Black hole Microstates

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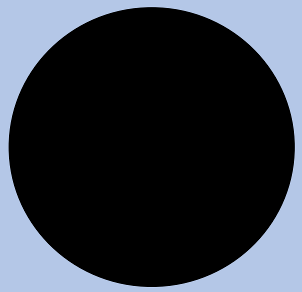
Strings 2021

Black holes as quantum systems

central dogma (hypothesis)

A black hole, as seen from the outside can be described in terms of a quantum system with $\exp\left(\frac{A}{4G_N}\right)$ states.

And it evolves unitarily.



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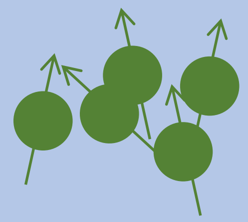


What are these states?

Key results from String Theory

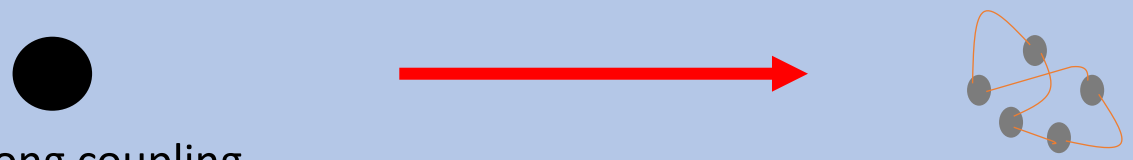
Extremal, Supersymmetric black holes

Supersymmetric black holes in supersymmetric string theories can be counted precisely using strings/D-branes

→ reproduce the Area formula + corrections to the formula

Strominger Vafa..... Sen…. Dabholkar, Gomes, Murthy…

See Murthy's and Pando Zayas' talks



Many alternative limits and possible counting schemes. (duality frames)

Can we see the microstates directly at strong coupling, using the Lorentzian gravity description ?

BPS, supersymmetric Fuzzballs

Large family of smooth horizonless gravity solutions. → reproduce the extremal entropy ?

State or the art: Bena, Shigemori, Warner (superstrata)

Appear to reproduce a fraction < 1 of the entropy.

How is AdS_2 connected to the these geometries? Average?
Which geometry do I see when I fall in ?

Black holes with nonzero Temperature

From AdS/CFT: Fluids or states in strongly interacting quantum systems.

Quantitative agreement is usually based on the Cardy formula for AdS_3/CFT_2 .

Also numerical computations in the BFSS / D0 quantum mechanics case.

Berkowitz, Rinaldi, Hanada, Ishiki, Shimasaki, Vranas

Entropy formulas and the black hole interior

- Recent developments starting from the RT formula have shown that the von Neumann entropy of a black hole depends on the geometry of the interior.
- → Microstate of the black hole is encoded in its interior. (Up to the RT surface)
- Problems:
  - Large number of possible interiors, apparently larger than the number of microstates (bags of gold). (State dependence)
  - There is a singularity.
- Maybe these two problems cancel each other.
- Perhaps the proper understanding of microstates is tied to the singularity?

Page curve and long time behavior

Penington, Almheiri, Engelhardt, Marolf, Maxfield
Saad Shenker Stanford.

- Recent results were obtained using wormhole = new topologies.
- Give results that can be interpreted as a averaging over coupling constants in the quantum system.

Coleman, Giddings, Strominger
Marolf, Maxfield
Penington, Shenker, Stanford, Yang
Stanford ….

Can microstates be understood in a single universe picture, or do we need a many universe wavefunction?

A string theory background with known microstates

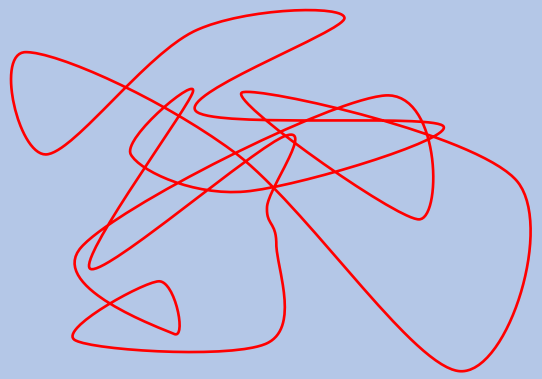
- A classical Euclidean solution with entropy $S \sim 1/G_N$
- Known microstates.

The self gravitating string solution

- The self gravitating string solution of Horowitz and Polchinski hep-th/9707170

(see also Damour, Veneziano)

- Two points of view:
  - Highly excited self gravitating string = “string star”
  - Smooth, time independent, Euclidean solution involving a winding condensate.



