The Correspondence Between Rotating Black Holes and Fundamental Strings

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Based on ongoing work with R. Emparan, A. Puhm, and M.Tomašević

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Black holes in string theory

- Black holes have large entropy

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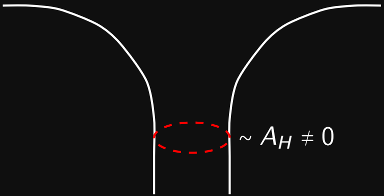

strong coupling

$\sim A_H \neq 0$

Black hole entropy

$$S_{\mathrm{BH}} \approx 2\pi\sqrt{N_1\,N_5\,N_P}$$

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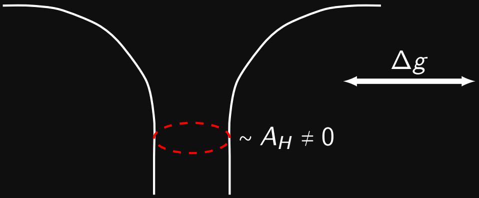

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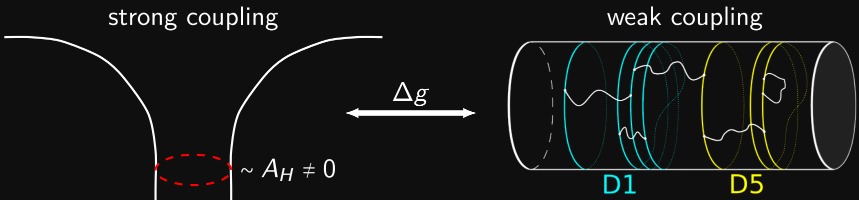

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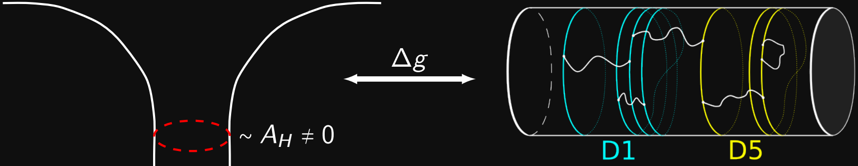

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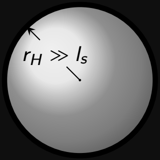
$$\boxed{S_{BH} = S_{\mathrm{Micro}}}$$

Schwarzschild black holes and fundamental strings

Schwarzschild Black Hole with mass M

$$g^2 \frac{M}{M_S} \gg 1$$

Black hole entropy
S_{BH}



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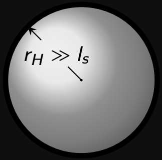

Closed strings with mass $M \sim \sqrt{N}\, M_s$

$$g^2 \frac{M}{M_S} \to 0$$

Microscopic Entropy
S_{Micro}

$$* \; g^2 \sim \left(\frac{l_P}{l_s}\right)^{D-2} \sim \left(\frac{M_s}{M_P}\right)^{D-2}$$

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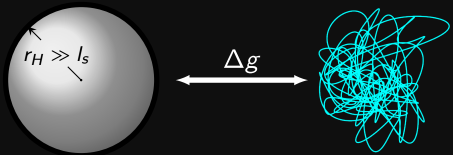

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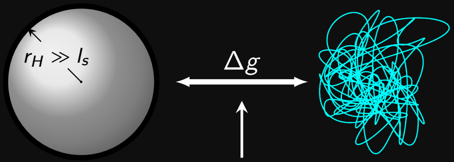

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If Δg adiabatic
$S_{\mathrm{BH}} \sim S_{\mathrm{Micro}}$

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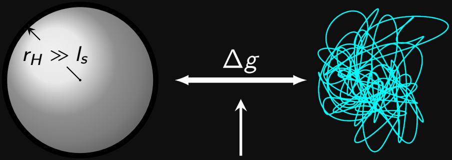

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- $r_H \sim \left(\frac{M}{M_P}\right)^{\frac{1}{D-3}} l_P \sim \left(g^2\, \frac{M}{M_s}\right)^{\frac{1}{D-3}} l_s\,,$

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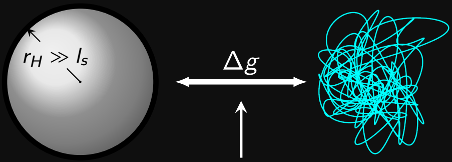

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- $r_H \sim \left(\frac{M}{M_P}\right)^{\frac{1}{D-3}} l_P \sim \left(g^2 \frac{M}{M_s}\right)^{\frac{1}{D-3}} l_s\,,$

- $S_{\rm Micro} \sim \frac{M}{M_s} \sim \sqrt{N}\,,$
- $\langle r \rangle \sim \sqrt{\frac{M}{M_s}}\, l_s \sim \sqrt{S_{\rm Micro}}\, l_s\,,$

$* \; g^2 \sim \left(\frac{l_P}{l_s}\right)^{D-2} \sim \left(\frac{M_s}{M_P}\right)^{D-2}$

The correspondence

[Susskind, Horowitz+Polchinski, Damour+Veneziano...]

