From black holes to strings, and back

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Outline

Review of the old story

Creating a new story:
rotation and its puzzles

What comprises a black hole

- The fact that black holes have entropy still boggles our minds even after 50 years of its conception
- And after 50 years, we still have only some incomplete understanding of the microscopic structure of black holes
- ~recently---some progress made in the **semiclassical understanding** of bh entropy, through islands and Euclidean wormholes

  [Penington *et al.* ‘19, Almheiri *et al.* ’19, Balasubramanian *et al.* ‘22]
- but our best shot lies within the framework of **string theory**---we now know of several examples where exact bh microstate counting has been done

  [Sen ‘95, Strominger-Vafa ‘96,…eurostrings participants,…Iliesiu-Murthy-Turiaci ’22]
- However, such exact calculations can be done only in a limited number of cases, with SUSY, dualities, D-brane charges, etc.

What comprises a black hole

- In essence, these calculations can be understood from the AdS/CFT perspective, where the bh ~ strongly coupled CFT, which is then connected to the weakly-coupled CFT (that we understand in much more detail)
- But we needed SUSY to fix for us certain properties of the state (like the mass and the charges), so that the entropy would remain the same function of those parameters for the entire 't Hooft coupling (λ) scale

Can we obtain a counting of states without the use of SUSY or other symmetries?

Yes! But we need to compromise.

What comprises a black hole

Observation:

- Black holes are highly degenerate objects with a large amount of entropy
- However, strings, when highly excited, are also highly degenerate

How can we relate them without any SUSY-like protection?

simply **fix the entropy** while changing the string coupling!

- Of course, without SUSY-like protection, the mass will get renormalized as we change the coupling---need to check that the mass changes *adiabatically* from one side to another

What comprises a black hole

However, no exact results and no complete picture

This framework was first proposed by Susskind ‘93, and developed in detail by Horowitz and Polchinski ’96/7

The correspondence principle between black holes and fundamental strings

Black hole side

$$R_{\rm sch} = MG = M g_s^2 \ell_s^2 \qquad \frac{R_{\rm sch}}{\ell_s} = M g_s^2 \ell_s$$

$$S_{\rm BH} = \frac{Area}{4G} = M^2 G = M^2 g_s^2 \ell_s^2$$

String side

$$M = \frac{L}{\ell_s^2} \qquad S_s = \frac{L}{\ell_s}$$

$$S_s = M \ell_s$$

$$g_s^2 \sim \frac{1}{S}$$

Matching:

$$\frac{R_{\rm sch}}{\ell_s} \sim 1 \qquad M \sim \frac{1}{g_s^2 \ell_s}$$

$$S_{\rm BH} \sim \frac{1}{g_s^4 \ell_s^2}\, g_s^2 \ell_s^2 \longrightarrow S_{\rm BH} \sim \frac{1}{g_s^2}$$

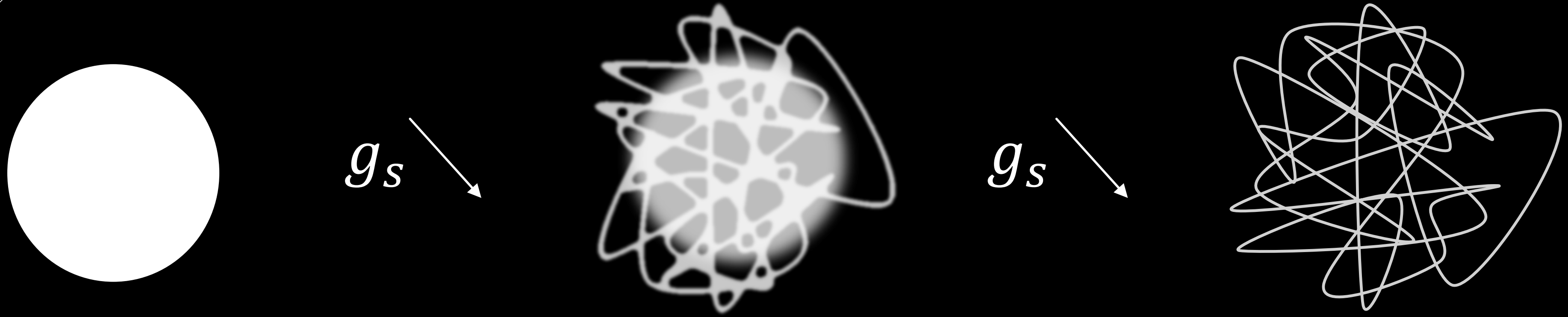
$$S_s \sim \frac{1}{g_s^2 \ell_s}\, \ell_s \longrightarrow S_s \sim \frac{1}{g_s^2}$$

