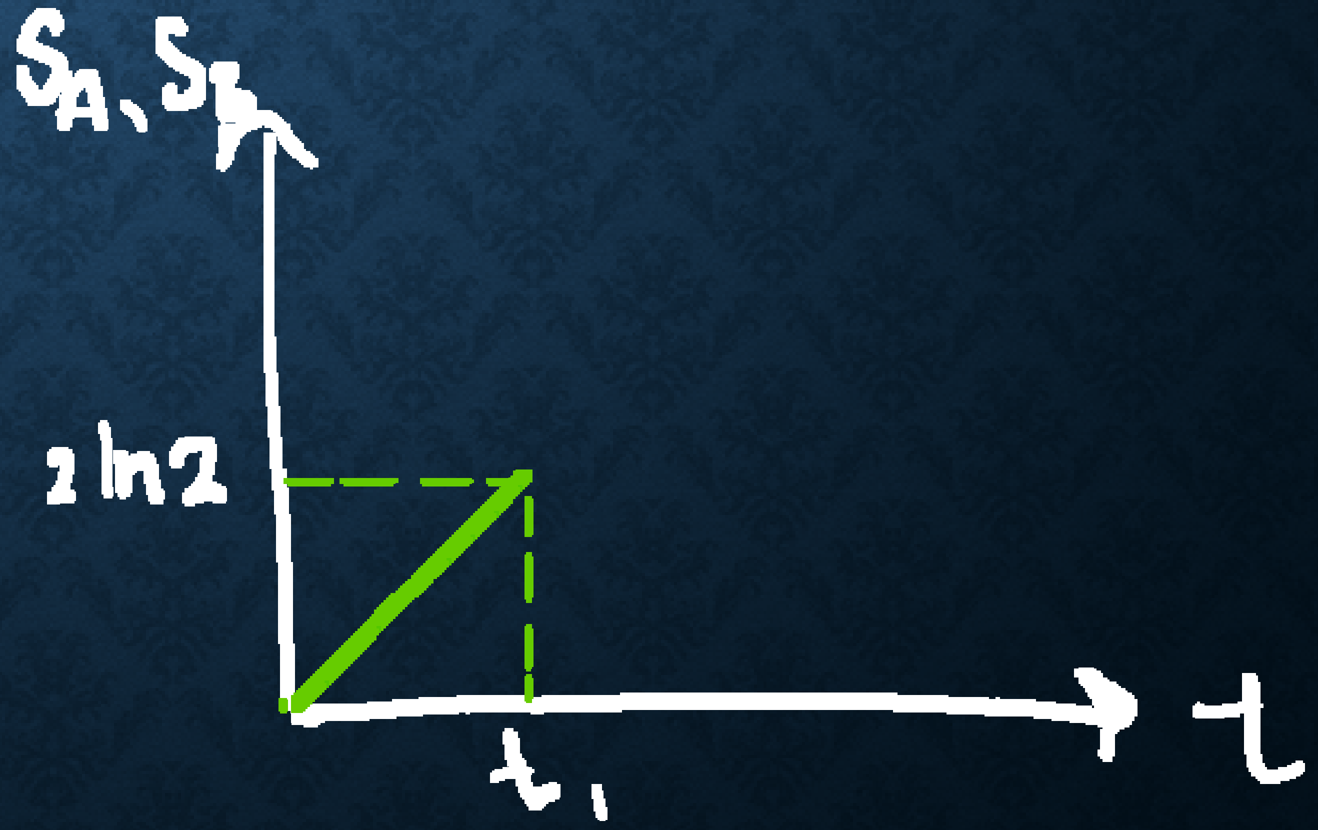
$t = t_1$

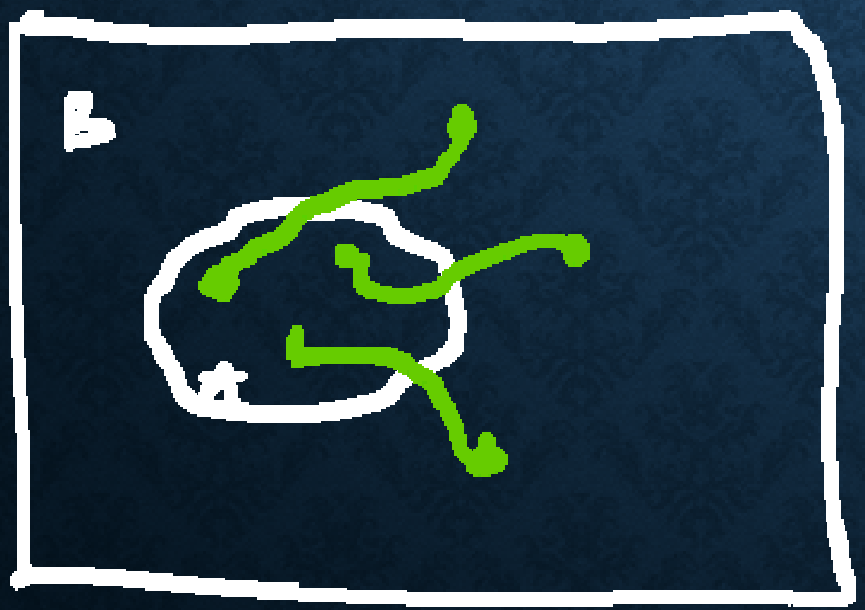


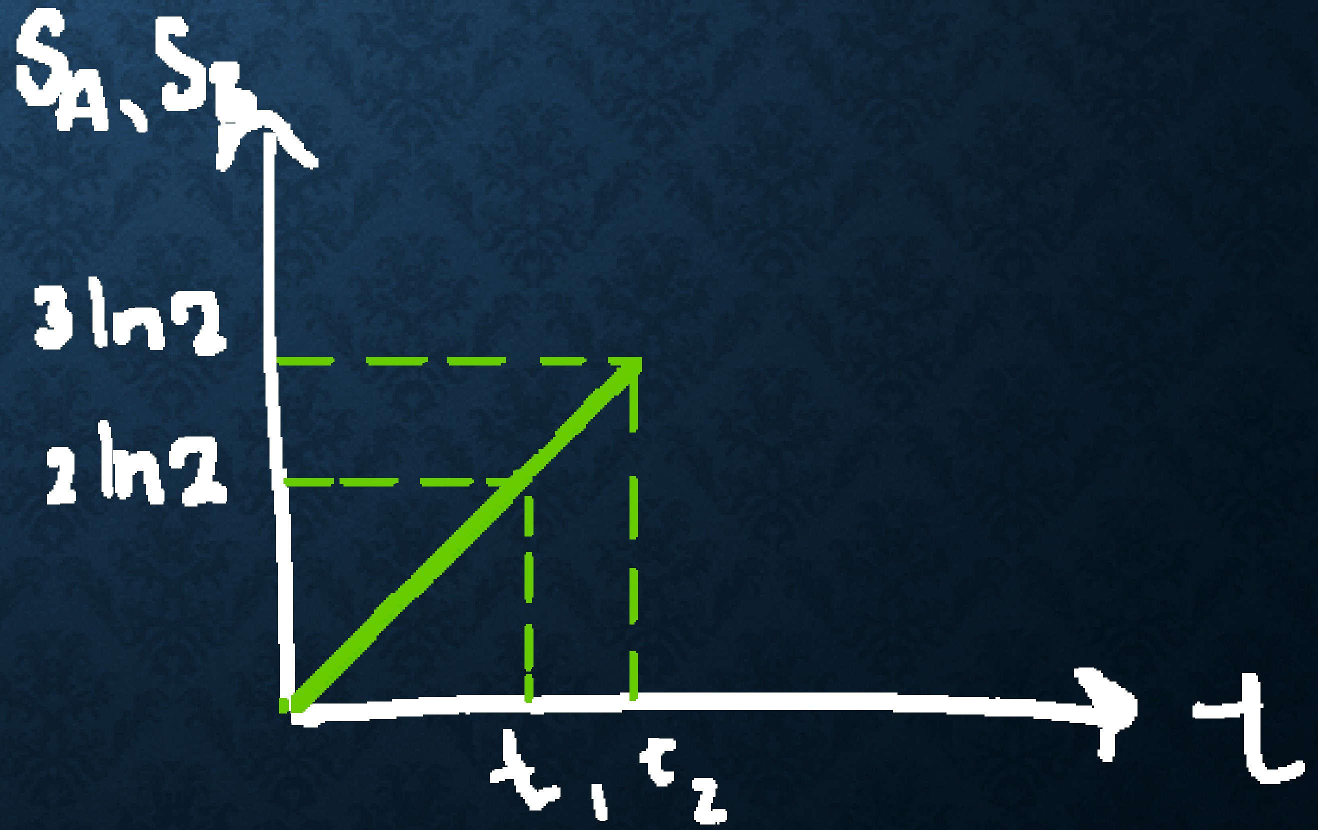


A PARADOX AND ITS PARTIAL RESOLUTION

- So what is this Page curve about?
- The Page curve tells us about the way the information is preserved when we let two systems interact