- Change the string coupling g while keeping the entropy S fixed.
- The black hole and free string descriptions change when the curvature at the horizon of the black hole becomes of the string scale.

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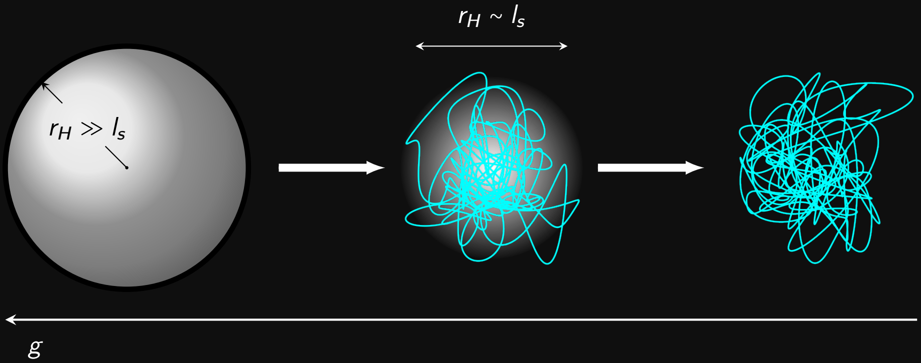
- For Schwarzschild Black holes the correspondence point is when the horizon radius is of the string scale:



[Susskind]

- Fix the entropy of a large black hole

$$S_{\mathrm{BH}} \sim \left(\frac{M}{M_P}\right)^{\frac{D-2}{D-3}} \sim g^{\frac{2}{D-3}} \left(\frac{M}{M_s}\right)^{\frac{D-2}{D-3}}$$

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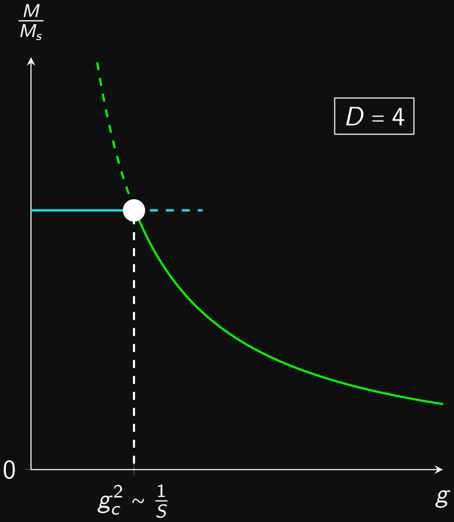
$$\boxed{g_c^2 \sim \frac{M_s}{M} \sim \frac{1}{S_{\mathrm{BH}}} \ll 1}$$



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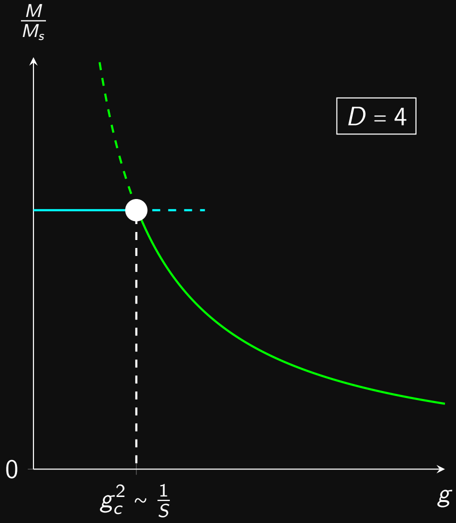

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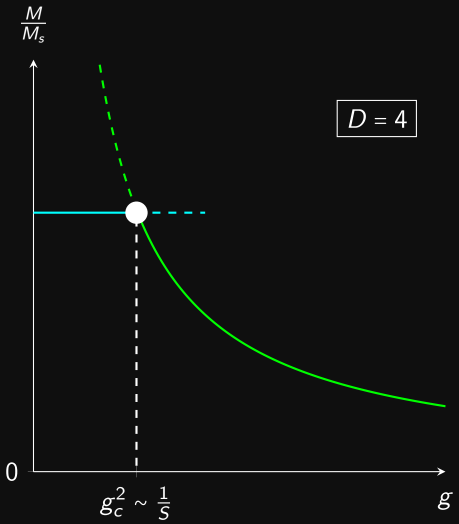

- A parametric match between black hole and string states up to $\mathcal{O}(1)$ factors.