4D results

The black hole-string transition

The black hole-string transition

curvature $\sim \frac{1}{\ell_s^2}$



curvature $\sim \frac{1}{(GM)^2} \sim \left(\frac{M_s}{g_s^2 M}\right)^2 \frac{1}{\ell_s^2}$

$$g_s^2 \sim \frac{M_s}{M} \ll 1$$

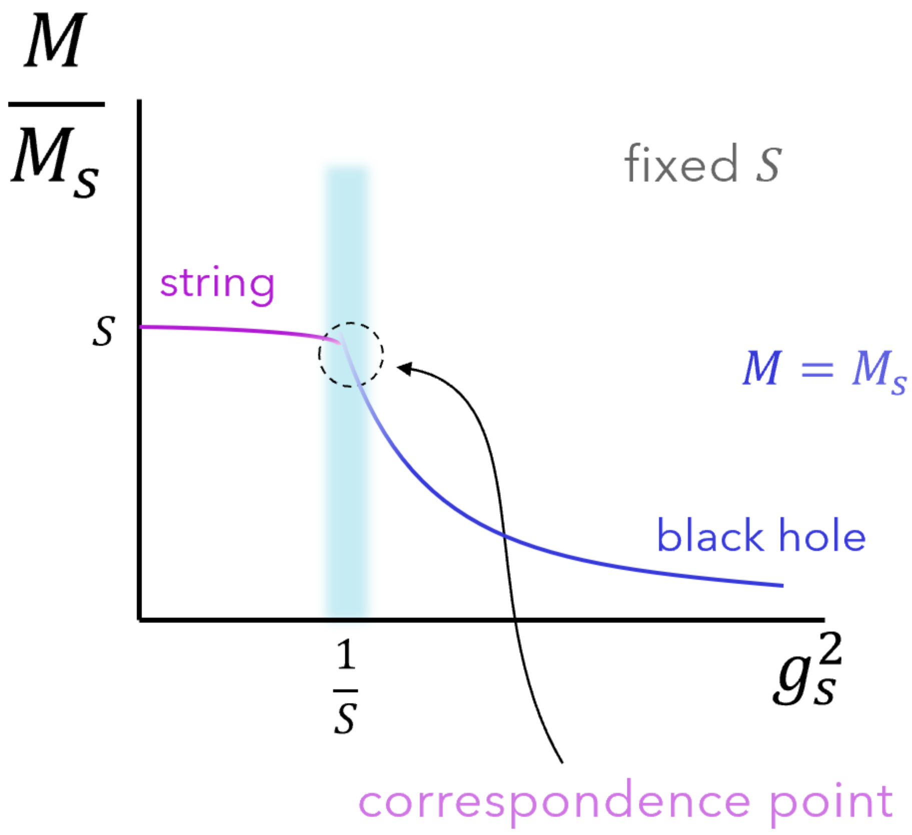
The black hole-string transition

The blue line is the line of fixed black hole mass in M_P

The pink line is the line of fixed string mass in M_s

They match up to O(1) factors for the coupling constant ~ 1/S

We can adiabatically* switch between the black hole and the fundamental string



Coming from the string side

- So far, we focused on decreasing the coupling coming from the black hole side

What about the string side?

