

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 (1)

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](#)

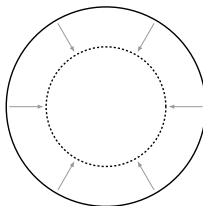
Still many open questions/problems:

- 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:



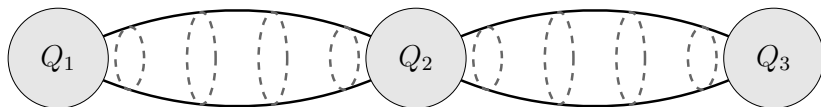
- Generic arguments [Kraus, Mathur 1505.05078](#) to form microstate by quantum tunneling

Black Hole Microstate Formation (2)

Concrete calculation of microstate formation

Bena, DRM, Puhm, Vercnocke 1512.05376

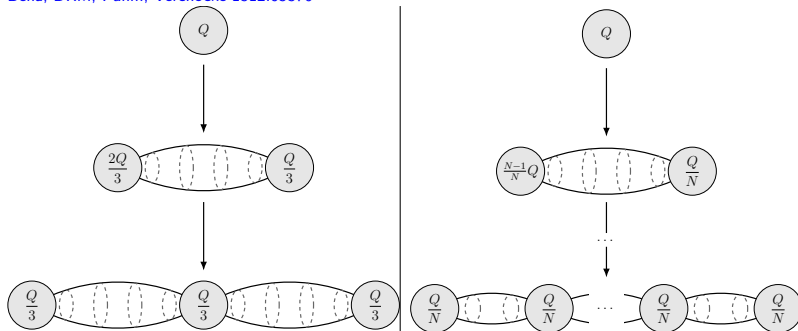
- SUSY solutions in 5D $\mathcal{N} = 1$ SUGRA with vectors
 - Multi-centered
 - Smooth
 - Horizonless
 - Same charges (at infinity) as three-charge (SUSY) BH
 - “Bubbled” 4D/5D Denef/Bena-Warner geometries
- “Formation process” of near-SUSY microstates
 - non-SUSY probes in SUSY background



Black Hole Microstate Formation (3)

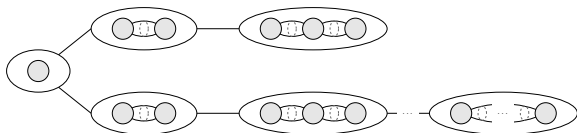
Concrete calculation of microstate formation:

Bena, DRM, Puhm, Vercoocke 1512.05376



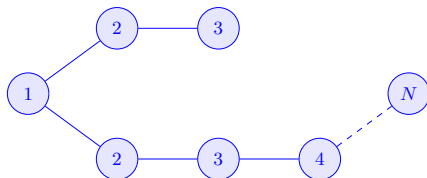
$\Gamma \sim \exp(-N^\delta)$ with $\delta \sim -1 \rightarrow$ easier to form more centers!

Formation and Evolution (1)



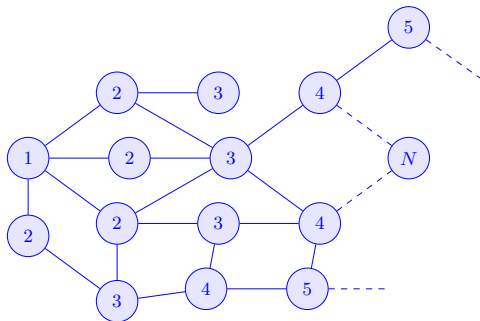
- Comparing forming few \leftrightarrow many centers
- Only along one path!
- Many other paths, many other possible microstates “in between”

Formation and Evolution (2)



- Comparing forming few \leftrightarrow many centers
- Only along one path!
- Many other paths, many other possible microstates “in between”

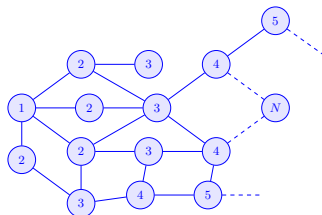
Formation and Evolution (3)



- 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 (1)



