The correspondence between rotating black holes and fundamental strings

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Quantum Information, Quantum Matter and Quantum Gravity

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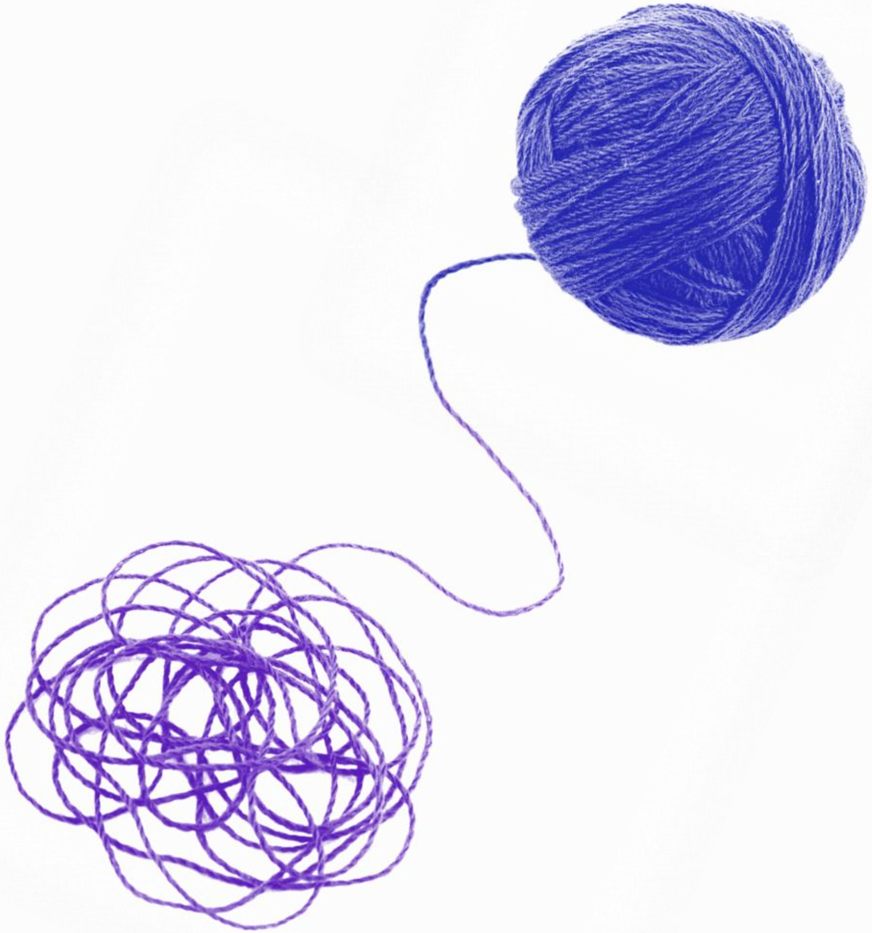

Black holes are massive, large, highly degenerate objects

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Strings have very massive, large, highly degenerate states

Black hole entropy (Bekenstein)

$$S_{BH} \propto M^2$$

String degeneracy (Hagedorn)

$$S_{st} \propto M$$

Different?

Black hole entropy (Bekenstein)

$$S_{BH} \propto M^2$$

String degeneracy (Hagedorn)

$$S_{st} \propto M$$

In what units?

Gravitational units

$$S_{BH} = \frac{M^2}{M_P^2}$$

$$M_P^2 = G^{-1}$$

String units

$$S_{st} = \frac{M}{M_s}$$

$$M_s^2 = \alpha'^{-1}$$

$$M_s = g\, M_P$$

g: string coupling

Perturbatively $g \ll 1$

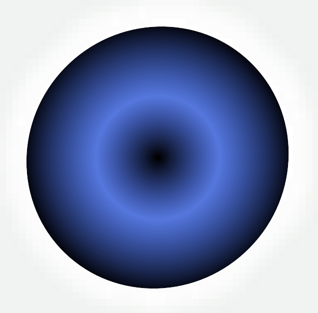
$$M_s \ll M_P$$

Black holes are strongly gravitating

Strings are weakly gravitating

$$\text{curvature} \sim \frac{1}{(GM)^2}$$

$$\sim \frac{1}{g^2 S} \frac{1}{\ell_s^2}$$



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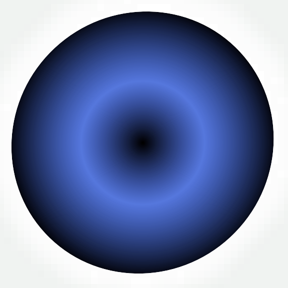


g

$$g^2 \sim \frac{1}{S} \ll 1$$

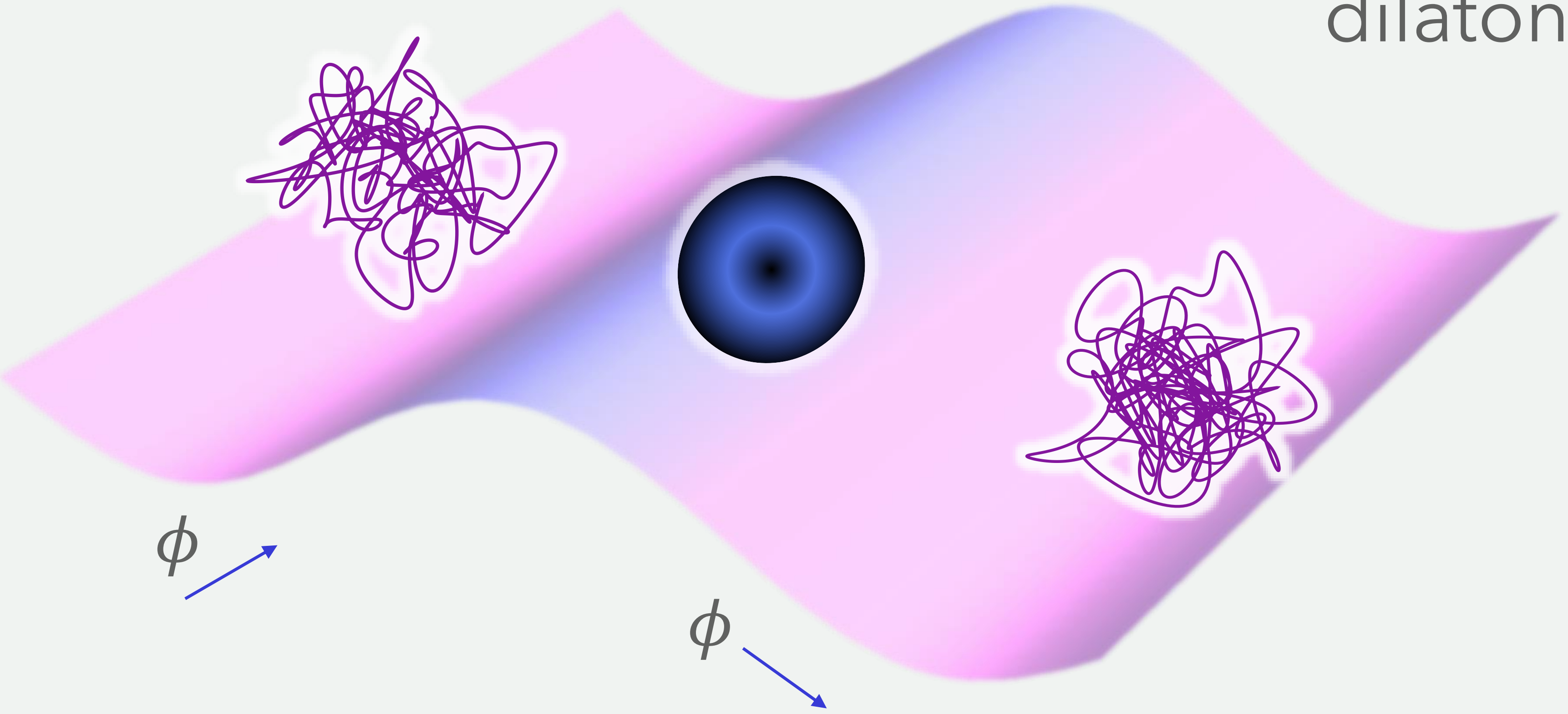
$$\text{curvature} \sim \frac{1}{(GM)^2}$$