Other properties

- Hawking temperature increases to the Hagedorn scale

$$T_{\mathrm{Haw}} \sim \frac{1}{r_H}\Big|_{g=g_c} \sim \frac{1}{l_s} \sim T_{\mathrm{Hag}}$$

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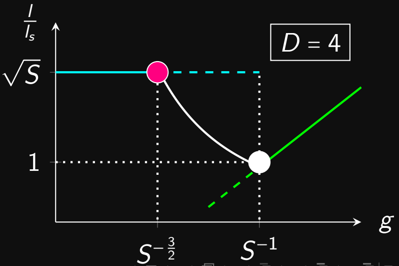
- Upshot: Self-interactions interpolate between black hole and free string sizes.
- Modelled using a winding condensate near the Hagedorn temperature.



Dilaton wave

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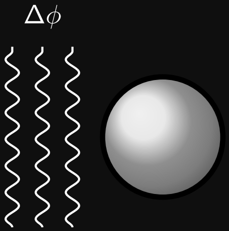

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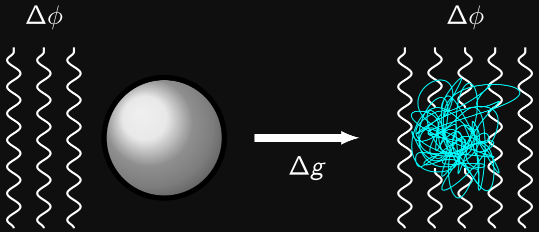

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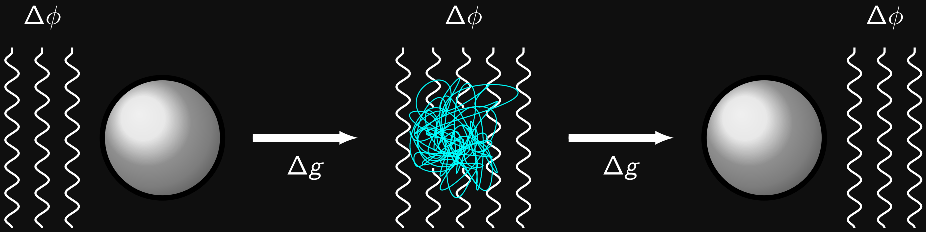

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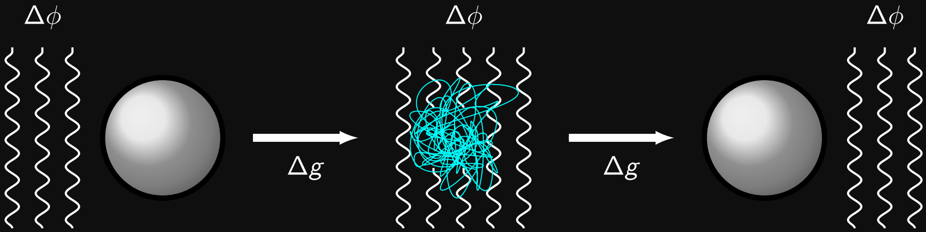

- Goldilocks rate of change for the string coupling

$$\frac{1}{S\, l_s} \lesssim \Delta t_g^{-1} \lesssim \frac{1}{l_s}$$

  - Fast enough to avoid significant evaporation,
  - Slow enough to avoid exciting stringy degrees of freedom.

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Stringy objects ($g = 0$)

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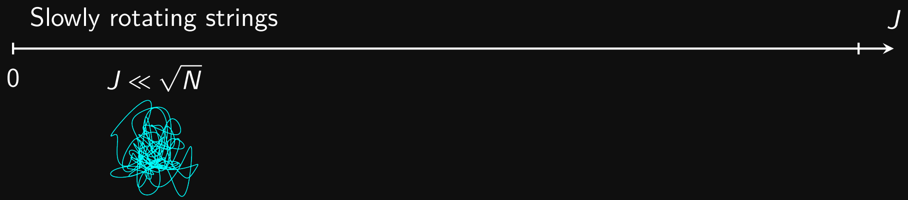

Slowly rotating strings

J

0

$J \ll \sqrt{N}$

$$\langle r^2 \rangle_\perp \sim \sqrt{N}\left[1 - \mathcal{O}\left(\frac{J^2}{N^2}\right)\right]$$

$$S \sim \sqrt{N}\left[1 - \mathcal{O}\left(\frac{J^2}{N^2}\right)\right]$$

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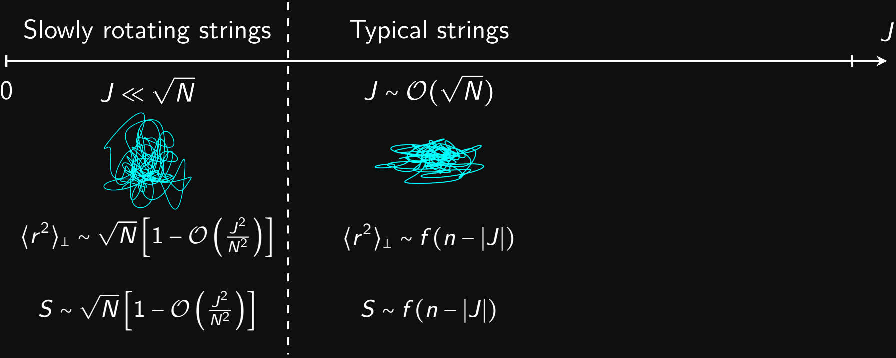