$t = t_2$





A PARADOX AND ITS PARTIAL RESOLUTION

- So what is this Page curve about?
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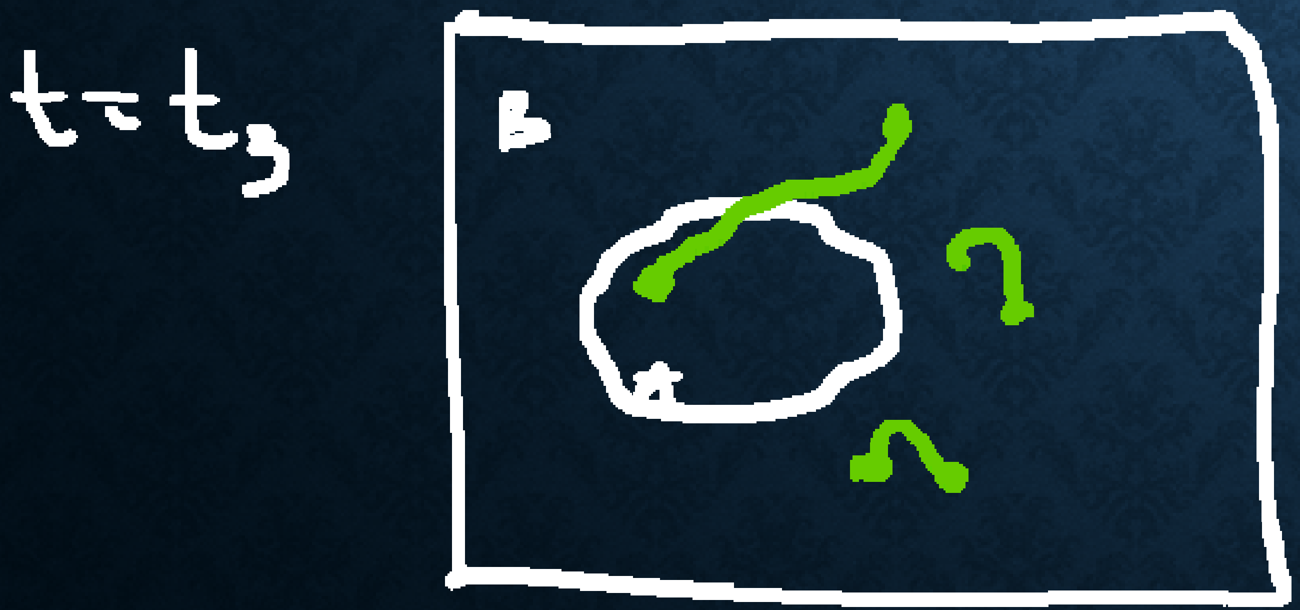
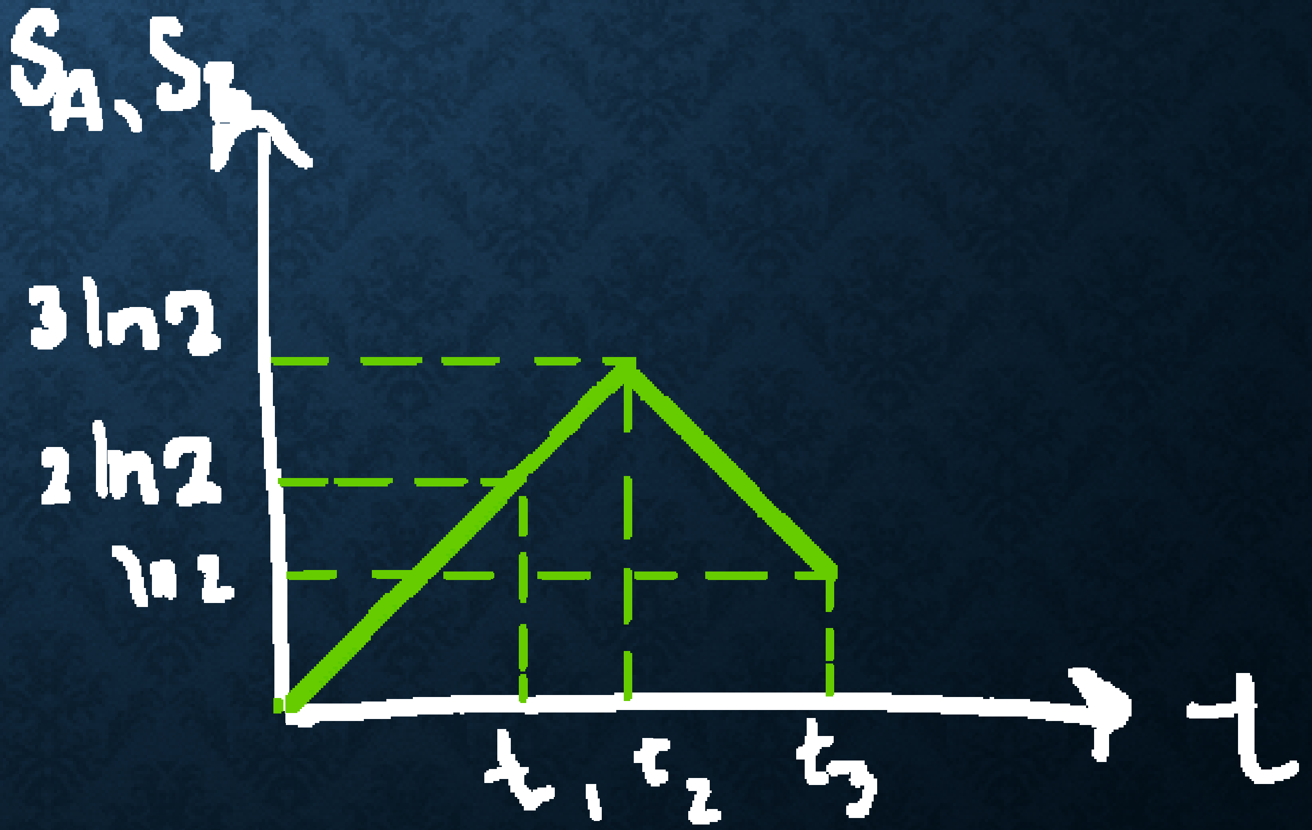
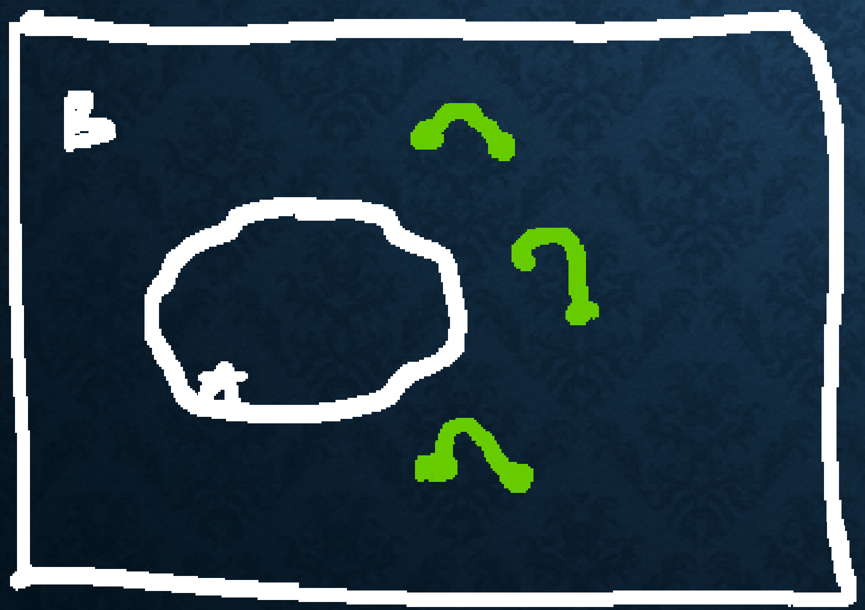