- A very good* model for strings is a random walk picture: each step of the random walk is one unit of l_s
- The full walk gives the length of the string, which is proportional to its mass and entropy, as expected

*Quantum string construction reproduces random walk results

Coming from the string side

- However, the size is too big: there are no constraints on this walk except for its length, and if it can explore the space, it will!

$$\text{size} \sim N^{\frac{1}{4}} \ell_s$$

$$N = (\#\text{ of steps})^2 \sim \left(\frac{M}{M_s}\right)^2$$

- HP: include backreaction of self-gravitation, and the ball will shrink

Horowitz, Polchinski '97

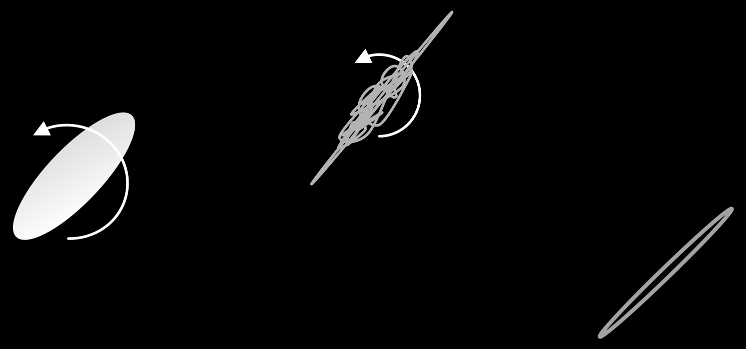
The black hole-string transition

- By relating a black hole to a set of weakly coupled string states, the correspondence principle provides a statistical description of black hole

- In contrast to the precise counting of states for extremal and near-extremal black holes, this method does not in general determine the numerical coefficient in the entropy since that would depend on the precise coupling at which the transition occurs

- However, it applies to a much wider class of black holes and reproduces the correct functional dependence on the mass and charges

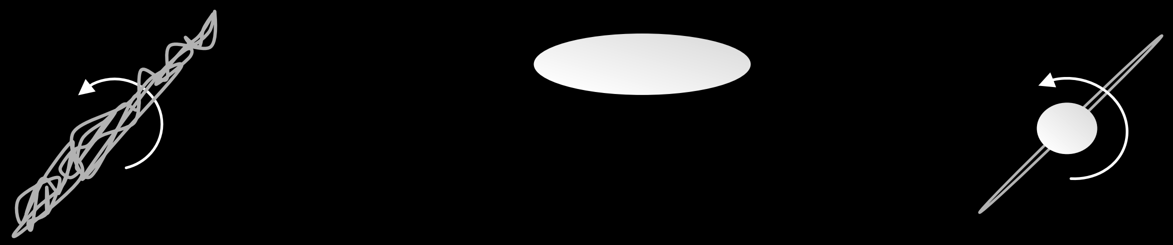
Adding rotation



The black holes and strings considered so far were static
---what changes once we add rotation?

First, the space of solutions increases drastically:

bhs with rotation in various dimensions exist in various shapes and forms;
same goes for strings!



The black hole zoo

- What are the main characters?
- First, we have the plumpest of all, Kerr-like black holes
- But then we also have other topologies and other shapes like rotating black rings, pancakes and bars: the higher the number of dimensions, the higher the number of shapes

- Aside from the different shapes, we have a new feature w.r.t. the old story: we have **bounds** on the angular momentum

The Kerr bound: $J \leq M^2$

- In 4D, the Kerr bound is an *existence bound*: black holes which violate the Kerr bound cannot exist
- In 5D and higher, this bound becomes a *stability bound*: there can be black holes with arbitrarily large J, but then they are dynamically unstable

They fragment into smaller pieces or quickly radiate away their angular momentum

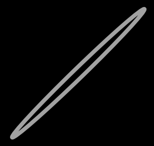
Myers, Perry '86
Emparan, Reall '01

The string zoo

- Strings can also exist in various shapes and forms
- And rotating strings also have a bound on their angular momentum