$$\sim \frac{1}{g^2 S}\frac{1}{\ell_s^2}$$

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

$$g^2 \sim \frac{1}{S} \ll 1$$

dilaton wave $g = e^{\phi}$



Adiabatically switch between
massive string and black hole

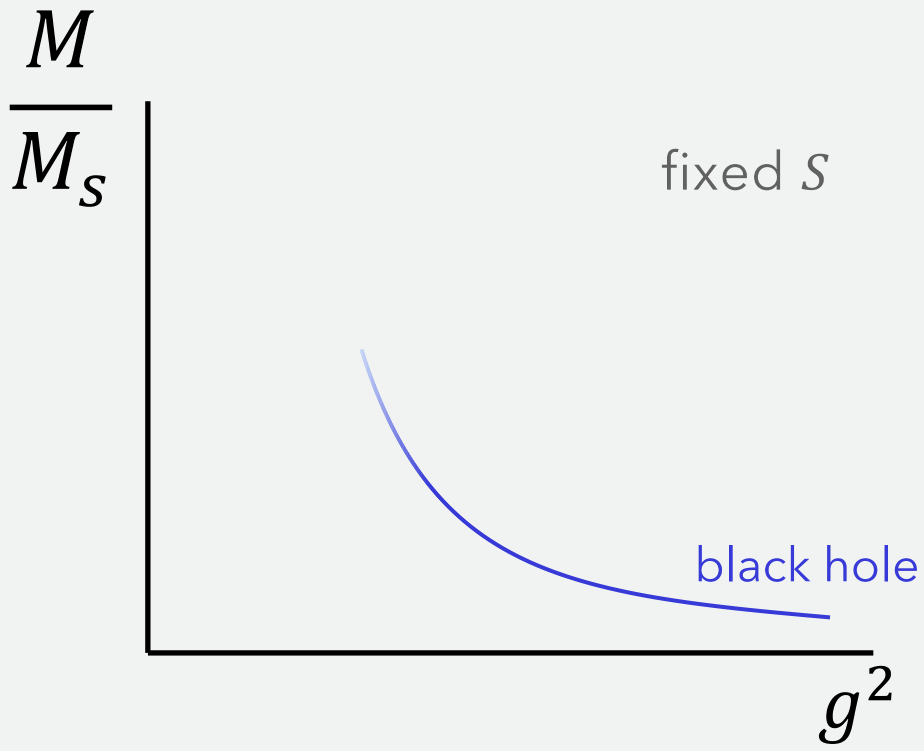
Susskind 1993
Horowitz+Polchinski 1996
Veneziano+Damour 1998

Susskind 1993

Fix entropy ≡ fix state

As g changes, mass gets renormalized by interactions

Black hole $M = M_s \frac{\sqrt{S}}{g}$

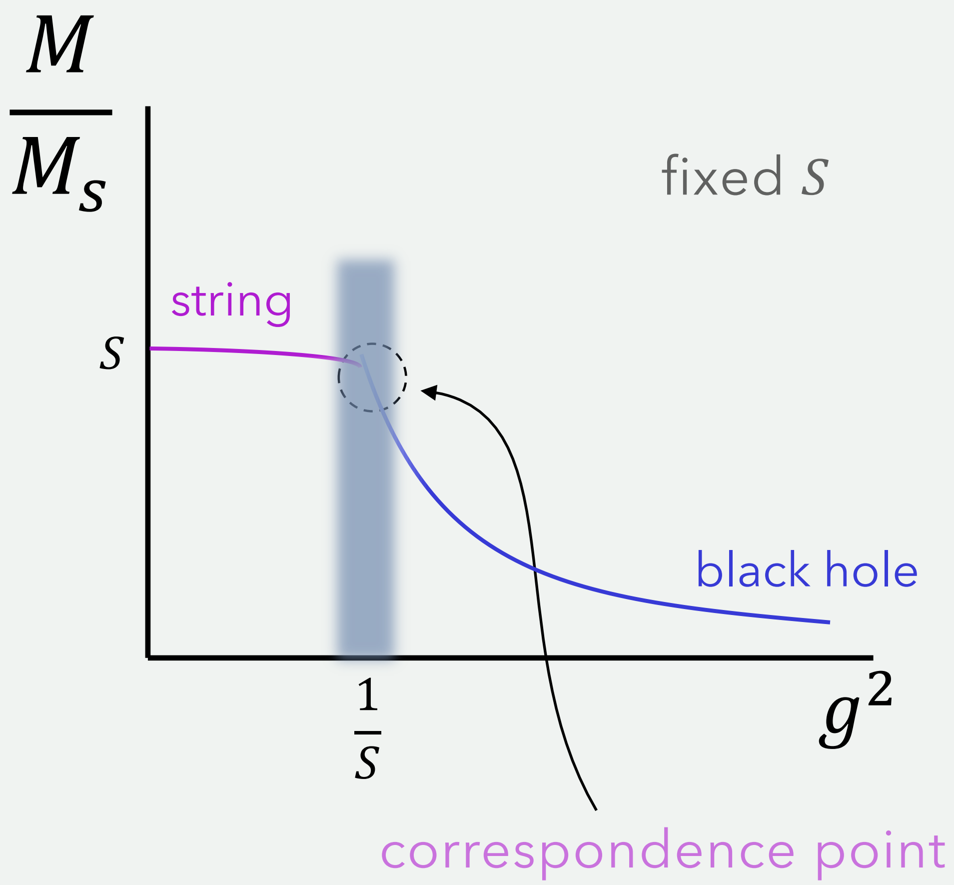


Susskind 1993

Black hole → string when

$$g^2 \sim \frac{1}{S} \sim \frac{M_s}{M}$$

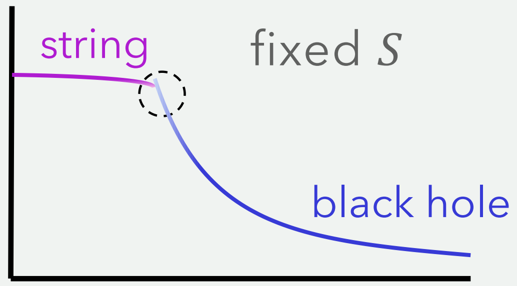
$$\frac{M}{M_s} = S_{string}$$



String/Black hole Correspondence

Parametric match of string states and black holes

Strings give microscopic account of black hole entropy



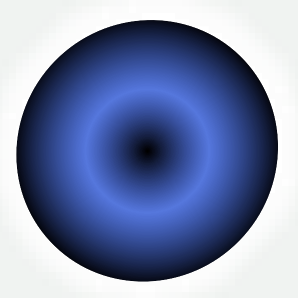
Overarching framework for microscopic understanding of black holes in string theory

Horowitz+Polchinski 1996

g^2S : "'t Hooft coupling"

