Black holes in string theory and gravitational wave observations

Bert Vercnocke
KU Leuven

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Why quantum modifications of GR horizon?
1. Why study black holes in string theory?

2. What is a black hole in string theory?

3. What are the observable consequences?
Outline

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

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

3. What are the **observable consequences**?
Why study black holes in string theory?

\[ S_{BH} = \frac{k_B c^3}{\hbar G_N} A_H, \quad T_H = \frac{\text{surface gravity}}{2\pi} \]

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

QFT in a fixed GR background:

1. Evaporation → information paradox?
2. Entropy → microstates?
3. Singularity → Experience of infalling observer?
Why study black holes in string theory?

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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
Ways to proceed

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2) Phenomenology—Exotic Compact Objects [Pani’s talk]
   - Investigate possible signatures of quantum modifications

This talk:
   - Study black holes in string theory and see what we get
Outline

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

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

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

Framework for Quantum gravity and other forces

- Original idea: particles as excitations of strings

- “Exotic”: Higher dimensions, Supersymmetry

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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Microscopic understanding $\rightarrow$ microstates?
Entropy from microstates

Thought experiment: “turn the knob” \[\text{[Sen '96, Strominger, Vafa '96, ...]}\]

\[S_{\text{micro}} = \log(N_{\text{micro}}) \quad \Leftrightarrow \quad S_{\text{macro}} = \frac{A_H}{4G_N}\]

GAUGE THEORY \[\Leftrightarrow\] classical GR (+ fields)
Main successes:

1) Black hole entropy from brane gauge theory

\[ S_{BH} = k_B \ln N_{micro} \]

…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
Gravitational interpretation of microstate

- 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

\[ G_N \sim g_s^2 \text{ larger} \]
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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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- Expectation values in **typical microstate** expected to be highly peaked around thermal expectation (= black hole) for **most observables**

[picture: http://www.science4all.org]
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Hence microstate potentially hard to distinguish from Kerr BH
Look for most promising 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 → axions** [Charles, Scalisi, Tielemans, BV in progress]
- **Emergent nature of spacetime** [e.g. Verlinde, Zurek 19]
- **Contraints from string landscape** (primordial GW’s, PBHs… )