Slowly rotating strings

Typical strings

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$J \sim \mathcal{O}(\sqrt{N})$

$\langle r^2 \rangle_\perp \sim \sqrt{N}\left[1 - \mathcal{O}\left(\frac{J^2}{N^2}\right)\right]$

$\langle r^2 \rangle_\perp \sim f(n - |J|)$

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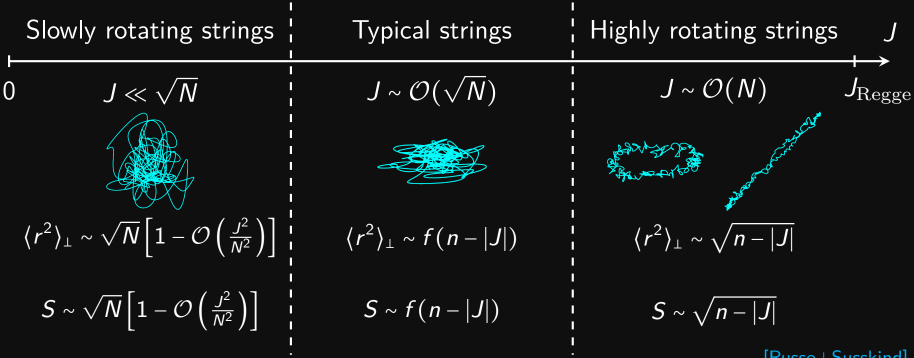

Slowly rotating strings	Typical strings	Highly rotating strings
$J \ll \sqrt{N}$	$J \sim \mathcal{O}(\sqrt{N})$	$J \sim \mathcal{O}(N)$
$\langle r^2 \rangle_\perp \sim \sqrt{N}\left[1 - \mathcal{O}\left(\frac{J^2}{N^2}\right)\right]$	$\langle r^2 \rangle_\perp \sim f(n - \lvert J \rvert)$	$\langle r^2 \rangle_\perp \sim \sqrt{n - \lvert J \rvert}$
$S \sim \sqrt{N}\left[1 - \mathcal{O}\left(\frac{J^2}{N^2}\right)\right]$	$S \sim f(n - \lvert J \rvert)$	$S \sim \sqrt{n - \lvert J \rvert}$

[Russo+Susskind]

Black hole zoo

- Two characteristic length scales:

$$\text{Mass length:} \quad L_M \equiv \left(\frac{M}{M_P}\right)^{\frac{1}{D-3}} l_P \,, \qquad \text{Spin length:} \quad L_J \equiv \frac{J}{M} \,,$$

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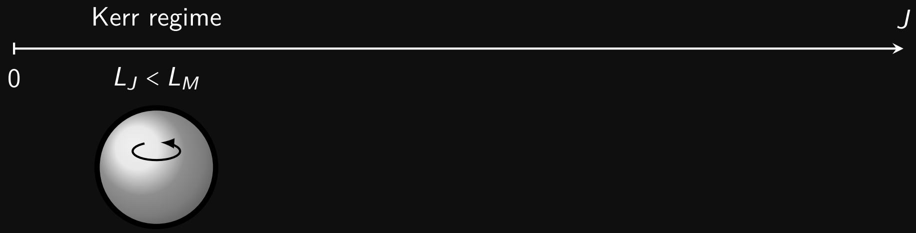

Kerr regime

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$L_J < L_M$

Kerr ($D = 4$) and
Myers-Perry ($D \geq 5$)
black holes

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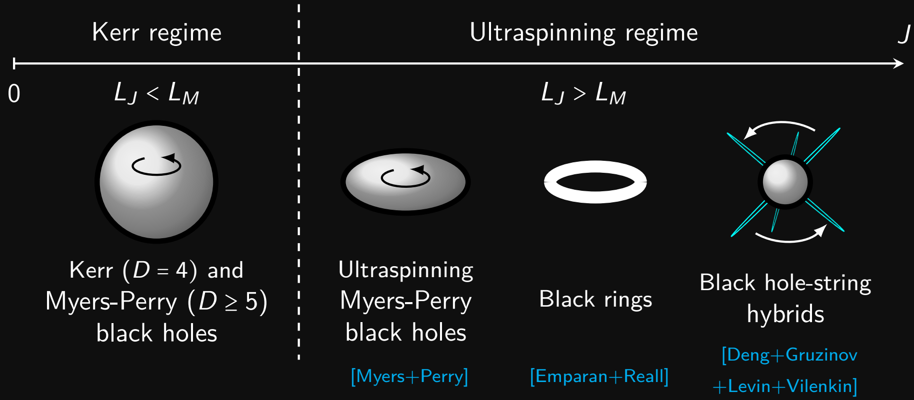