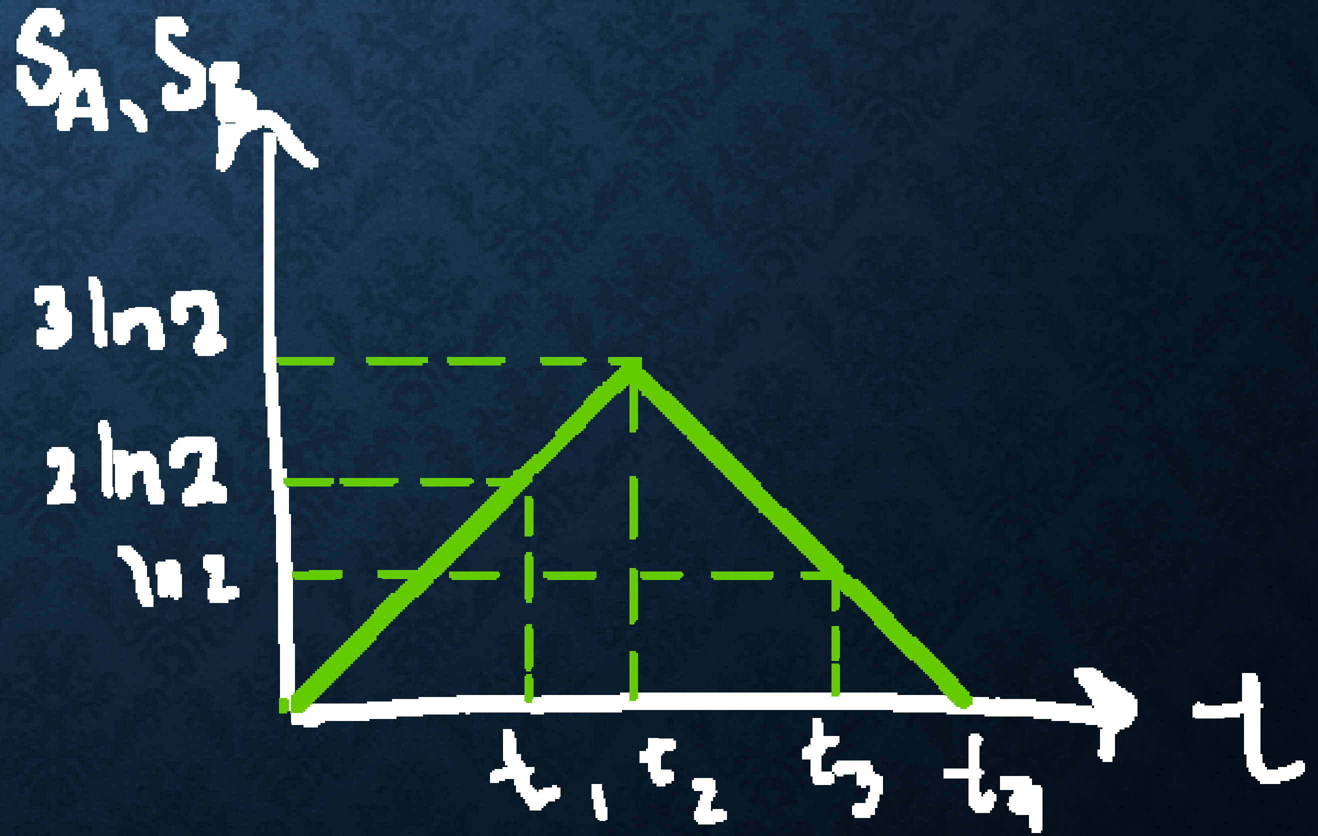


A PARADOX AND ITS PARTIAL RESOLUTION

- So what is this Page curve about?
- The Page curve tells us about the way the information is preserved when we let two systems interact

$t = t_4$





A PARADOX AND ITS PARTIAL RESOLUTION

In other words: in order to have unitary evolution, we must have our amount of ignorance brought to zero at the end --- this is what von Neumann entropy calculation tells us about

But if we calculate the same quantity for a black hole, we obtain

We obtained this curve only in 2019: almost 50 years after Hawking's calculation!

