Black holes in string theory and gravitational wave observations

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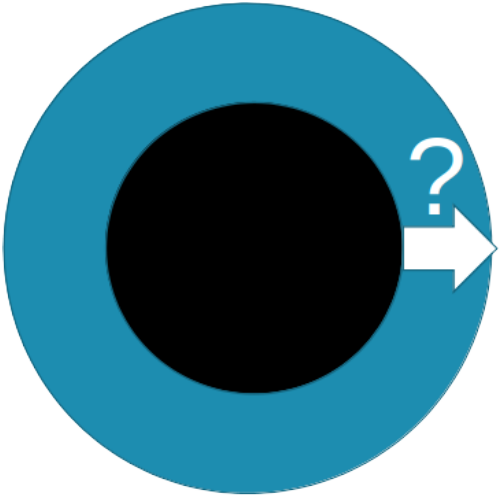
Why quantum modifications of GR horizon?



Outline

1. **Why** study black holes in string theory?

2. **What** is a black hole in string theory?

3. What are the **observable consequences?**

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Why study black holes in string theory?

$$\boxed{S_{BH} = \frac{k_B c^3}{\hbar G_N} A_H \,, \qquad T_H = \frac{\text{surface gravity}}{2\pi}}$$

[Bekenstein; Hawking; BH thermodynamics Bardeen, Hawking, Carter . . .]

QFT in a fixed GR background:

1. Evaporation $\rightarrow$ information paradox?
2. Entropy $\rightarrow$ microstates?
3. Singularity $\rightarrow$ Experience of infalling observer?

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Resolution is QUANTUM gravitational in nature

Resolving the information paradox

Need to give up at least one of:

1. Unitarity
2. No high-entropy remnants
3. Effective Field Theory outside horizon (GR + QFT)
4. Quantum gravity corrections heavily suppressed near horizon
5. Or other hidden assumptions

Resolve information paradox?

Need to give up at least one of:

1. Effective Field Theory (GR + QFT) breaks down

2. Large quantum gravity corrections near horizon

Other assumptions for which we have theoretical motivations not to change (unitarity. . .)

Resolve information paradox?

Need to give up at least one of:
Some proposed resolutions from the string community

1. Effective Field Theory (GR + QFT) breaks down
   non-local interactions [Giddings], wormholes from entanglement[ER=EPR, Maldacena-Susskind]
2. Large quantum gravity corrections near horizon
   firewalls [AMPS '13], fuzzballs [Mathur '01 + many more]

Other assumptions for which we have theoretical motivations not to change (unitarity…)

observables in quantum mechanics depend on black hole microstate [Papadodimas-Raju '15]

Ways to proceed

Bottom-up:

1) Effective field theory: [morning talks]

- If violated, then we expect EFT to show the scale of new physics

$$\mathcal{L} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \ldots$$

2) Phenomenology—Exotic Compact Objects[Pani's talk]

- Investigate possible signatures of quantum modifications

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This talk:

- Study black holes in string theory and see what we get

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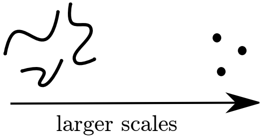
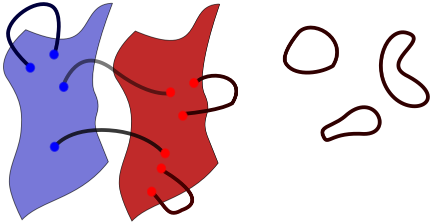
String theory

Framework for Quantum gravity and other forces

- Original idea: particles as excitations of strings



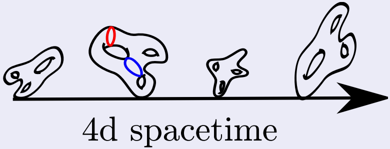
- “Exotic”: Higher dimensions, Supersymmetry
- Rich non-perturbative spectrum: “D-branes” [Polchinski ’96]

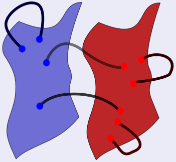


Black holes in string theory

Black holes from branes

- Make 6 dimensions small (compactification)
- Wrap branes on internal dimensions at one position in 4d





- Large number of branes: 4d black hole

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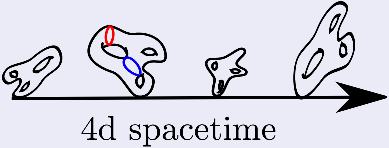