Kerr regime

Ultraspinning regime

J

0

$L_J < L_M$

$L_J > L_M$

Kerr ($D = 4$) and Myers-Perry ($D \geq 5$) black holes

Ultraspinning Myers-Perry black holes

[Myers+Perry]

Black rings

[Emparan+Reall]

Black hole-string hybrids

[Deng+Gruzinov +Levin+Vilenkin]

Stability of solutions

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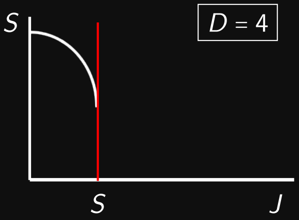

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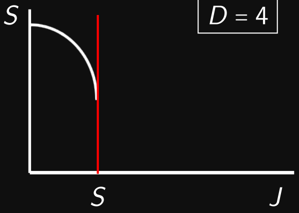

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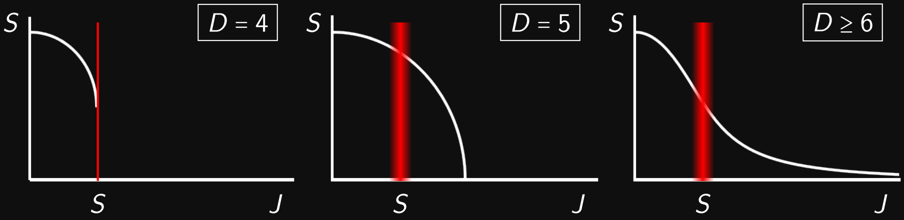
- In $D = 4$, the Kerr bound is an existence bound: No solutions with $J > S$.
- In $D \geq 5$, the "Kerr bound" is a dynamical bound.
  - Solutions with $J \lesssim S$ are stable,
  - Solutions with $J > S$ exist, but are unstable. (Except $D = 5$ ultraspinning Myers-Perry black holes)



Stability of solutions

- Kerr bound can be rewritten as

$$L_J \leq L_M \,, \qquad \Longleftrightarrow \qquad \boxed{J \leq S}$$

- In $D = 4$, the Kerr bound is an existence bound: No solutions with $J > S$.
- In $D \geq 5$, the "Kerr bound" is a dynamical bound.
  - Solutions with $J \lesssim S$ are stable,
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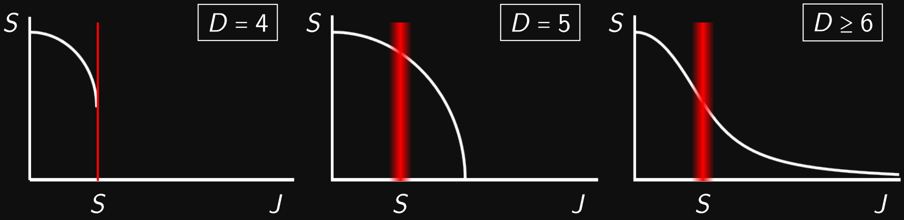
[Emparan+Harmark+Niarchos+Obers]



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Adding angular momentum to the correspondence

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Problem 2: In $D \geq 5$ there are black hole solutions with arbitrary large angular momentum, which can be larger than the Regge bound.

Problem 3: Stringy configurations that saturate the Regge bound (String rods) have low degeneracy: ($S \sim \sqrt{N - |J|}$) and look nothing like black holes.

General principle

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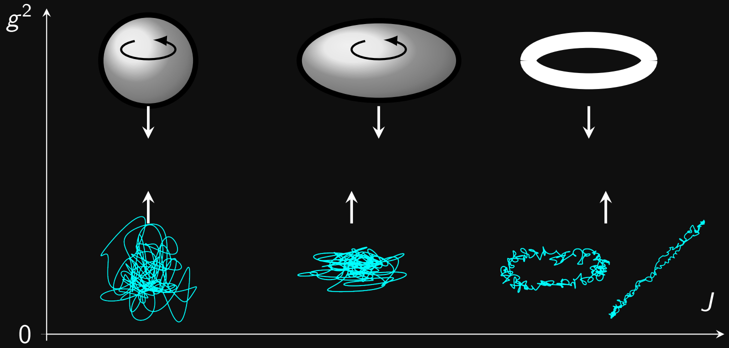

