Tunneling Branes into Microstates

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- I. Bena, D. Mayerson, A. Puhm, B. Vercnocke, [arXiv:1512:xxxxx]

Black Hole Formation... or Not? (1)

Understanding black holes and their entropy:

- Black hole entropy in string theory Strominger, Vafa; ...
- Constructing microstates in SUGRA Lunin, Mathur supertubes; superstrata

Still many open questions/problems:

- Typicality? Enough microstates in SUGRA?
- Non-extremal microstates? Bena, Puhm, Vercnocke; JMaRT; ...
- Time evolution? Hawking radiation?
- Formation?

Black Hole Formation... or Not? (2)

Formation of black hole (microstates):

- SUSY: no real evolution; no physical process constructs SUSY BH
- No dynamics between different SUSY states (BH $\leftrightarrow$ microstates)
- Near-extremal: probes in SUSY background

Black Hole Formation... or Not? (3)

Non-extremal dynamics for black hole (microstate) formation:

- Difficult to study
- Lots of confusion Firewalls...

Classical intuition:

- Infalling shell of matter forms horizon (well before singularity)
- Stringy/quantum corrections small at horizon $\rightarrow$ picture robust?

Why does this fail? $\rightarrow$ large phase space

Microstate Formation from Tunneling (1)

Analogy: particle in d-dimensional well with wavefunction $\Psi = \psi(x_1)\psi(x_2)\ldots$

Kraus, Mathur 1505.05078

- Leaking out in 1D: $\int_0^a dx_1 |\psi(x_1)|^2 \sim e^{-\epsilon t}$
- Leaking out in dD: $\int d^d x |\Psi|^2 = \left(\int_0^a dx_1 |\psi(x_1)|^2\right)\left(\int_0^a dx_2 |\psi(x_2)|^2\right)\ldots \sim e^{-d\epsilon t}$
- $d \gg 1/\epsilon \rightarrow$ almost instantaneous decay $\tau \sim 1/(d\epsilon) \ll 1$.

Microstate Formation from Tunneling (2)

$\{|i\rangle\}$ collection of microstates/fuzzballs:

- Large number of states $\mathcal{N} \sim e^{S_{BH}}$
- Probability of tunneling into one of these states very small:

$$\Gamma_i \sim e^{-B}, \qquad B \sim \int \sqrt{-g} R = \alpha S_{BH}$$

- If $\alpha \sim 1$, then $\Gamma_{tot} \sim \mathcal{N}\Gamma_i \sim O(1)$
- $\alpha \leq 1 \rightarrow$ fast tunneling: horizon never forms
- Kraus, Mathur 1505.05078 Consider Hawking radiation with backreaction: $\alpha = 1$

Microstate Formation from Tunneling (3)

Some issues:

- Assumptions, rough estimates
- All fuzzballs exactly same individual tunneling amplitude?
  - Initial state?
  - Intrinsic differences?

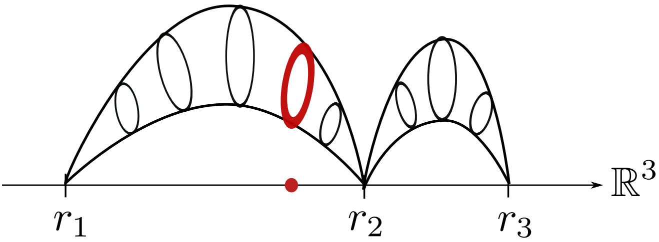
Goals

Goals: study B ($\Gamma \sim e^{-B}$)

- Study assumption $\alpha \leq 1$ $\left(\Gamma \sim e^{-\alpha S_{BH}}\right)$
- α same for all microstates?
- $\rightarrow$ Study specific class of microstates, their tunneling rate
- NOT all microstates! (not $\Gamma_{tot} \sim \mathcal{N}\Gamma_i$)

Forming Microstates: Background & Probes (1)

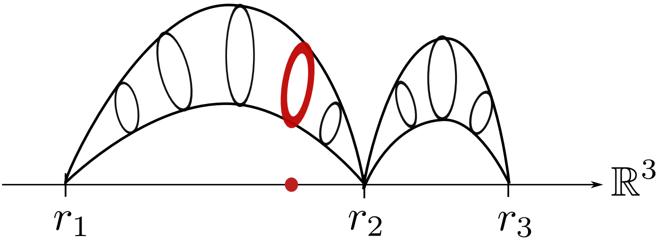
Background geometries:



- "Bubbled" 4D/5D Denef/Bena-Warner geometries
- Microstates of three-charge (M2-M2-M2) BH
- "centers" $=$ extra (5D) fibre pinches off ($\rightarrow$ bubbles)
- Position centers and fluxes related by "bubble equations"

Forming Microstates: Background & Probes (2)

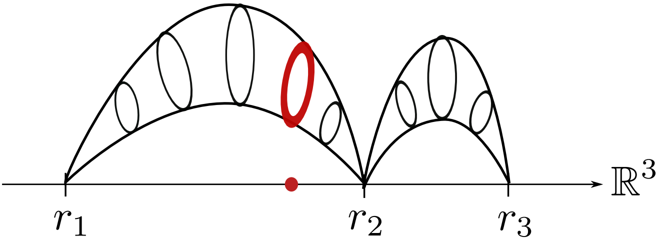
Background geometries, 10D/11D perspective:



- Center $\leftrightarrow$ D6/KKM
- Fluxes $\leftrightarrow$ D4/M5 dipole; F flux on D6
- Charges $\leftrightarrow$ D2/M2; from $F \wedge F$ on D6
- Also D0/ang. mom. charge; from $F \wedge F \wedge F$ on D6

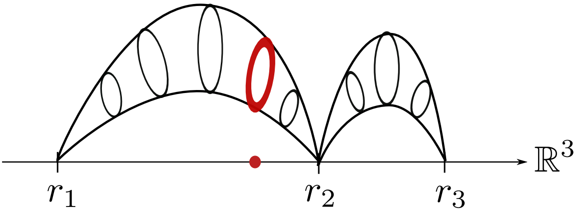
Forming Microstates: Background & Probes (3)

Probes:

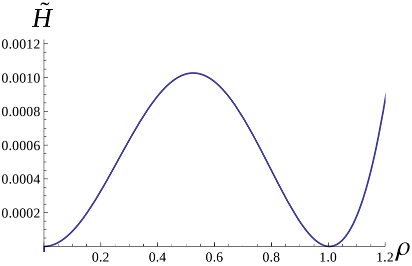


- Supertube wrapping fibre (D4 dipole along fibre, D2 charges)
- Explicit supertube potential, SUSY minima in $\mathbb{R}^3$
- Move supertube on center $\rightarrow$ only branes

Forming Microstates: Background & Probes (4)



Typical potential looks like:



$\rightarrow$ Tunnel SUSY$\rightarrow$SUSY

Forming Microstates: Background & Probes (5)

$\Gamma \sim e^{-B}$

- $B = \int_\gamma S_{eucl,on-shell}$
- For probe in microstate: $B = \int d\vec{x} \langle \Gamma, H(\vec{x}) \rangle$
- Γ: charge vector probe; $H(\vec{x})$: harmonic functions background

Interpretation:

- SUSY minima probe: $\langle \Gamma, H(\vec{x}_{SUSY}) \rangle = 0$
- Bubble equations (SUSY minima backreacted center): $\langle \Gamma_i, H(\vec{x}_i) \rangle = 0$
- (Bena-Warner notation: $\langle \Gamma, H(\vec{x}) \rangle = |d_3|^{-1} |q_1^{eff} q_2^{eff} V - d_3^2 Z_3|$)

Forming Microstates: Background & Probes (6)

For this class of N-centered "bubbled" geometries:

- Which N preferred?
- $\rightarrow$ calculate tunneling amplitude to form N-centered microstate
- Study scaling $B \sim N^{\beta}$ ($\Gamma \sim e^{-B}$)

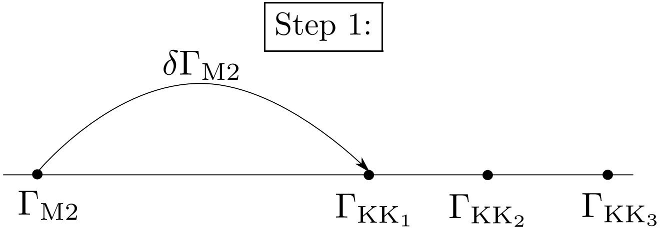
(Note: not enough states for correct scaling entropy!)

Forming Microstates: Process (1)

Go from N centers to $N + 1$:

- **Step 0:** Start from N-center configuration on a line

Forming Microstates: Process (2)

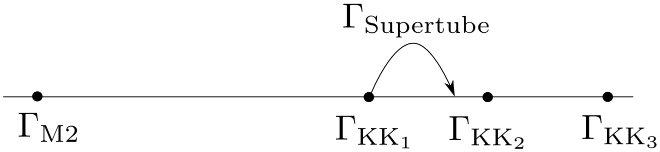


Go from N centers to $N+1$:

- **Step 1:** Bring in new M2-charge from infinity to left-most center
  - No tunneling (no cost)!
  - Allow ang. mom. (D0) charge to vary continuously/adiabatically
  - Needs to be small charge (bubble eqs!)