  ---the Regge bound

$$J \leq M^2 ?$$



Kerr and Regge bound are NOT the same: $M_s = g_s M_P \ll M_P$

$$J_{Kerr} = \frac{M^2}{M_P^2} = g_s^2 \frac{M^2}{M_s^2} \ll J_{Regge} = \frac{M^2}{M_s^2}$$

Higher dimensions

This is even more apparent in higher dimensions where

$$J_{Regge} = \frac{M^2}{M_s^2} = S_0^2 \quad \text{but} \quad J_{Kerr} = M(GM)^{\frac{1}{D-3}} = S$$

Puzzles…

There are two puzzles that emerge:

1) There are bhs that have arbitrarily large angular momentum; if so, how can they connect with strings which have some bound on their J?

2) Since Regge bound is at higher J than the Kerr bound, how can highly-spinning strings connect with bhs beyond the 4D Kerr (existence) bound if such bhs don't exist?

…and their resolutions

- The second puzzle is partially resolved once we recall that the **Regge string has zero entropy**: since we always fix our entropy to be of some finite (and large) value, this effectively pushes the Regge bound out of the correspondence*.
- However, there still exist strings below the Regge bound but above the Kerr bound which have large entropy

The resolution of both puzzles then lies in a **hidden assumption**: that the matching must happen between two stationary solutions

*this is also consistent with the fact that there are no zero entropy black holes