$g^2S \ll 1$

$g^2S \sim 1$

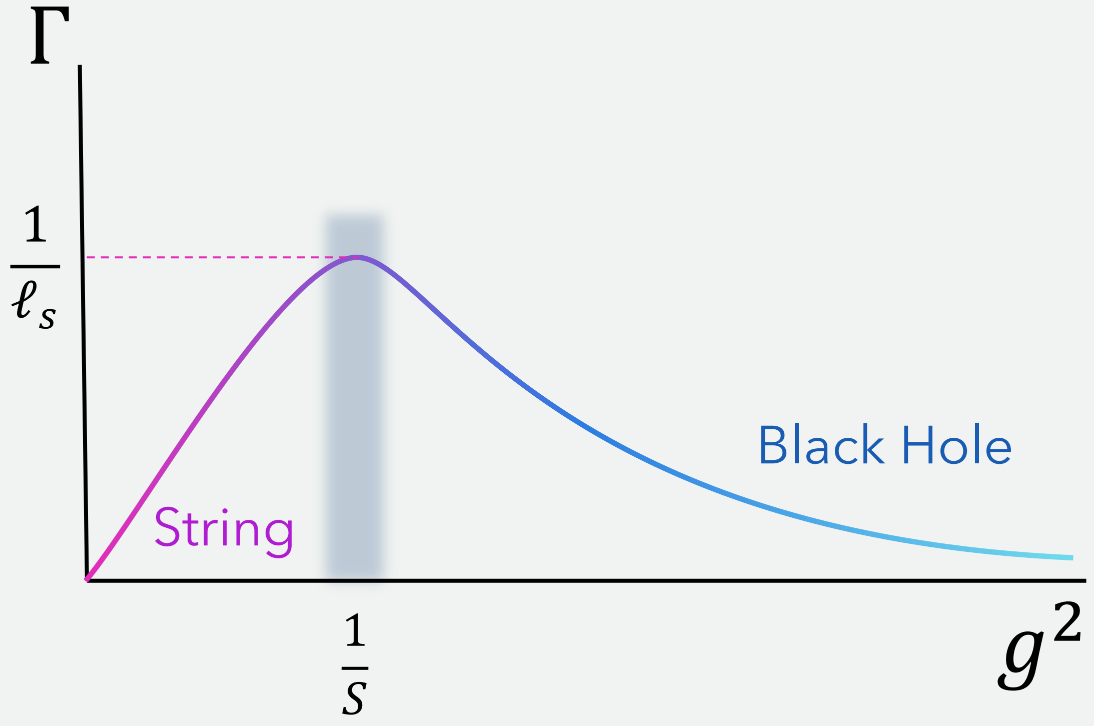


$g^2S \gg 1$

Radiative decay

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

Black hole decay $\Gamma \sim T_H \sim \frac{1}{\sqrt{g^2 S}\,\ell_s}$



Goldilocks adiabaticity

Rate of change Δt^{-1} of g

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

50 years back

Clues and puzzles

Kerr bound on black holes

$$J \leq M^2$$

Regge bound on strings

$$J \leq M^2$$

black holes = strings?

$$J \leq M^2$$

Misleading!

$$J \leq M^2$$

What units?

$$J \leq M^2$$

gravitational units

$$J \leq \frac{M^2}{M_P^2}$$

string units

$$J \leq \frac{M^2}{M_s^2}$$

$$M_S = gM_P \ll M_P$$

$$J_{Kerr} = \frac{M^2}{M_P^2} = g^2 \frac{M^2}{M_S^2} \ll J_{Regge} = \frac{M^2}{M_S^2}$$

Puzzles

Strings → Black Holes

$$J_{Kerr} \ll J_{Regge}$$

Massive string states with high enough spin

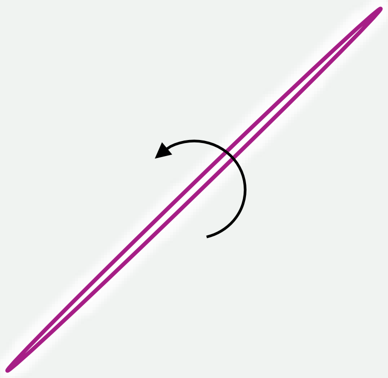
$$J_{Kerr} < J \leq J_{Regge}$$

don't have black hole counterparts

Strings with $J = J_{Regge}$

do not look like black holes at all

Non-degenerate, rigidly rotating rods



$J = M^2 \ell_s^2$

Black Holes → Strings

Black holes: $J \leq J_{Kerr} = \frac{M^2}{M_P^2}$

No problem

There exist string states with the same degeneracy, spin, and (parametric) mass

But $J \leq GM^2$ is a bound for 4D black holes

In $D \geq 5$ $\exists$ black holes with arbitrarily large spins

But Regge bound $J \leq \frac{M^2}{M_S^2}$ is for strings in any D

Ultraspinning black holes with

$$J \gg J_{Regge}$$

don’t have string counterparts

Start with fast spinning string

As g grows, what does it turn into?

Start with fast spinning black hole

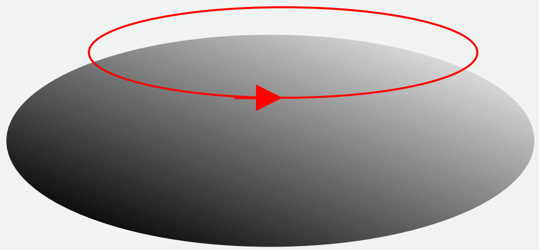
As g decreases, what does it turn into?