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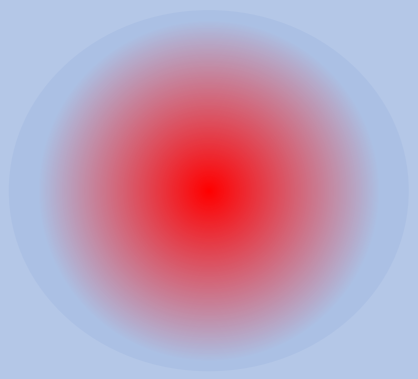
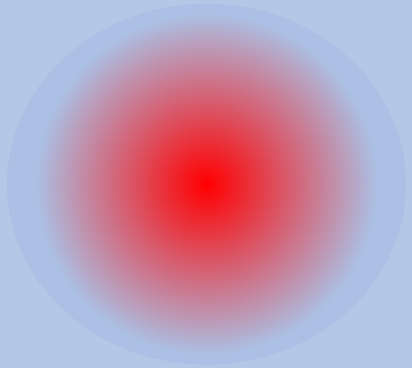




Solution to the Euclidean action;

$$\mathrm{I} = \frac{1}{16\,\pi G_N}\left[-\int R + \int |\nabla\chi|^2 + m^2(G_{00})|\chi|^2 \right]$$

Euclidean time $=$ circle of length β

χ = winding mode on the Euclidean circle.

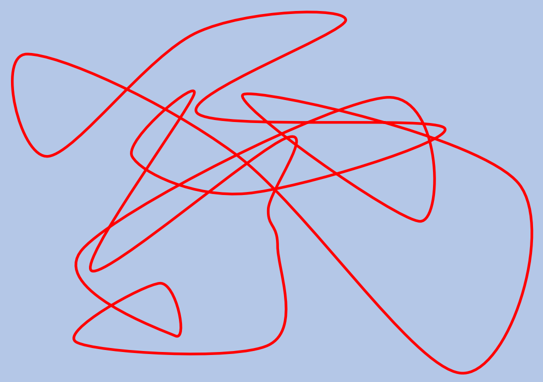
Smooth solution when $0 < \beta - \beta_H \ll l_s$. Size larger than the string scale. Works nicely in D=4.

$\beta - \beta_H \propto (g^2 M)^2$

Has a non-zero classical entropy!