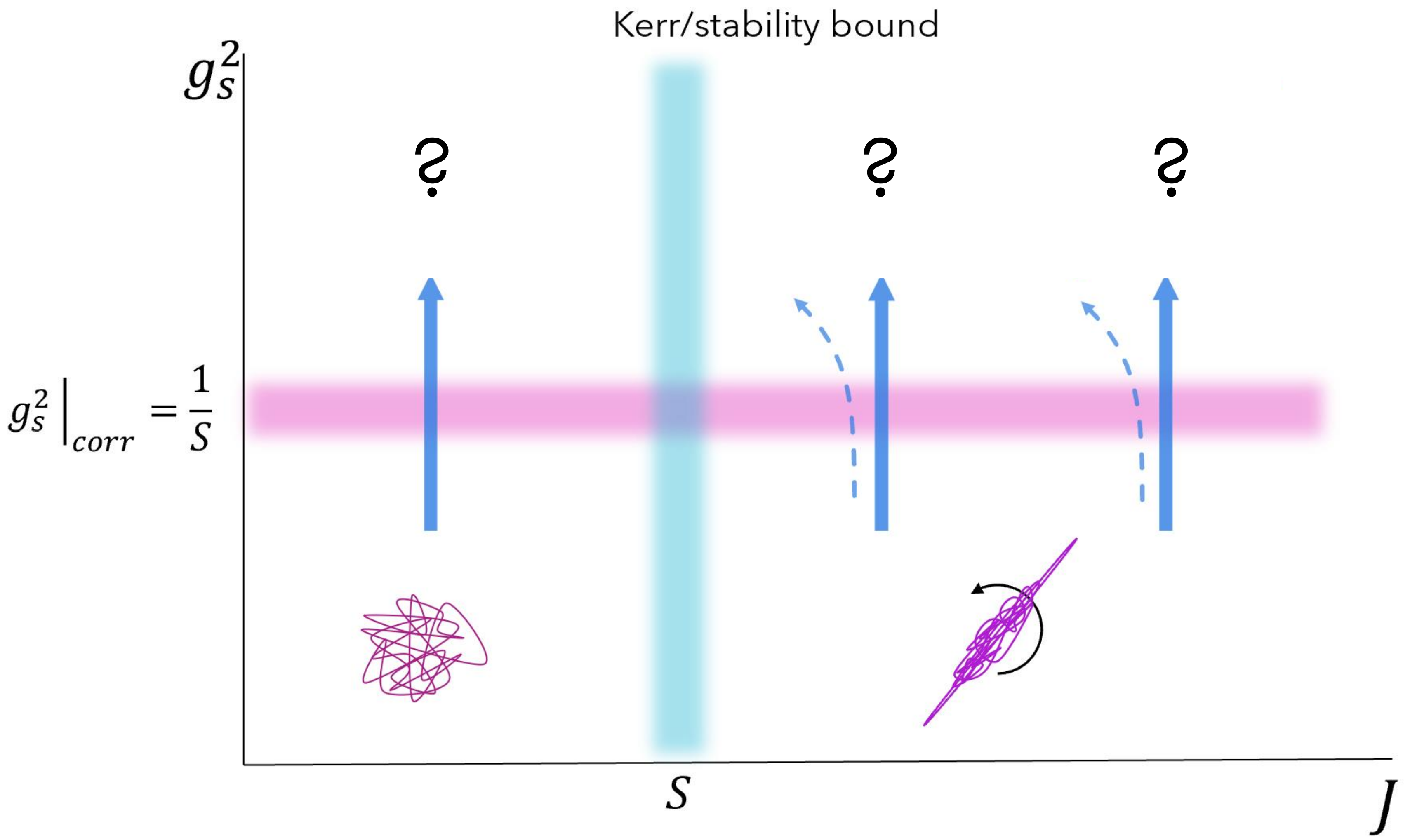
…and their resolutions

- Namely, even though we can write down the solution for the ultraspinning black holes, these solutions are *dynamically unstable*

In other words, they are non-adiabatic for some time until they transition into quasi-stationary solutions

- It is only then that we can define the adiabats and start connecting with strings!
- Same goes for strings: they are also expected to radiate angular momentum once self-gravity is accounted for

Strings to black holes:



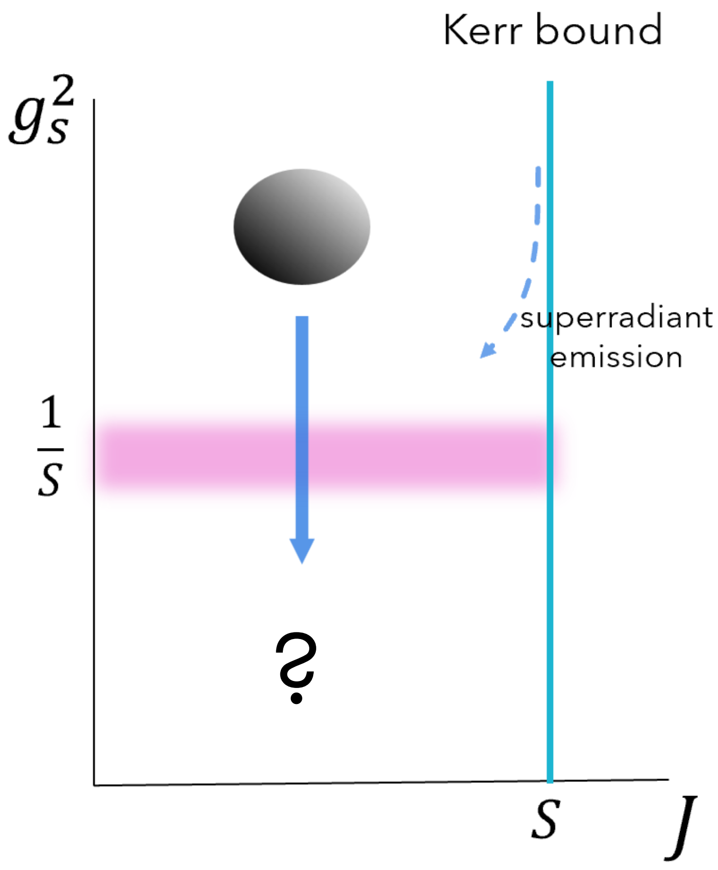
Ultraspinning black holes → black hole/string hybrids