Cast of characters

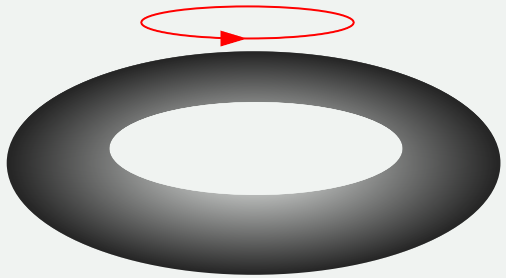
Rotating black holes in higher D

$D \geq 5$ with rotation in a single plane

$\exists$ black holes/rings with arbitrarily large J



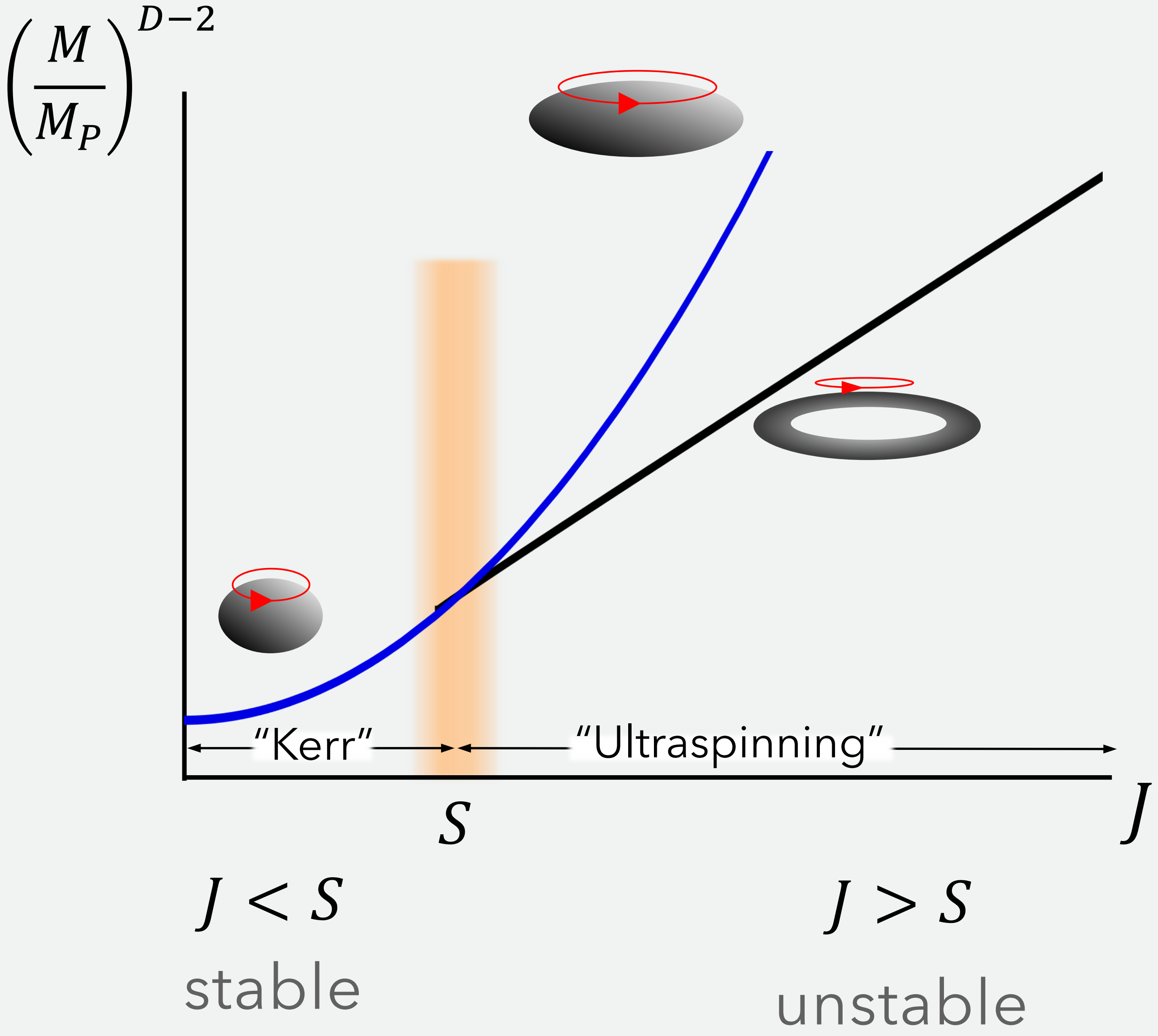
Myers+Perry 1986



RE+Reall 2001

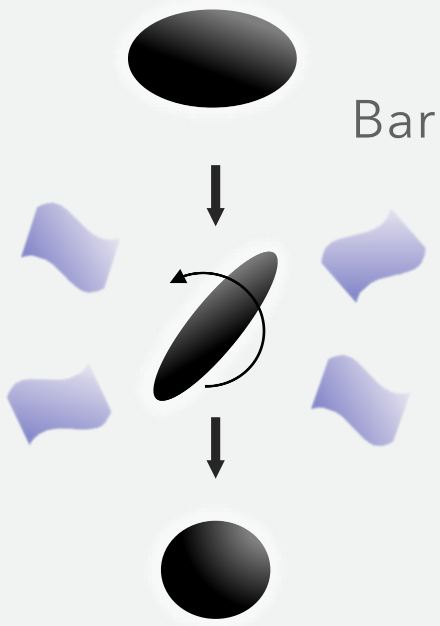
Phases

fixed entropy S

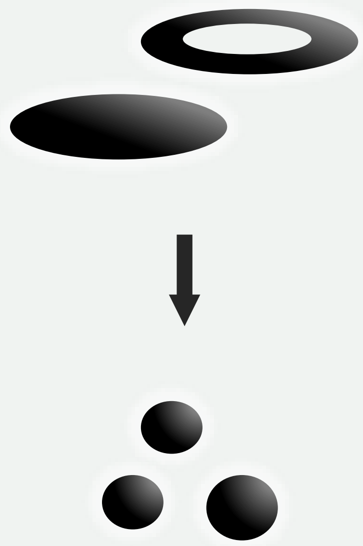


$J > S$: Ultraspinning instabilities

RE+Myers 2003

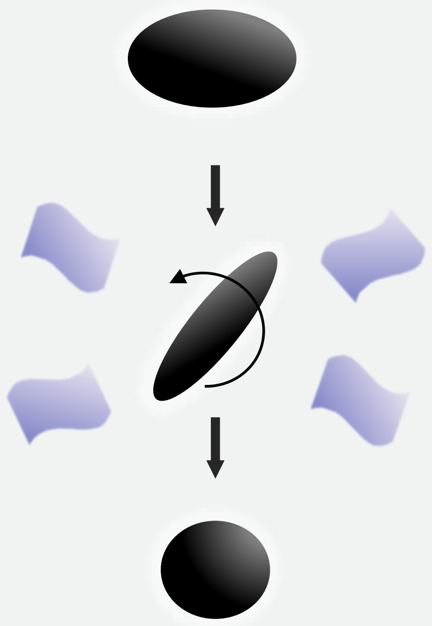


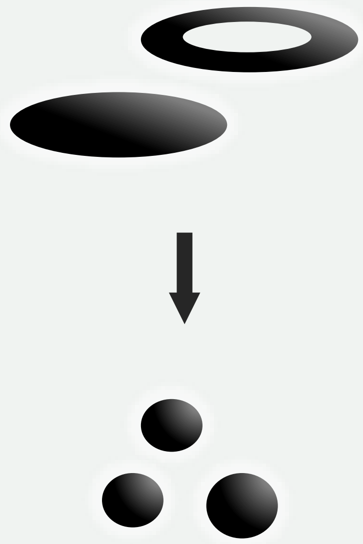
Death by radiation



Death by fragmentation

$J > S$: Ultraspinning instabilities





Fast deaths $\Gamma > \frac{1}{\ell_s}$: too fast for Goldilocks

String states

String balls

$$X^i = \frac{1}{2}(A^i(\tau - \sigma) + B^i(\tau + \sigma))$$

A^i, B^i arbitrary oscillations

(up to $|\partial_\sigma A^i|^2 = |\partial_\sigma B^i|^2 = 1$)

Random walk

Degeneracy $S \sim \text{Length} = M$

Mitchell+Turok 1987
Mañes 2004

Add rotation

Russo+Susskind 1994

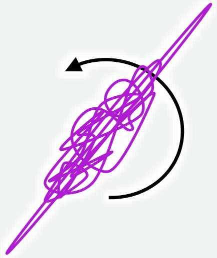
$$S \sim \sqrt{M^2 - J}$$

Large, when away from Regge bound

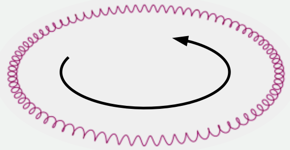
Highly degenerate spinning string states

String balls

String bars (wiggly rods)



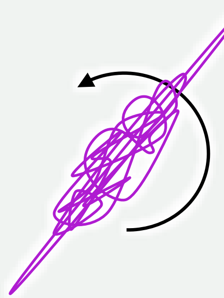
Plasmid strings



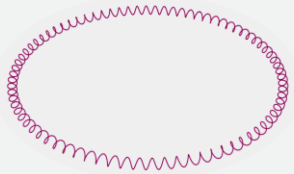
can construct both classical and quantum

When $g > 0$ they all become unstable

Gravitational antennas

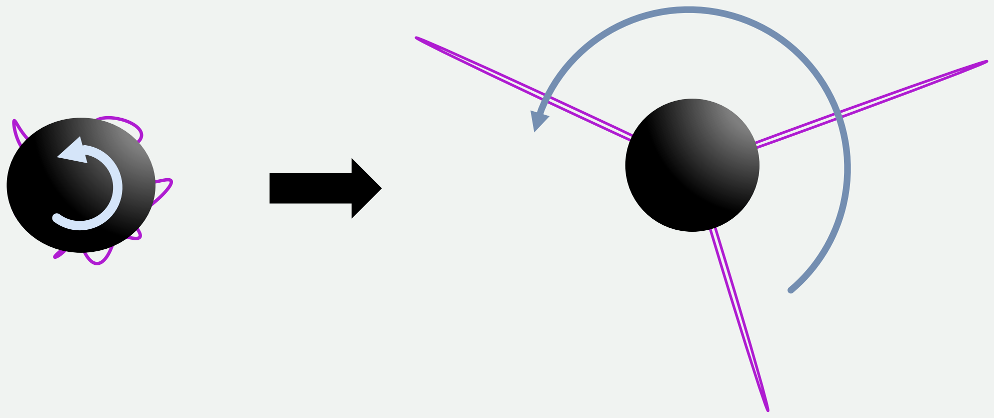


Thermal radiation



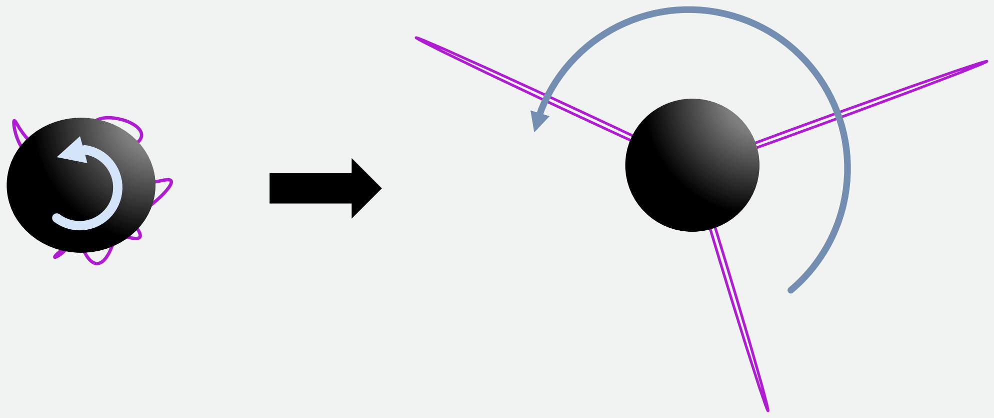
$\Gamma < \frac{1}{\ell_s}$: Slow enough decay for Goldilocks