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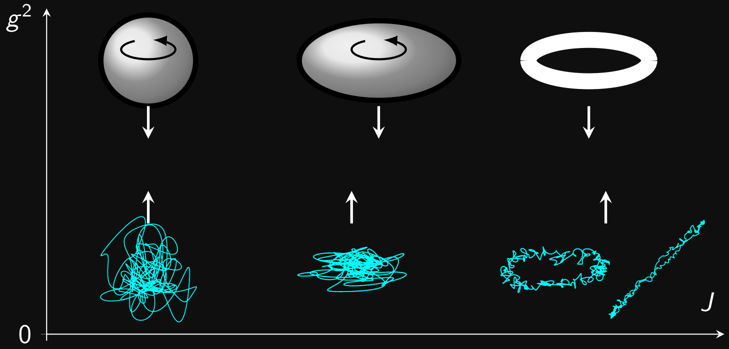

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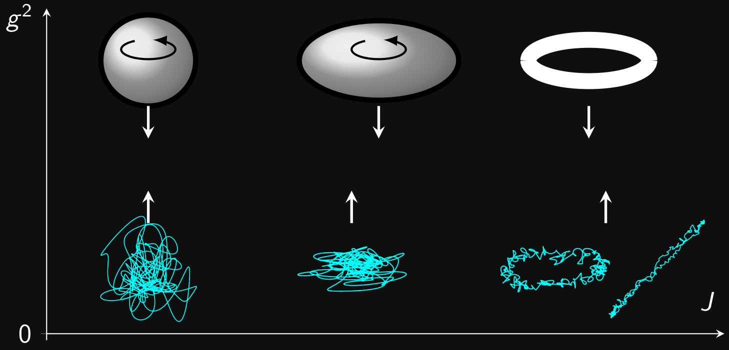

- New ingredient: transition into non-stationary objects.

The correspondence for black holes

- In Kerr regime ($J \lesssim S$) angular momentum contributes an $\mathcal{O}(1)$ factor

$$r_+ = \frac{M}{M_P}\left[1+\sqrt{1-\frac{M_P^4}{M^4}\,J^2}\,\right] l_P\,, \qquad S_{\rm BH} = \frac{M^2}{M_P^2}\left[1+\sqrt{1-\frac{M_P^4}{M^4}\,J^2}\,\right],$$

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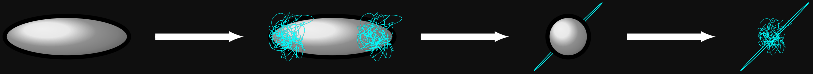

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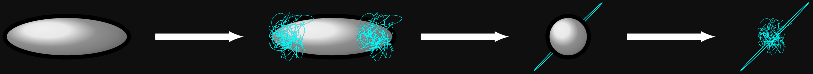

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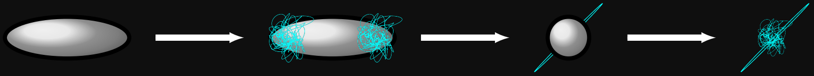

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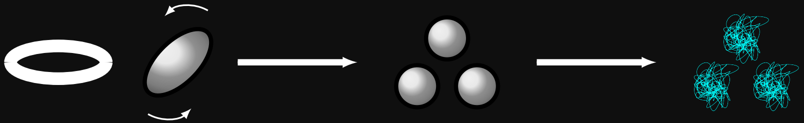

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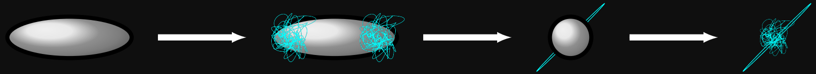

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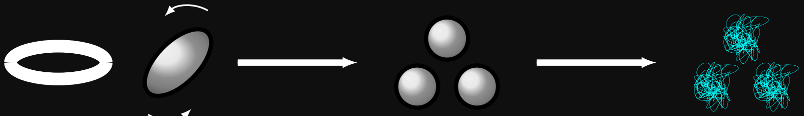
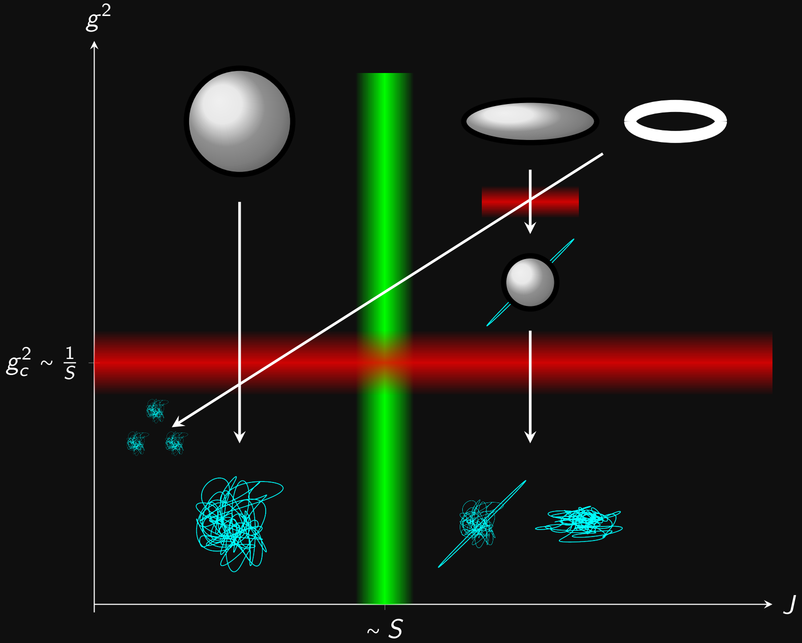


