Probing Black Hole Microstate Evolution with Networks

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• A. Charles (MI → Leuven), J. Golden (MI → World), D. Mayerson (MI → Saclay), (W.I.P.)
1 Black Hole Puzzles: Situation Sketch

2 Microstate Formation

3 Microstate Evolution and Networks

4 Discussion
Black hole puzzles in GR:

- Singularity resolution? (Scale?)
- Horizon?
  - Entropy $\leftrightarrow$ many microstates: where are they? ($\leftrightarrow$ uniqueness)
  - Hawking radiation, information loss
  - Small corrections not enough [Mathur]
Black Hole Puzzles (2)

Understanding black holes and their entropy in string theory:

- Black hole entropy in string theory  
  Strominger, Vafa; ...

- Constructing microstates in SUGRA  
  Lunin, Mathur supertubes; superstrata

Still many open questions/problems:

- Non-extremal microstates?  
  Bena, Puhm, Vercnocke; JMaRT; ...

- Formation?  
  Kraus, Mathur 1505.05078; Bena, DRM, Puhm, Vercnocke 1512.05376

- Time evolution? Dynamics?

**Goal**: Fall into BH (microstate) — what do I expect to see?
Black Hole Microstate Formation (1)

Matter in collapsing shell:

- Generic arguments \textcolor{blue}{Kraus, Mathur 1505.05078} to \textcolor{blue}{form} microstate by \textcolor{blue}{quantum} tunneling
Concrete calculation of microstate formation

Bena, DRM, Puhm, Vercnocke 1512.05376

- SUSY solutions in 5D $\mathcal{N} = 1$ SUGRA with vectors
  - Multi-centered
  - Smooth
  - Horizonless
  - Same charges (at infinity) as three-charge (SUSY) BH
  - “Bubbled” 4D/5D Denef/Bena-Warner geometries

- “Formation process” of near-SUSY microstates
  - non-SUSY probes in SUSY background
Concrete calculation of microstate formation:

Bena, DRM, Puhm, Vercnocke 1512.05376

\[
\Gamma \sim \exp \left( -N^\delta \right) \text{ with } \delta \sim -1 \rightarrow \text{easier to form more centers!}
\]
Comparing forming few $\leftrightarrow$ many centers

Only along one path!

Many other paths, many other possible microstates “in between”
Comparing forming few ↔ many centers

Only along one path!

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Many other paths, many other possible microstates “in between”

→ Network!

Inspired by cosmology application of networks

Carifio, Cunningham, Halverson, Krioukov, Long, Nelson 1711.06685
Microstate networks:

**Microstate phase space**
- One microstate
- Transition (rate)
- Late time probability $\|\psi[state]\|^2$
- ...

**Network**
- Node
- Edge (weight)
- Eigenvector centrality
- ... Newman, “Networks: An Introduction”

“Eigenvector centrality”: let network “evolve” for a while - how important are nodes?
Microstate Networks (2): First simple model

Simple toy model:

- Node only characterized by number of centers $N$
- Degeneracy: $w(N) \sim N^\beta$
  - $\beta < 0$: “more ways to wiggle/excite” less centers ($\leftrightarrow$ larger bubbles)
- Transition rate $\Gamma(N \rightarrow N + 1) \sim \exp(-N^\delta)$
  - $\delta < 0$: easier to create many centers ($\leftrightarrow$ smaller bubbles)
- $\rightarrow \beta$ (less centers) $\text{vs.} \ \delta$ (more centers)
Microstate Networks (3): First simple model

Simple toy model:

\[ w(N) \sim N^\beta; \Gamma(N \rightarrow N + 1) \sim \exp(-N^\delta) \]
Simple toy model:

\[ w(N) \sim N^\beta; \Gamma \sim \exp(-N^\delta) \]
Microstate Networks (5): First simple model

Simple toy model:
\[ w(N) \sim N^\beta; \Gamma \sim \exp(-N^\delta) \]
Further Directions

Just getting started!

- More detailed analysis (more parameters) in simple toy model
- Next step toy model: Assign charge to each center.
  - Microstate ↔ Partition of total charge $Q$ (e.g. $9 = 7 + 1 + 1$)
  - Related: D1/D5 system!
    - $N = N_1 N_5$, twist sectors $n$: $N = \sum_n nN_n$ with $N_n$ divided over 8 bos + 8 ferm excitations
    - Twist sector $n ↔ long string wrapped n times (F1/P frame)
    - Dynamical process splitting/combining long/short strings?
    - → Model with network!
Summary:

- Very little known about formation/evolution BH microstates
- Large phase space makes our intuition break down
- Networks: tools to study evolution

Goal: Fall into BH (microstate) — what do I expect to see?

- Toy network models that capture physics, point at important features
- Much more to come! (Better models, D1/D5 model, ...)

Thank you!
Some possible issues to raise (1/2):

- Issues of distinguishability/typicality? Cfr. Typicality vs. thermality Balasubramanian, Czech, Hubeny, Larjo, Rangamani, Simón hep-th/0701122:
  “variances of local correlation functions computed in generic microstates of a system with entropy $S$ are suppressed by a factor of $e^{-S}$”

- Assumptions: Local correlations functions; generic microstates; other assumptions (scaling correlation functions)
- Not what we are concerned with (at the moment)! Now just looking at actual microstate evolution, not questions about ensemble or distinguish between microstates; (see also below)
- Side note: Interesting to distinguish microstate behaviour from black hole (not same as distinguishing individual microstates); cfr. GW echoes from horizon structure
Some possible issues to raise (2/2):

- Always expect evolution to take us to "typical states"; (ETH) "eigenstate thermalization hypothesis" (isolated QM system well described by equilibrium stat. mech.)?!
  - ETH not proven (QM very different than CM)
  - Not obvious that BH microstates have ergodic behaviour (↔ ETH)
- Cfr. meta-stable non-extremal microstates and glassy BH physics
  - Anninos, Anous, Barandes, Denef, Gaasbeek 1108.5821; Bena, Puhm, Vercnocke 1109.5180 & 1208.3468; ...
- Note also that BH not in equilibrium (Hawking radiation)
- A lot will depend on the relevant time scales considered! (Not discussed in our work yet!)

In any case: more careful thought definitely needed!