black hole/string hybrids



Deng+Gruzinov+Levin+Vilenkin 2023

fast-spinning black holes → hybrids

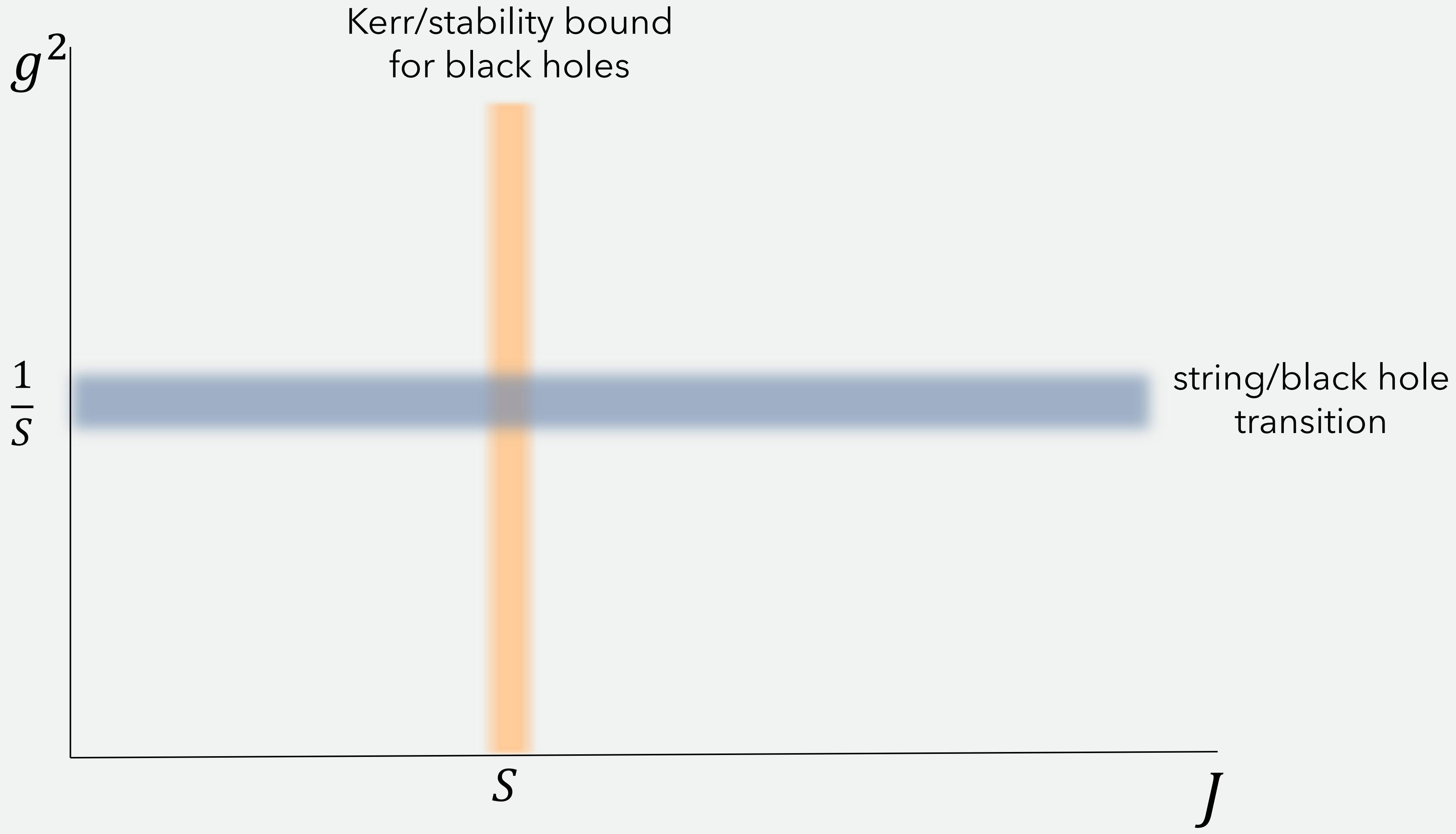


Curvature on horizon first becomes
string-size near the equator

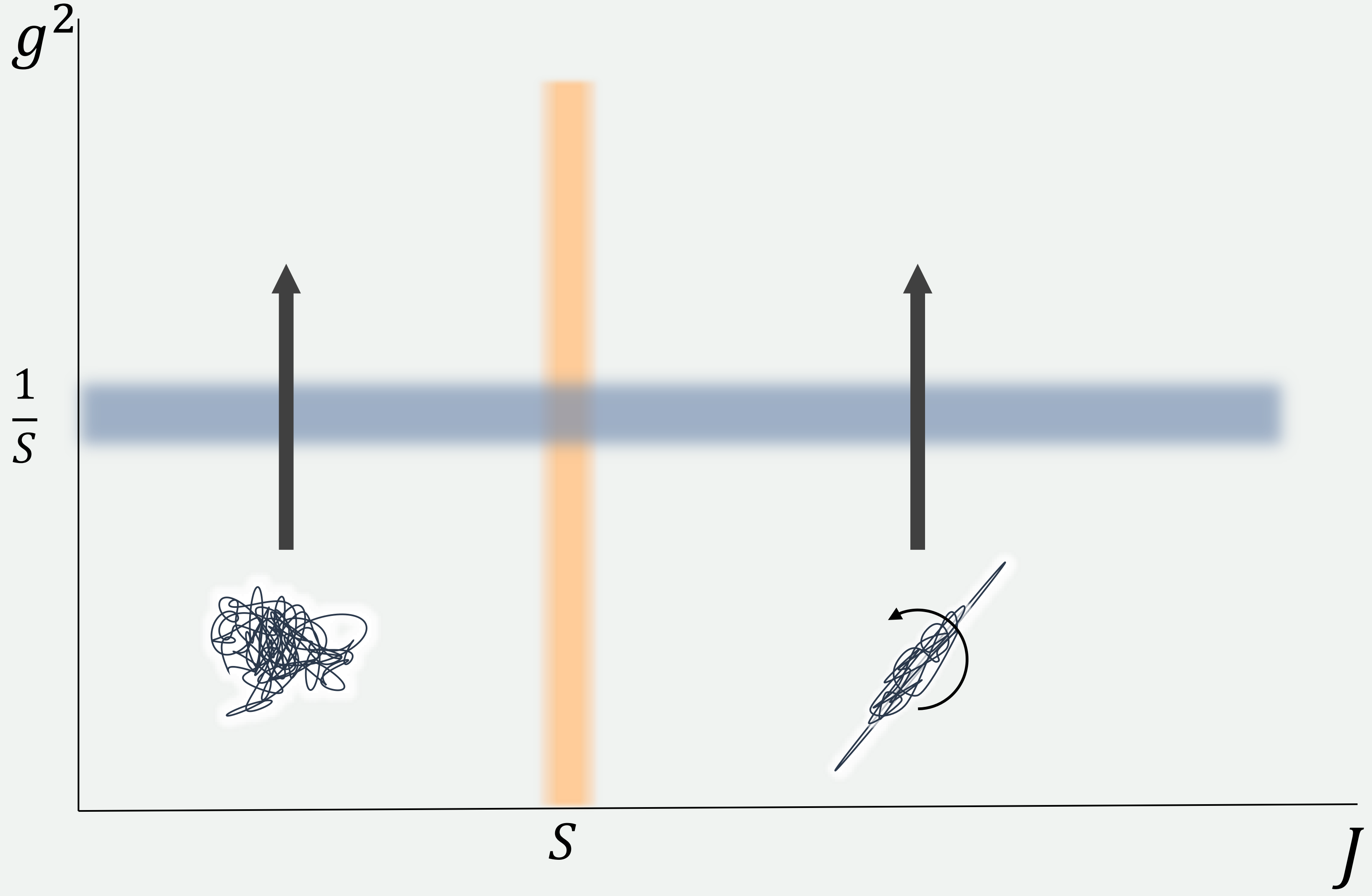
"Staged correspondence"