- Each individual fragment will transition into a (slowly rotating) string.


g^2
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J
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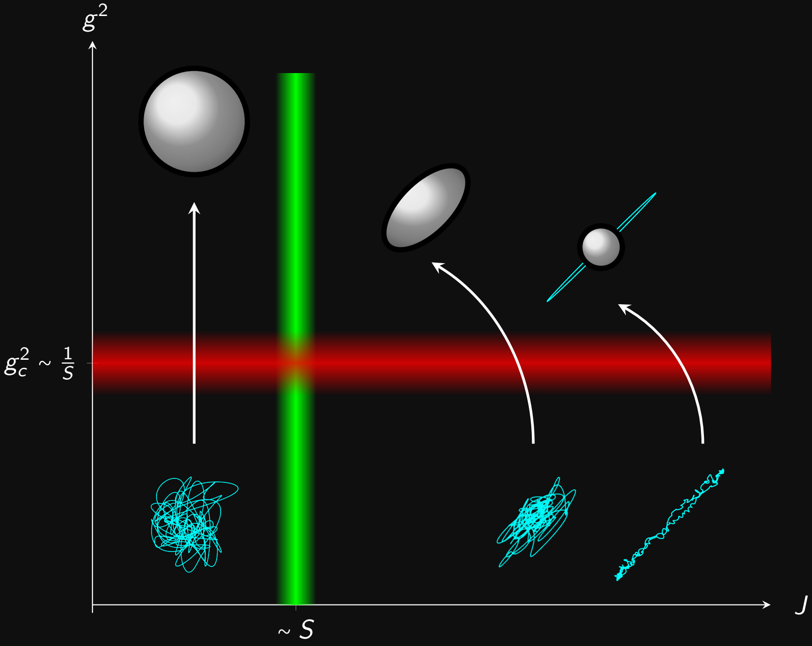
- If sufficiently long lived, a string hybrid can form non-adiabatically [Deng+Gruzinov+Levin+Vilenkin].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- Some transitions depend on the direction in which we change the coupling: Non-reversible changes due to unstable solutions.
- This resolves several puzzles for the correspondence of highly rotating objects.

Outlook

- Details of transitions?
  ⇒ For which configurations with angular momentum can one find bound states at $g > 0$? [Horowitz+Polchinski]

- What happens near the extremal bound in $D = 4$?

- Other asymptotics (AdS/dS)?
- Adding Ramond charges?

- What is the microstructure at strong coupling?

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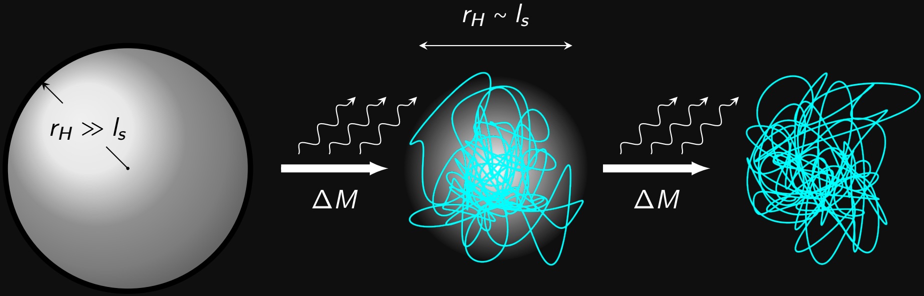
Dynamical evaporation

- Hawking evaporation: Fix g at a large value and decrease M and S.
- When $r_H \sim l_s$

$$M \sim \frac{1}{g^2} M_s \,, \qquad S_{\rm BH} \sim \frac{1}{g^{\frac{2}{D-3}}} \,, \qquad T_{\rm Haw} \sim \frac{1}{l_s} \sim T_{\rm Hag} \,,$$

you can think of the black hole becoming a hot soup of weakly interacting strings ⇒ Possible endpoint of BH evaporation



Calculating the Goldilocks regime

- The upper bound is obtained by demanding that no additional stringy state is excited

$$\frac{1}{\Delta t_g} = \frac{\dot{g}}{g} = \dot{\phi} \lesssim \frac{1}{l_s} \,,$$

$\Rightarrow$ Dilaton wave Wavelength must be larger than the string length.