Penington '19
Almheiri, Engelhardt, Marolf, Maxfield '19

SEMICLASSICAL BLACK HOLES

However, this still leaves many questions open: what's the dynamics, what's the infalling observer's experience, how's the singularity resolved…

For these questions, it seems we will need to go away from the semiclassical path integral---perhaps string theory can help us?

BLACK HOLES IN STRING THEORY

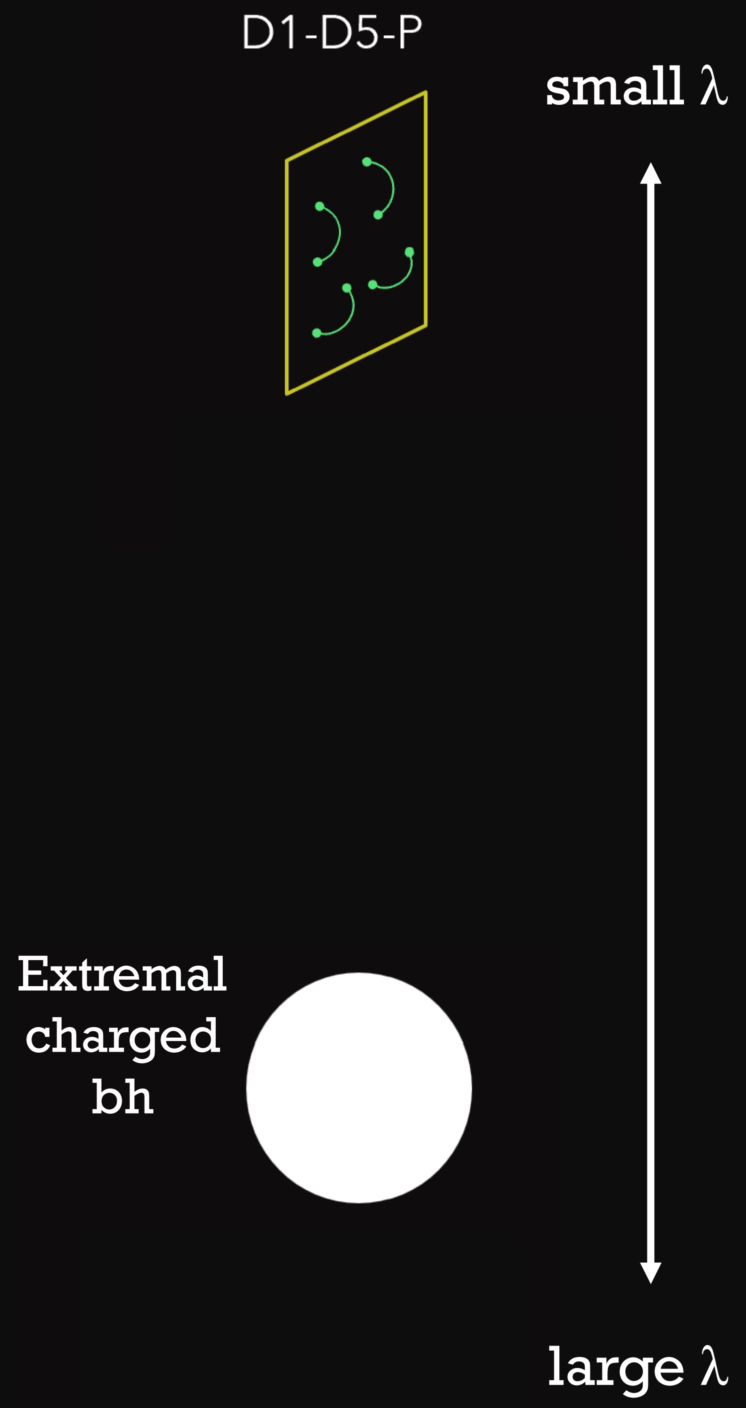
BLACK HOLES IN STRING THEORY

- String theory is by far the most promising candidate for a theory of quantum gravity
- Its main ingredients are no longer particles and quantum fields, but strings and branes, and all sorts of higher-dimensional objects
- But even though the theory started being developed already in the 60s, it was only in the 90s that we managed to talk about its connection to black holes
- This was done rigorously in the seminal paper by Strominger and Vafa, and many other examples then followed
- Notably, S+V did the calculation for very specific black holes, but Horowitz and Polchinski (in the same year) realized they can perform a perturbative calculation for all types of black holes!