This is enough to establish the correspondence $\forall J$ as we vary g

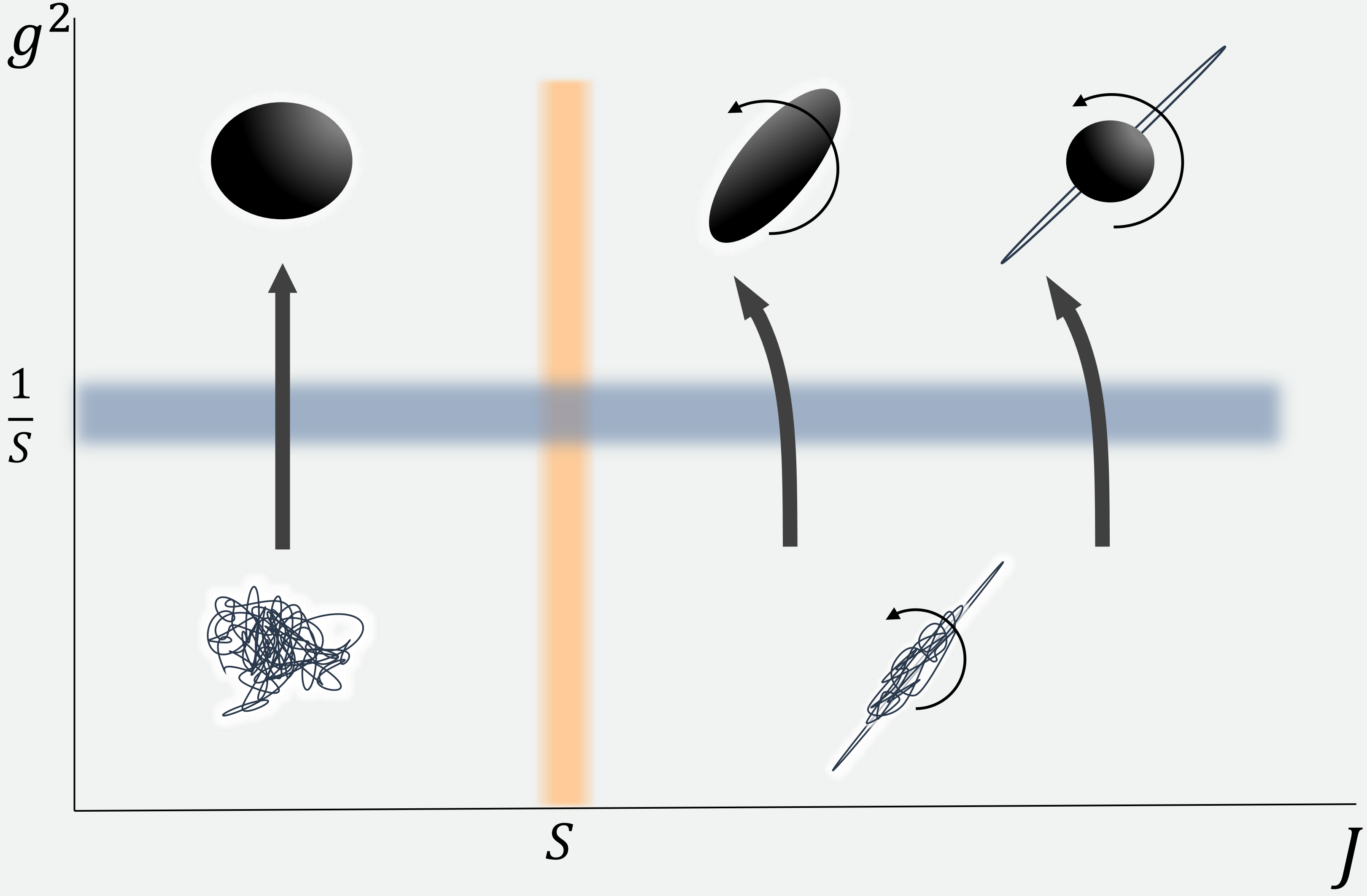
Fixed entropy S



Strings to black holes

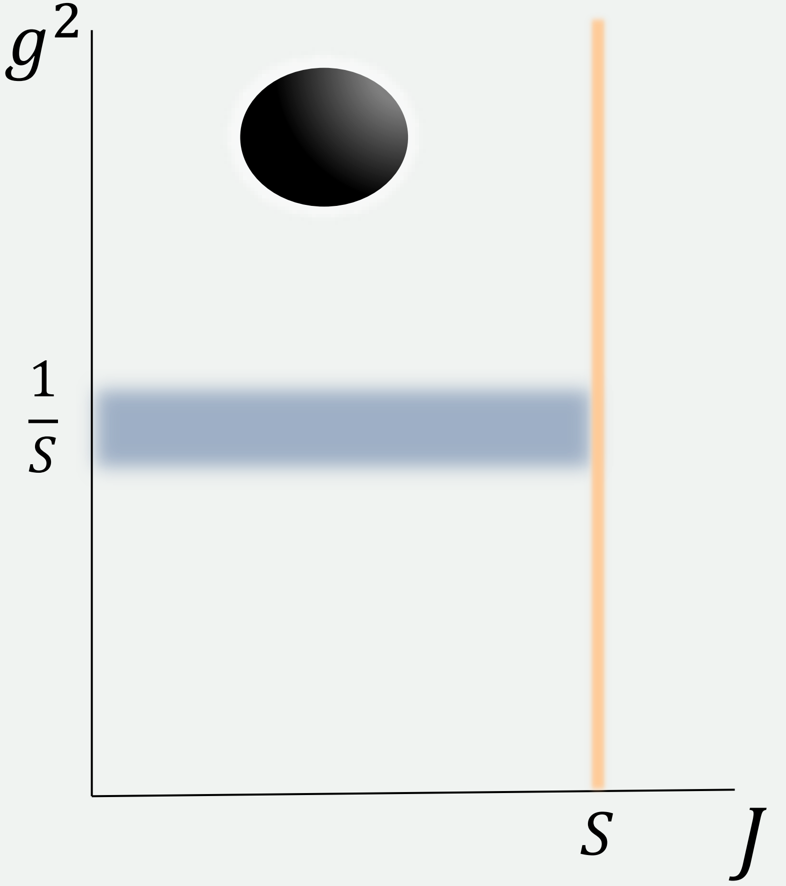


Strings to black holes

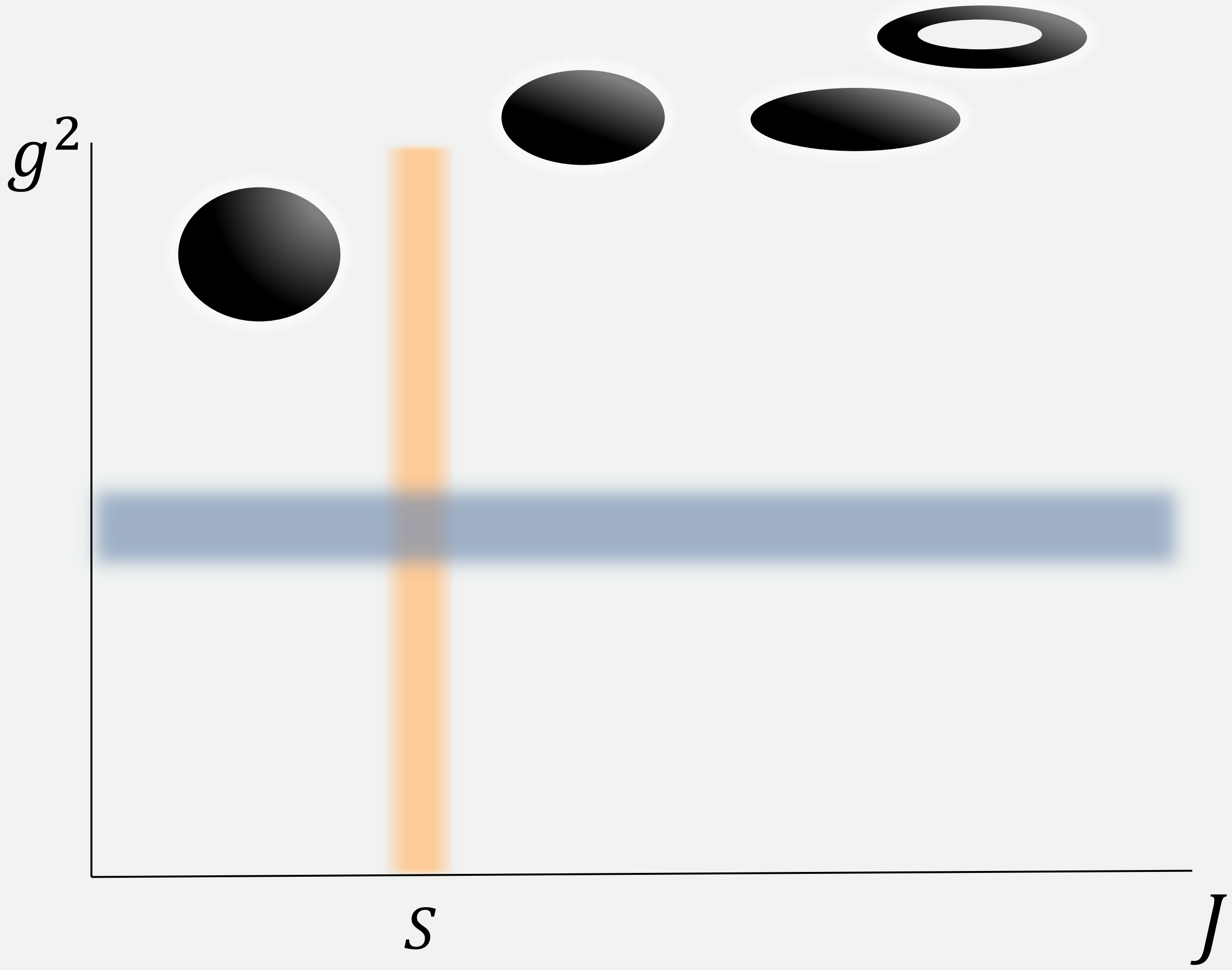


Black holes to strings

D=4

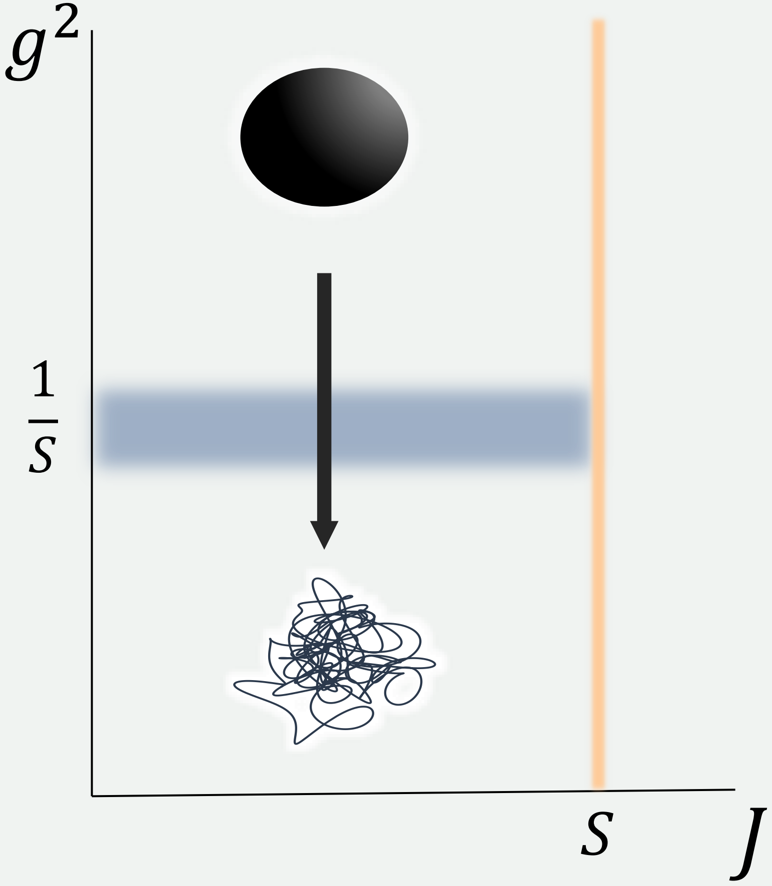


D≥6

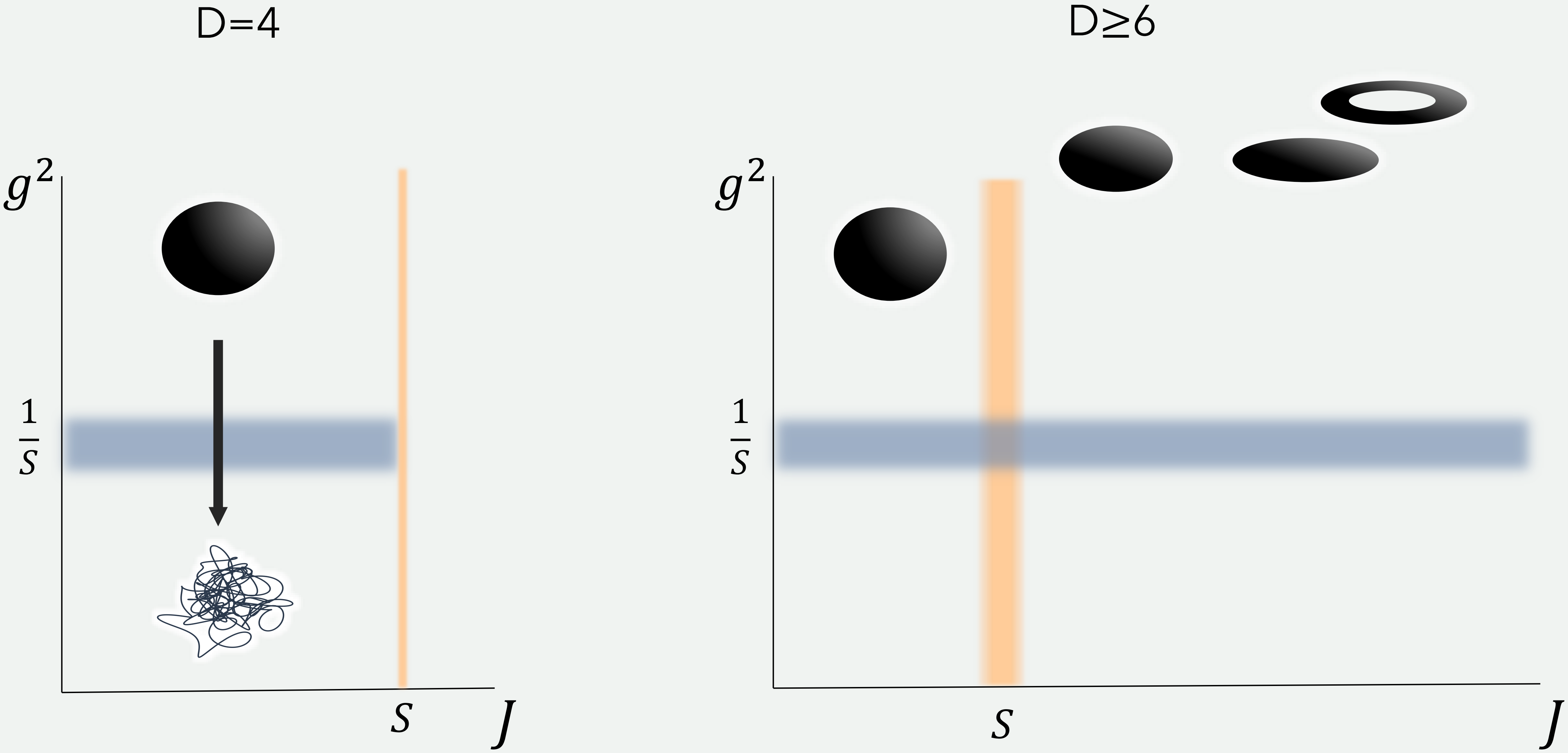


Black holes to strings

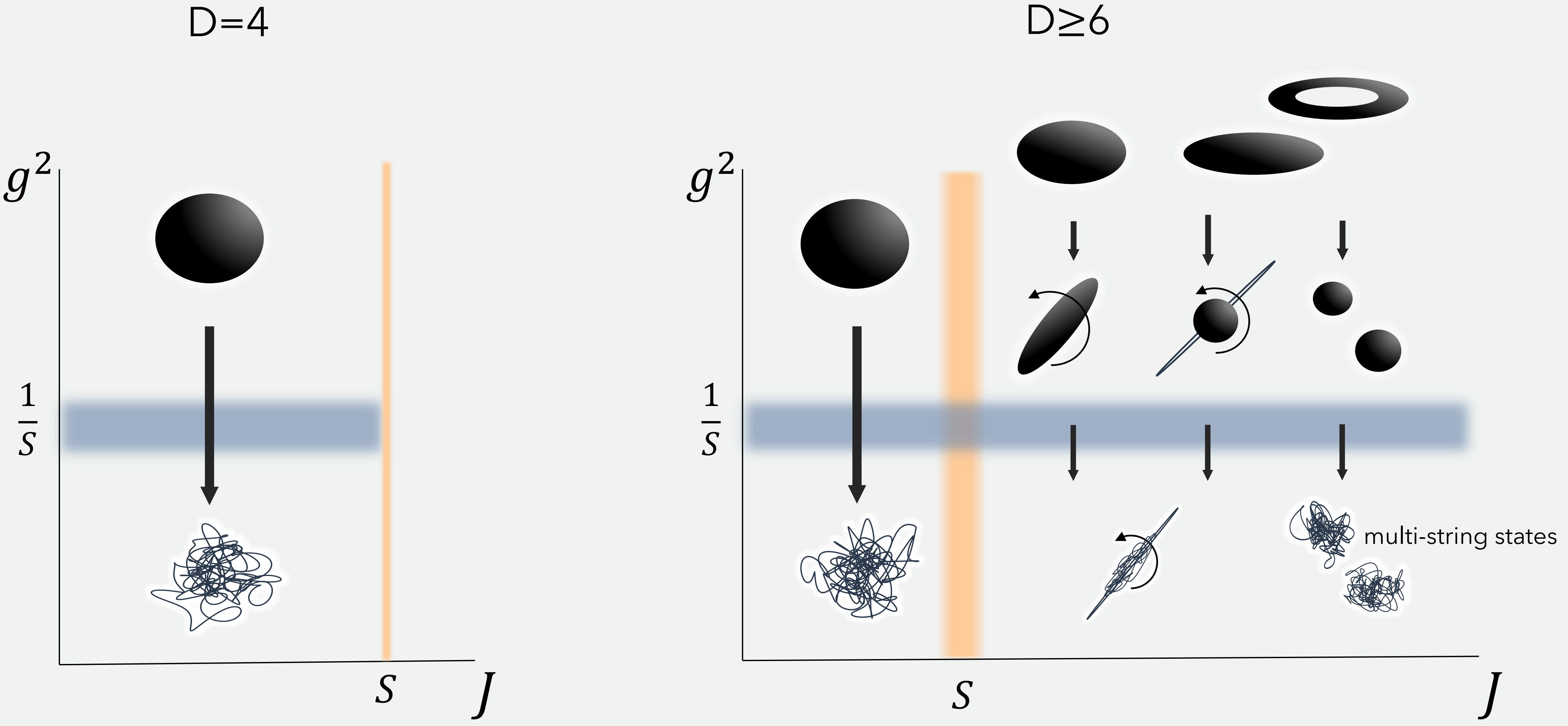
D=4



Black holes to strings



Black holes to strings



Picture readily extends to several angular momenta

Outliers

Near-extremal, non-ultraspinning black holes

Entropy can be matched to string ball

