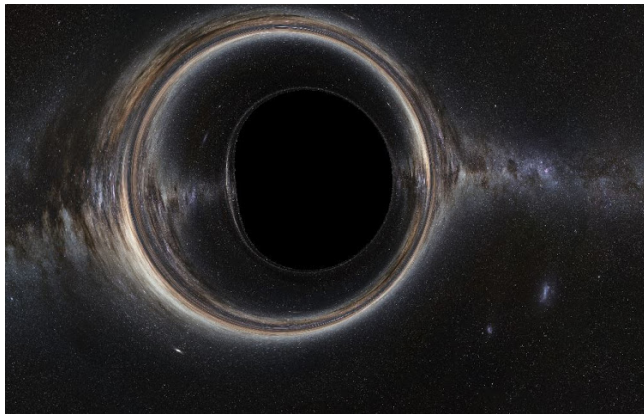Chiara Toldo | Amsterdam University

# Updates on the search for Multicenter AdS black holes

Eurostrings Lyon, April 28, 2022

*Based on work with R. Monten*

# Black holes and quantum gravity

Black holes are often seen as a theoretical laboratory for quantum gravity



Gravity knows about thermodynamics,
and it is holographic

$$S_{BH} = \frac{c^3}{G_N \hbar} \frac{A}{4}$$

Black holes in theory of supergravity provide a very valuable framework

- one can construct explicit solutions + interpretation in terms of D–branes

- String theory allows to identify the microscopic d.o.f. responsible for their entropy [Strominger, Vafa '96]

# Black holes in Anti de Sitter space

Mapping the black hole entropy counting into a problem in QFT. When bulk and boundary are supersymmetric perform detailed counting of states!

Counting made possible via *supersymmetric localization*



**CFT lives on the boundary of AdS**

**black hole in AdS**
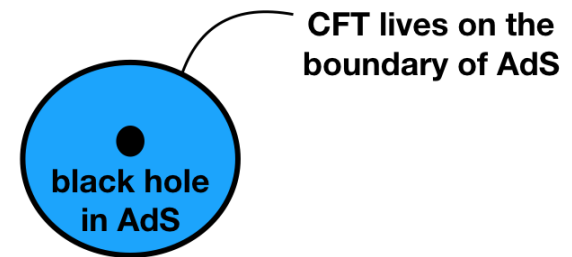
Black hole with temperature in the bulk corresponds to a thermal QFT in the boundary. Possible to model strongly coupled field theory processes by gravity dual via AdS/CFT

i.e. superconductivity modeled by AdS black holes with scalar hair [Gubser '08], [Hartnoll, Herzog, Horowitz '08]

# Multicenter black holes

Asymptotically flat multicenter black holes exist and well studied in string theory (e.g. [Denef, '99] + connection to interesting mathematics [Kontsevich, Soibelman '08])

Multicenter in AdS spacetime: <u>long standing challenge</u>. Presence of potential might spoil equilibrium conditions between the centers.

"Composite" AdS configurations exist: hovering black holes [Iqbal,Horowitz, Santos '14; Horowitz, Santos, **Toldo** '18] + dynamical BHs in spaces with negative $\Lambda$ [Chimento, Klemm '13]

Black hole bound states model glassy phase of matter in the dual theory [Denef et al.'13]

# Multicenter black holes and holographic glass

Glass: disordered yet rigid/ exponentially many local free energy minima. Poorly understood.
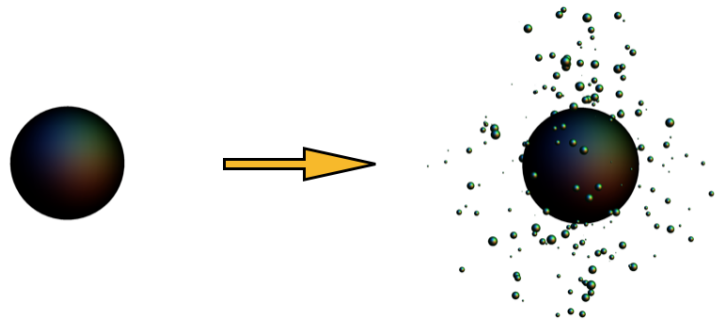


**High T**: unique, **single** center black hole → liquid phase

**Low T**: zoo of **multi** center black holes → glass phase

Multiple black holes induce electric and magnetic dipole charges, corresponding to inhomo-geneities in charge densities and magnetic fields in the dual field theory → High viscosity

# Our approach: Multicenter BHs in probe approximation



- Work in probe approximation: small probe black hole around a big, massive one
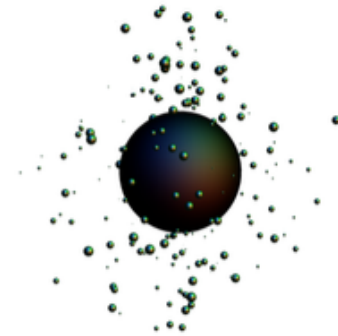
Stable and metastable probes exist in the background of a T > 0 4d black hole with neutral scalars [Anninos, Anous, Denef, Peeters '13]. **True both in Minkowski and AdS.**

In the $AdS_4$ compactification dual to ABJM theory, one linear combination of the gauge fields is Higgsed, thus massive [Aharony, Bergman, Jafferis, Maldacena '08].

Aim: study probe stability in a more general black hole background – charged scalars and massive vector field.