Forming Microstates: Process (3)

Step 2:



Go from N centers to $N+1$:

- **Step 1:** Bring in new M2-charge from infinity to left-most center
- **Step 2:** Tunnel supertube (M2 charge) away → new center
  - Split (old KK center)+(new M2 charge) → (new KK center)+(supertube)
  - spectral flow: supertube → KK center

Forming Microstates: Process (4)

One tunneling event $\rightarrow$ total process:

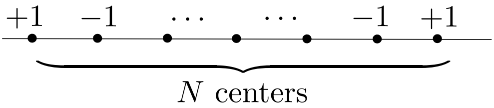
- Calculate $\Gamma_{N\rightarrow N+1} = Ae^{-B}$ at different N
- Extrapolate scaling behaviour of N:
  - $B_{N\rightarrow N+1} \sim q_{probe} Q_{bg}^{1/2} N^{\beta'}$
  - N_{tot} centers in final microstate; $q_{probe} = Q_{tot}/N_{tot}$
  - $B_{tot} = \sum_i B_{i\rightarrow i+1} \sim Q_{tot}^{3/2} N_{tot}^{\beta}$
- If $\beta < 0$: faster to tunnel into more centers

Forming Microstates: Results

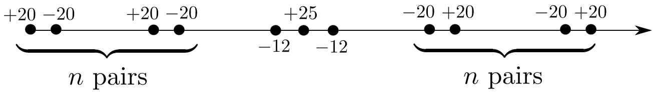
$$\Gamma \sim e^{-B}, \qquad B \sim N^{\beta}$$

If $\beta < 0$: faster to tunnel into more centers

- Non-scaling microstate: $\beta = -3/2$



- Scaling microstate: $\beta = -0.93$



Discussion: SUSY vs. Γ (1)

Tunneling vs. SUSY:

- Remember: SUSY = no dynamics ($\Gamma = 0$)
- $\rightarrow$ We need small extra metastability energy $E > 0$ for $\Gamma > 0$
- cfr. 1D QM potential barrier width a, height V_0:

$$\Gamma \sim E_{ms}\, e^{-2a\sqrt{2V_0}} + \mathcal{O}(E_{ms}^2)$$

- Only interested in exponent at leading order in E_{ms} so $E_{ms} = 0$ OK

Discussion: SUSY vs. Γ (2)

Tunneling vs. SUSY:

- Very crucial that branes wrapped on compact manifold
- If branes have non-compact direction $\rightarrow O(d)$ symmetric decay Coleman '77

$$B_{O(d)} = \frac{B_1}{E_{ms}^{d-1}} + \mathcal{O}(E_{ms}^{-(d-2)}) \qquad (\Gamma = Ae^{-B})$$

- Compare with particle:

$$B_{particle} = B_0 + \mathcal{O}(E_{ms}), \qquad A = A_0 E_{ms} + \mathcal{O}(E_{ms}^2)$$

- Cosmological examples; also decay metastable states in LLM geometries

Discussion: Other Remarks (1)

$$\Gamma \sim e^{-B}, \qquad B \sim N^{\beta}$$

$\beta < 0$ (non-scaling $\beta = -3/2$, scaling $\beta = -0.93$): What does this imply?

- $\rightarrow$ Faster to tunnel into more centers
- $\rightarrow$ Bound only by quantizing fluxes?

But...

Discussion: Other Remarks (2)

Faster to tunnel into more centers...?

But:

- Exact value β depends on details of (family of) microstates
- Microstates of max spinning BH ($J_R^2 = 4Q_1Q_2Q_3 - O(1/N)$) $\leftrightarrow$ not obvious how to generalize to lower J
- Says nothing about number of states available; maybe more states at small N ($\leftrightarrow$ superstrata)
- $\leftarrow$ depends on how (many ways) E_{ms} can be realized as excitation of microstate
- Formation first bubble? ("catalyst")

Summary & Outlook

Summary/future directions:

- $\Gamma \sim e^{-B}$ with $B \sim N^{\beta}$ and $\beta < 0$
- More centers preferred
- (First) clear calculation of tunneling amplitude into microstates
- But: J_R maximal; how many states per N? Formation first bubble?
- Future: relax restrictions? Relation Γ vs. entropy? $\Gamma_{tot} = \sum_{i \in \mathcal{N}} \Gamma_i \sim 1$?