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

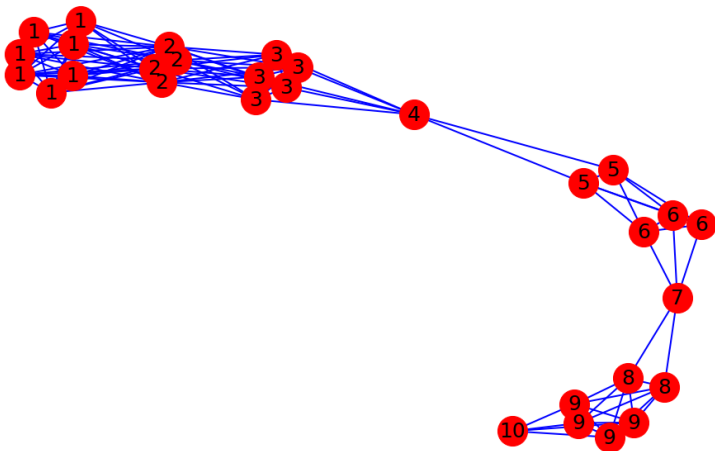
Simple toy model:

- 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) vs. δ (more centers)

Microstate Networks (3): First simple model

Simple toy model:

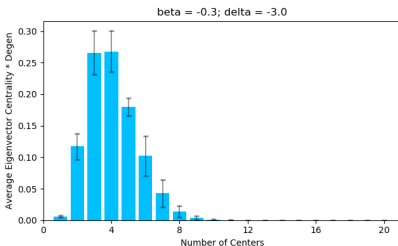
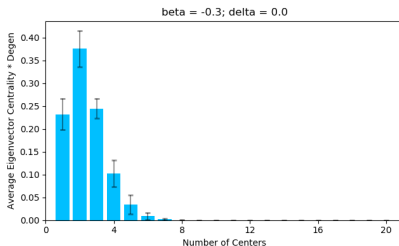
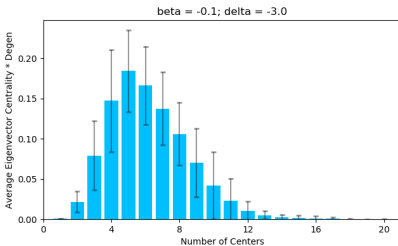
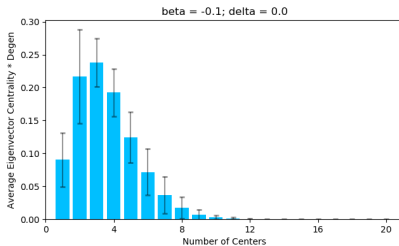
$$w(N) \sim N^\beta; \Gamma(N \rightarrow N+1) \sim \exp(-N^\delta)$$



Microstate Networks (4): First simple model

Simple toy model:

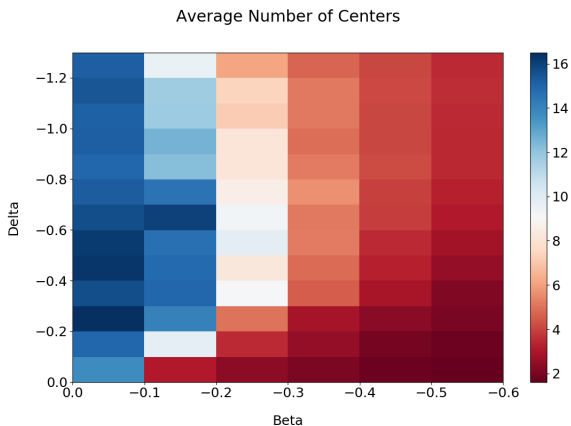
$$w(N) \sim N^\beta; \Gamma \sim \exp(-N^\delta)$$



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 \leftrightarrow Partition of total charge Q (e.g. $9 = 7 + 1 + 1$)



- Related: D1/D5 system!
 - $N = N_1 N_5$, twist sectors n : $N = \sum_n n N_n$ with N_n divided over 8 bos + 8 ferm excitations
 - Twist sector $n \leftrightarrow$ long string wrapped n times (F1/P frame)
 - Dynamical process splitting/combining long/short strings?
 - \rightarrow Model with network!

Summary

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!

Extra: Thermality, typicality, distinguishability, etc.

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

Extra: Thermality, typicality, distinguishability, etc.

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 (\leftrightarrow ETH)
 - Cfr. meta-stable non-extremal microstates and glassy BH physics [Anninos, Anous, Barandes, Deneff, Gaasbeek 1108.5821](#); [Bena, Puhm, Vercoocke 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!