- Black holes and strings radiate at finite g

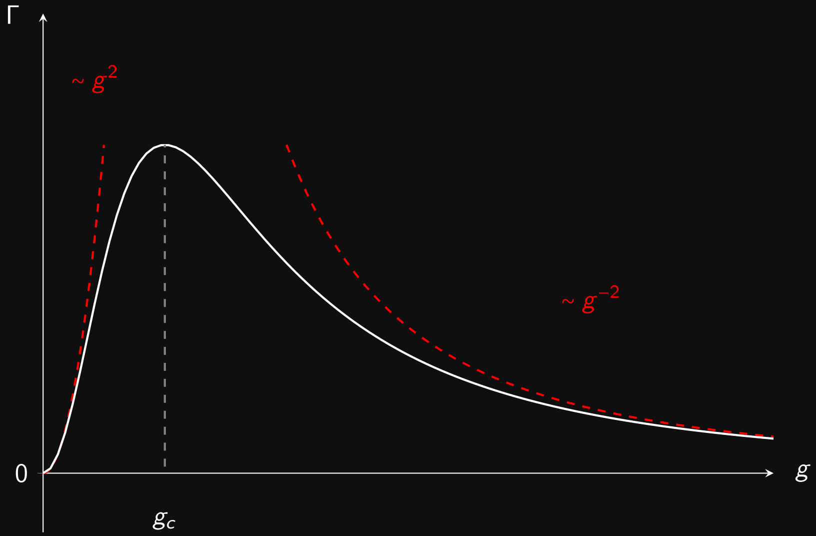
$$\Gamma_{\mathrm{BH}} \sim T_H \sim \frac{(g^2\, S)^{-\frac{1}{D+2}}}{l_s} \,, \qquad \Gamma_{\mathrm{String}} \sim g^2\, M \sim \frac{g^2\, S}{l_s} \,,$$

and these two rates match at the correspondence point.

- For a Black hole, a quantum is emmited every thermal time T_H^{-1}. In Δt_g we want the change of entropy to be negligible

$$|\Delta S| \sim \Delta t_g\, T \ll S \,, \quad \Longrightarrow \quad \frac{1}{\Delta t_g} \gg \frac{T}{S} \sim \frac{1}{S\, l_s} \,,$$

where we took the maximal temperature at $g = g_c$.


Γ
$\sim g^2$
$\sim g^{-2}$
0
g
g_c

Black objects in $D = 4$

- Kerr black hole
- Radius of the outer horizon

$$r_+ = \frac{M}{M_P}\left[1 + \sqrt{1 - \frac{M_P^4}{M^4}\, J^2}\,\right] l_P\,,$$

- Entropy

$$S_{\mathrm{BH}} = \frac{M^2}{M_P^2}\left[1 + \sqrt{1 - \frac{M_P^4}{M^4}\, J^2}\,\right],$$

- Temperature

$$T_{\mathrm{Haw}} \sim \frac{\sqrt{1 - \frac{M_P^4}{M^4}\, J^2}}{r_+}$$

- Kerr Bound

$$J_{\mathrm{Kerr}} \leq \frac{M^2}{M_P^2}\,.$$

$D \geq 5$

- I will focus on black objects with only one plane of rotation.
- Simplest solutions are Myers-Perry black holes [Myers+Perry]

$$ds^2 = -dt^2 + \frac{\mu}{r^{D-5}\,\Sigma}\left(dt - a\,\sin^2\theta\,d\phi\right)^2 + \frac{\Sigma}{\Delta}\,dr^2 + \Sigma\,d\theta^2 + \left(r^2 + a^2\right)\,\sin^2\theta\,d\phi^2$$
$$+ r^2\,\cos^2\theta\,d\Omega_{D-4}^2\,,$$

where

$$\Sigma = r^2 + a^2\,\cos^2\theta\,, \qquad \Delta = r^2 + a^2 - \frac{\mu}{r^{D-5}}\,,$$

and

$$\mu = \frac{16\,\pi\,G}{(D-2)\Omega_{D-2}}\,M\,, \qquad a = \frac{D-2}{2}\,\frac{J}{M}\,.$$

Myers-Perry Black holes

- The event horizon is determined by

$$r_0^2 + a^2 - \frac{\mu}{r_0^{D-5}} = 0\,,$$

- The entropy is proportional to

$$S_{\mathrm{MP}} \sim r_0^{D-4}\,(r_0^2 + a^2)\,.$$

Black rings ($D \geq 5$)

[Emparan+Reall]

- Gravitational attraction is balanced out by angular momentum.
- Can also have arbitrary large angular momentum.

- We will consider two cases:
  - Neutral black rings
  - Dipole black rings (additional fundamental string dipole charge) [Emparan]