But not the temperature: not adiabatic

String ball chokes the throat

Final remarks

Puzzles arose because of implicit assumption:

“*Stationary* black holes and *single* string states must be in 1-to-1 correspondence”

But when coupling is finite, time evolution for spinning states is not negligible, and can be fast

Ultraspinning black holes evolve into multi-strings, string bars, or hybrids

Fast spinning strings evolve to black bars or hybrids

Fundamental strings allow to go as close as possible to black holes in a Quantum theory of Gravity, while using a spacetime description

Correspondence describes the transition between them

Must understand how it works

Rotation:

First step ✓

More work ahead

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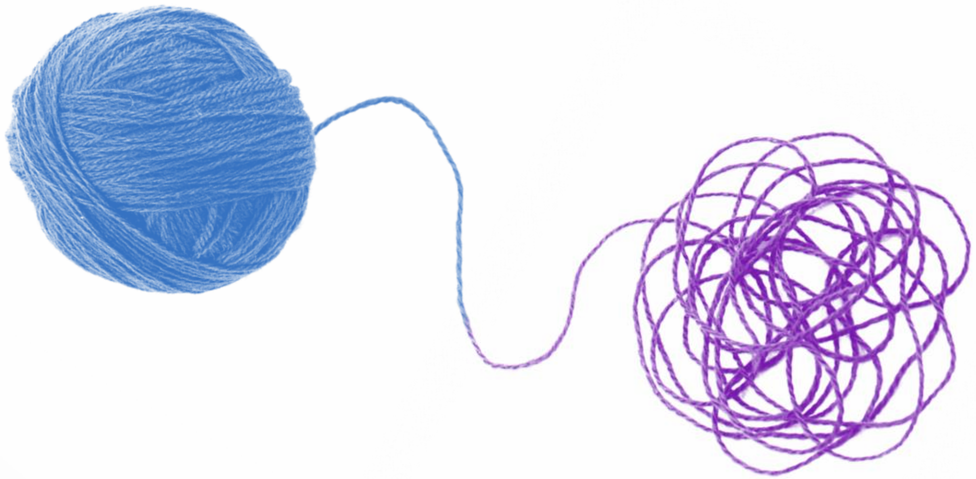
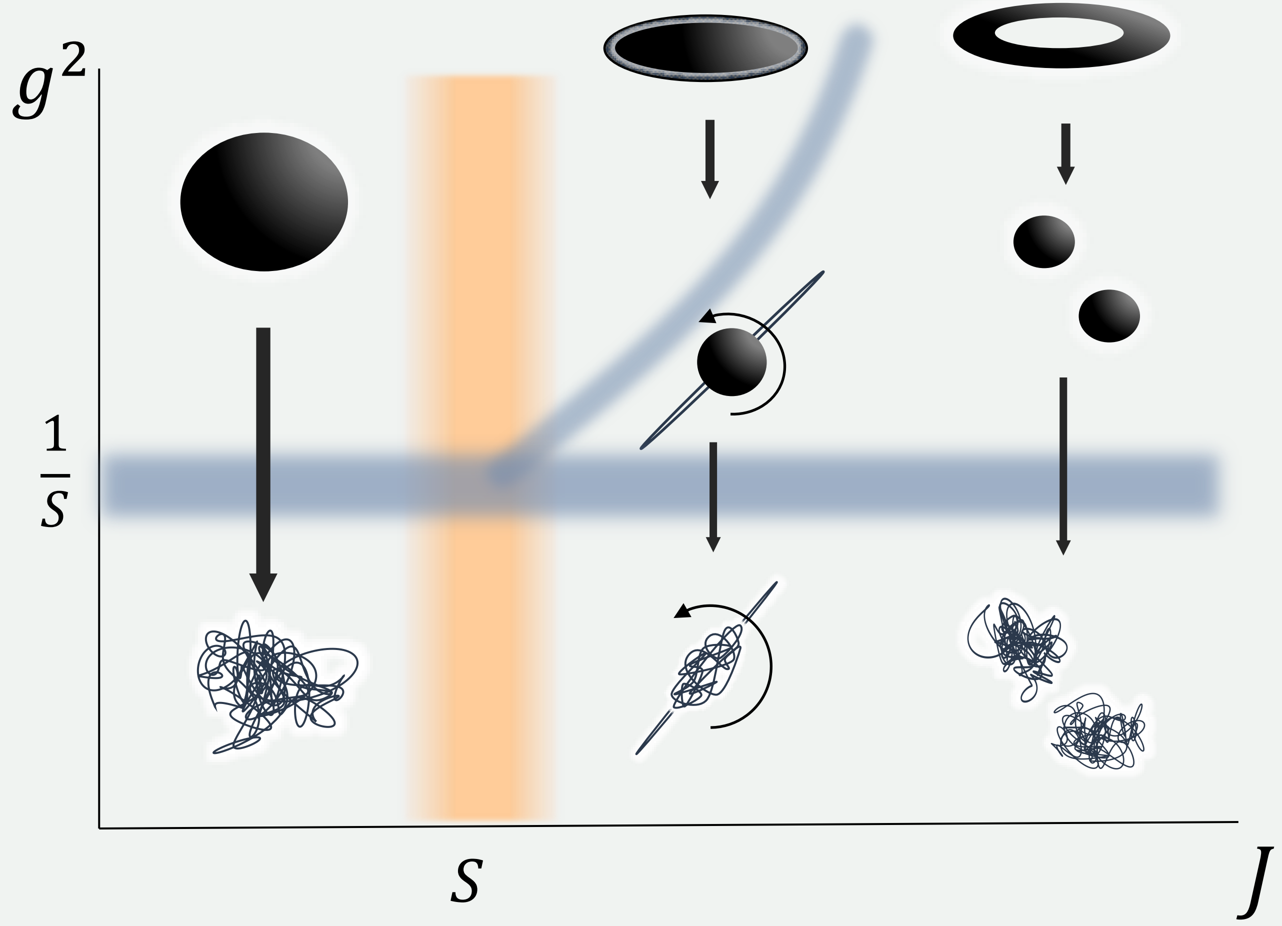


Thank you

Extra slides

Black holes to strings D=5



Near extremality the description changes

Near-extremal with charge:

Gravitational decoupling of throat

Relevant degrees of freedom are not long massive strings, but short (open) strings moving along brane: CFT

Near extremality the description changes

Near-extremal rotating:

Gravitational decoupling of throat

Relevant degrees of freedom are not long massive strings, but...?