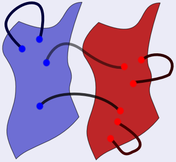

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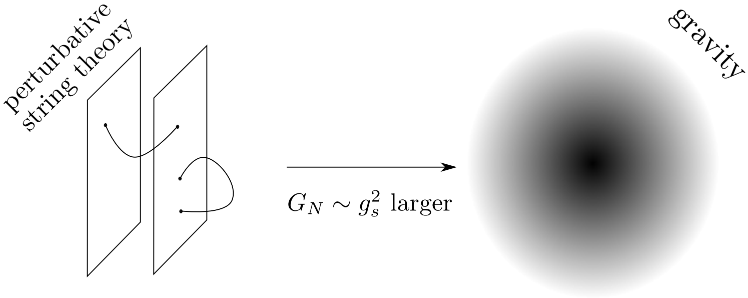
Microscopic understanding → microstates?

Entropy from microstates

Thought experiment: "turn the knob" [Sen '96, Strominger,Vafa '96,. . .]



$S_{\text{micro}} = \log(N_{\text{micro}})$ $\longleftrightarrow$ $S_{\text{macro}} = \frac{A_H}{4G_N}$

protected (susy)

GAUGE THEORY $\Leftrightarrow$ classical GR (+ fields)

Main successes:

1) Black hole entropy from brane gauge theory

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…by supersymmetry

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2) Holographic interpretation of spacetime: ['t Hooft'93, Susskind '95]

- Gauge theory has lower dimension than gravitational theory
- Concrete realization: "AdS/CFT correspondence" [Maldacena '97]
- Idea of 'emergent spacetime' permeates modern string theory

Gravitational interpretation of microstate

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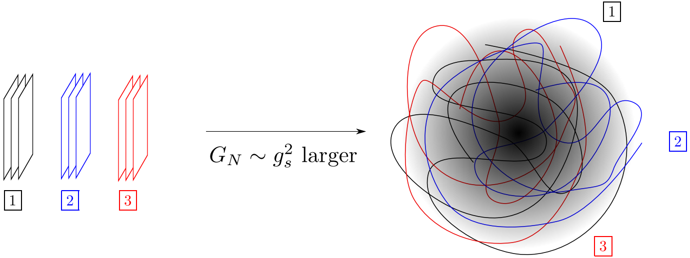
- Branes+strings can give gravitating objects the size of black holes.



- "Fuzzball programme" (mainly for 5d BHs)
- Could address also information paradox and singularity resolution

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Statistical expectations for Kerr BH microstate

String theory cannot yet describe a Kerr microstate . . . what to expect?

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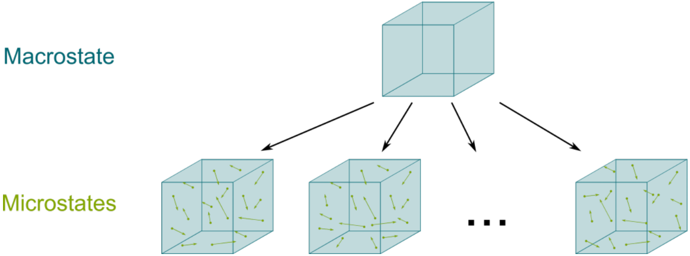

[picture: http://www.science4all.org]

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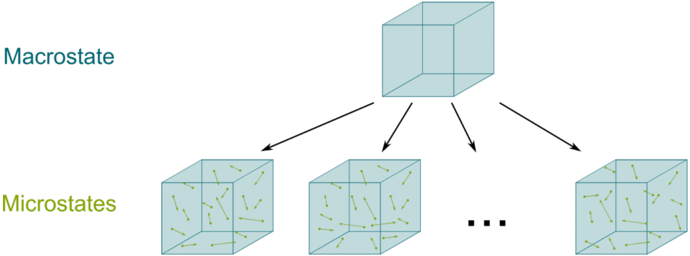

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- Hence microstate potentially hard to distinguish from Kerr BH

Look for most promosing stringy observables

Binary black holes:

- GW echoes? [Dimitrov, Lemmens, Mayerson, Min, BV in progress]
- focus on quantum dynamics: e.g. in merger
  [Bena, Mayerson, Puhm, BV ’15, Hartle, Hertog ’17]

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“Microstate geometries” as new black hole mimickers

[Hertog, (Kuechler), Lemmens, BV ’19 + in progress]

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Other hints of string theory:

- Many dimensions $\rightarrow$ axions [Charles, Scalisi, Tielemans, BV in progress]
- Emergent nature of spacetime [e.g. Verlinde, Zurek 19]
- Contraints from string landscape (primordial GW's, PBHs…)