Curvature on horizon first becomes string-size near the equator

Deng, Gruzinov, Levin, Vilenkin ’23

Black holes to strings:

D=4



Dynamical transition

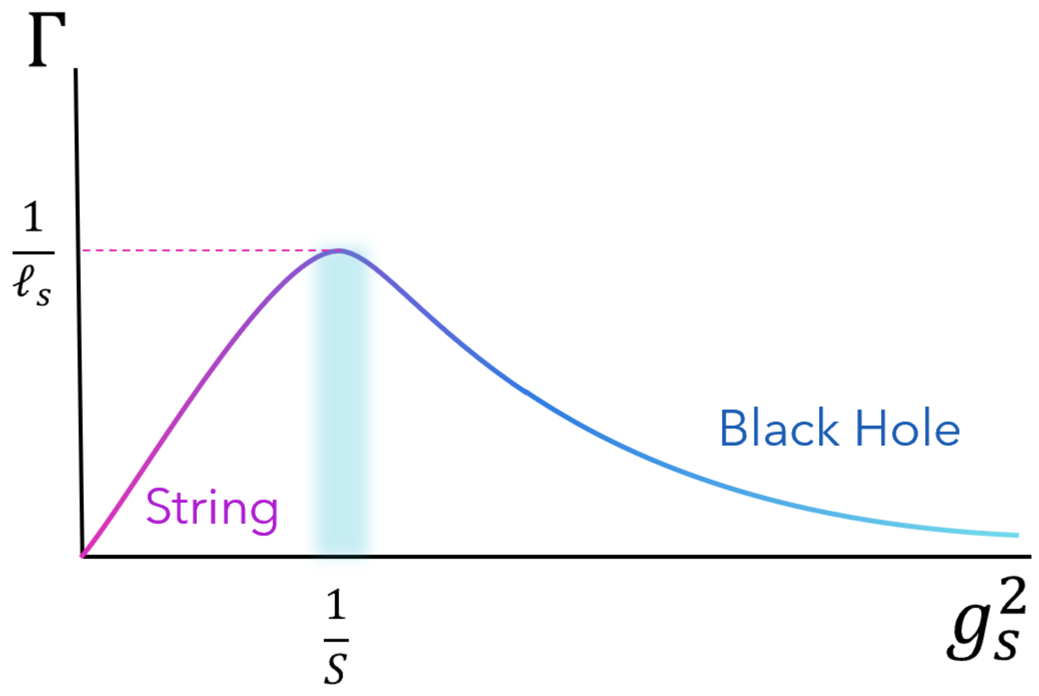
We see that in order to establish a correspondence, we have to introduce non-stationary solutions:

dynamics must be taken into account

This includes *quantum* dynamics as well, even for non-rotating solutions

String decay $\Gamma \sim g_s^2 M \sim g_s^2 \frac{S}{\ell_s}$

Black hole decay $\Gamma \sim T_{BH} \sim \frac{1}{g_s \sqrt{S}\, \ell_s}$



Damour, Veneziano '98

Goldilocks adiabaticity

Rate of change Δt^{-1} of the coupling g_s

Not too fast, not too slow

$$\frac{1}{S\,\ell_s} \ll \Delta t^{-1} \ll \frac{1}{\ell_s}$$

Not too slow: not lose entropy through quantum emission

Not too fast: not pump energy into system (adiabaticity)

Summary, conclusion

Main lesson:

the correspondence principle must take dynamics into account

Then we do not have any puzzles and one can establish a correspondence between rotating black holes and fundamental (multi-)strings

- However, this was the first step: we now need to construct a solution at non-zero string coupling which incorporates rotation---and check if all string theories allow for such a solution
- Also: adding charges of other kinds? Superradiance? Different backgrounds e.g., AdS?

Chen, Maldacena, Witten '21
Santos, Zigdov '23

Thank you!