Size $\propto \frac{1}{g^2 M}$

$$S = 2\,\frac{\beta_H^2}{(\,2\,\pi\alpha')^2}\int |\chi|^2$$

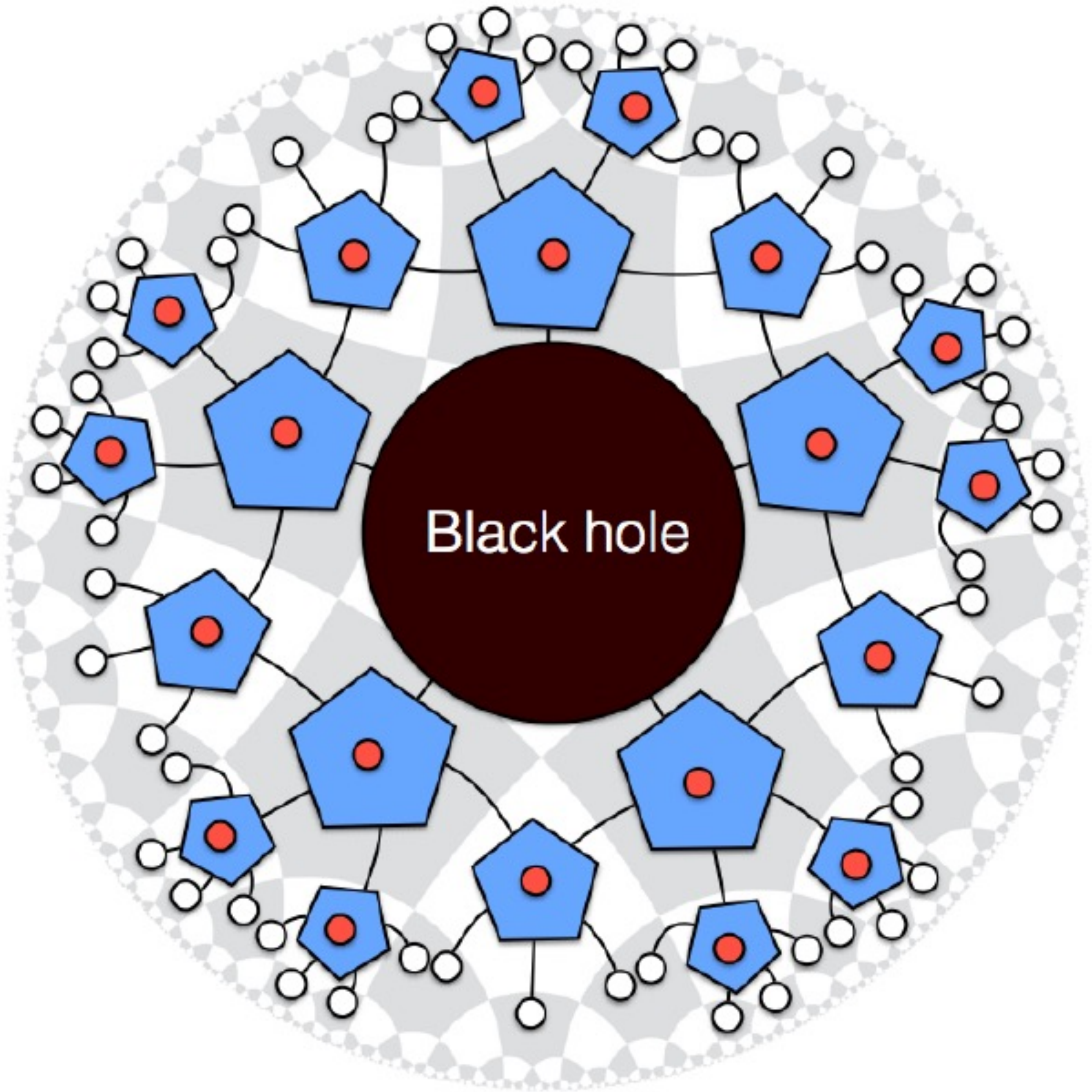


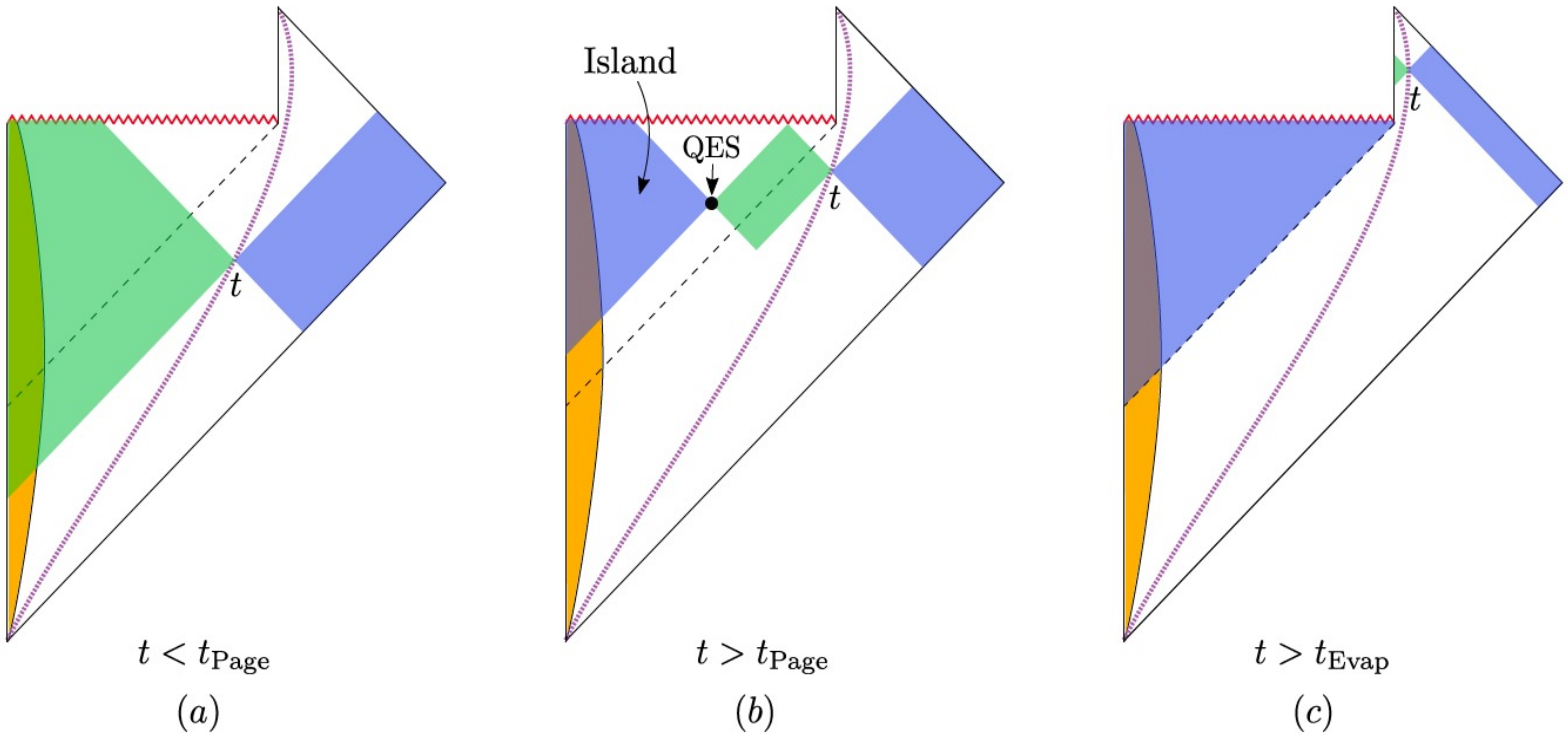
Microstates

Exercise: generalize it for the black hole case…

Thank you

Extra slides


Black hole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