$\delta\lambda = N\delta g$

WHAT COMPRISES A (SUSY) BLACK HOLE

- Our current understanding of black holes in string theory comes from a paper by Strominger and Vafa in 1996
- There are objects in string theory (such as D-branes) that we understand well for small string coupling g_s and **small** 't Hooft coupling $g_s{*}N = \lambda$
- But black holes are non-perturbative objects, with **large** 't Hooft coupling, so their understanding seems pretty much out of reach
- Cue SUSY---we can count the microscopic dofs (the index*) which will give the same answer at any value of the 't Hooft coupling λ
- This is how we can compare the two and obtain a microscopic understanding of black hole entropy



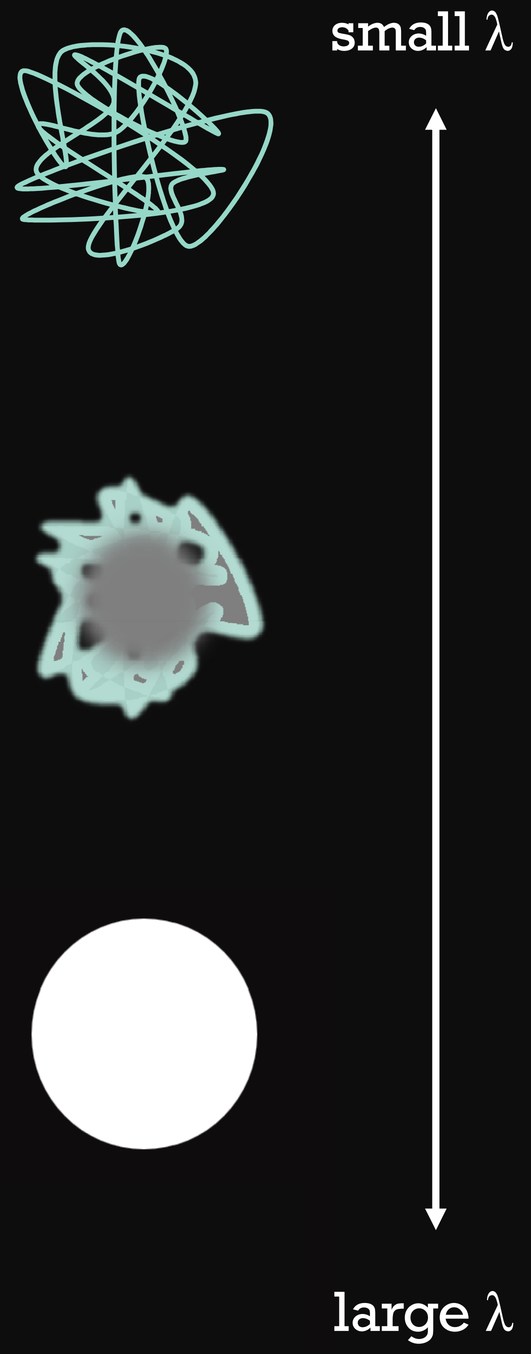
*at large λ, it is equivalent to the entropy

$$\delta\lambda = S\delta g^2$$

WHAT COMPRISES A (NEUTRAL) BLACK HOLE

Observation:

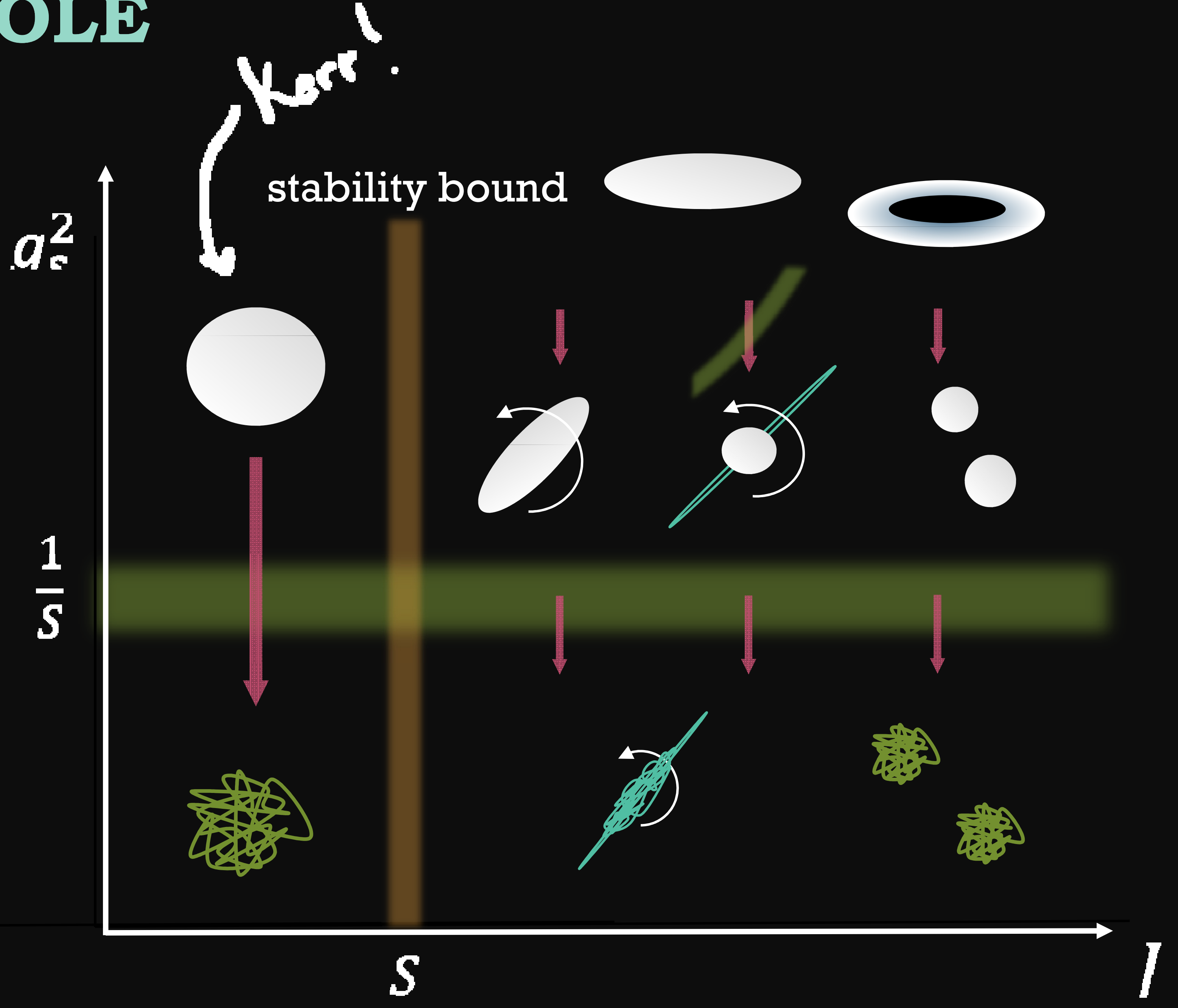
- Black holes are highly degenerate objects with a large entropy
- However, strings, when highly excited, are also highly degenerate
- So Horowitz and Polchinski in 1996 calculated the entropy and other thermodynamic properties of gravitating strings (‘string stars’) and saw that they match those of black holes up to some factors of order 1!
- The crucial point is that this correspondence must happen at a special value of the string coupling, gs ~ 1/S
- Therefore, we can have a microscopic understanding of non-SUSY black holes as well



WHAT COMPRISES A (ROTATING) BLACK HOLE

Indeed, we established the correspondence principle also for rotating black holes

Not only do their thermodynamic properties match, but the shapes and sizes do as well!



Ceplak, Emparan, Puhm, MT '23, '24

SUMMARY

- We are making enormous progress in our understanding of black holes
- In astrophysics, we have opened a new era of black hole observations that is bound to bring great new insights
- And when it comes to semiclassical black holes, we have cracked an enigma that lasted for almost 50 years
- Additionally, we are now starting to understand how to incorporate real-life black holes within a string theory description
- There are still many questions left, but one thing is for sure:

now is the best time to work on black holes!

THANK YOU!