# Outline

Multicenter black holes in $AdS_4$ in the probe approximation

- Background black hole

  – Construction of $AdS_4$ thermal black holes from M–theory on $Q^{111}$

- Probe black holes

  – Stability of spacetime filling and internally wrapped branes

  – Supersymmetric limit

  – Caged wall crossing and microstate counting

# The Model: M theory on $Q^{111}$

M-theory truncation on homogeneous $SE_7$ manifold $Q^{111}$: 4d $\mathcal{N} = 2$ gauged supergravity with hypermultiplets with susy $AdS_4$ vacuum [Cassani, Koerber, Varela '12].

Dual is a $\mathcal{N} = 2$ Chern–Simons matter theory [Benini, Closset, Cremonesi '09], [Jafferis '09]

$$S = \int d^4x \sqrt{-g} \left( \frac{R}{2} - g_{i\bar{j}} \partial_\mu z^i \partial^\mu z^{\bar{j}} - h_{uv} D_\mu q^u D^\mu q^v + I_{\Lambda\Sigma} F^\Lambda_{\mu\nu} F^{\mu\nu,\Sigma} + \epsilon_{\mu\nu\rho\sigma} R_{\Lambda\Sigma} F^{\mu\nu,\Lambda} F^{\rho\sigma,\Sigma} - V \right)$$

Gravity, 3 vector multiplets and universal hypermultiplet. The linear combination $\zeta = 6A_0 + 2A_1 + 2A_2 + 2A_3$ becomes massive via Higgs mechanism.

Ansatz: All hypermultiplets scalars except one set to zero. Scalar modes have masses $m^2 = (16, 10, 4, -2, -2, -2, -2)$ corresponding to $\Delta = (6, 5, 4, (2, 1) \times 4)$
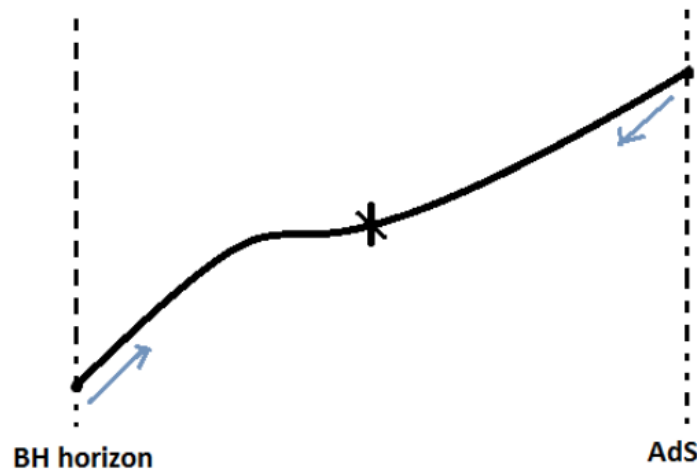
# Black hole solutions

Need to find BH with temperature. Static and spherically symmetric ansatz:

$$ds^2 = -e^{-\beta(r)}h(r)dt^2 + \frac{dr^2}{h(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\phi_I = \phi_I(r) \qquad A^\Lambda = \tilde{q}^\Lambda dt - P^\Lambda \cos\theta d\phi$$

Maxwell's equations yield $P^\Lambda k^a_\Lambda = 0$. Massive vector is purely electric.



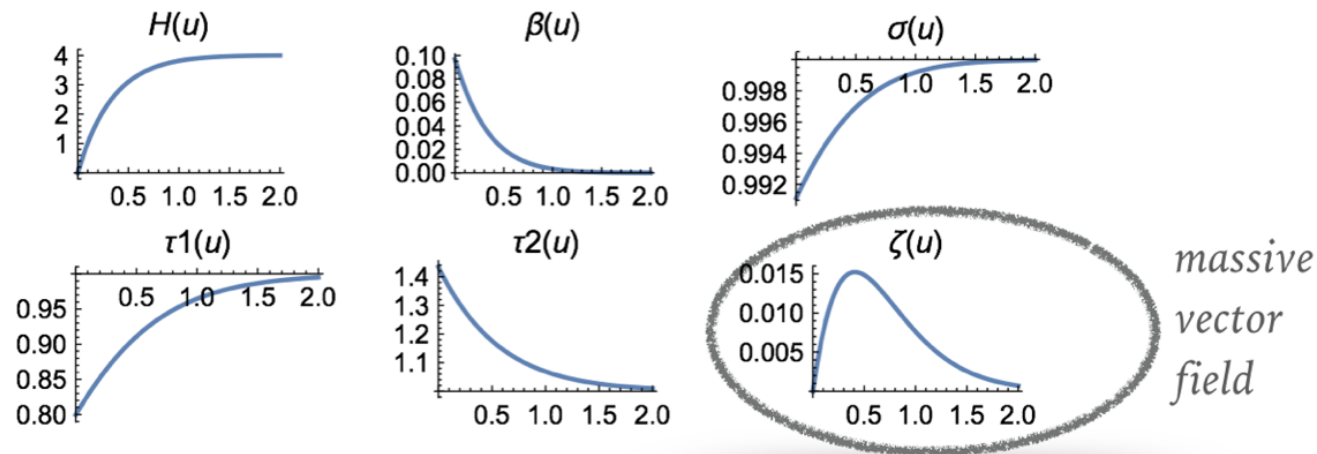BH horizon                                                    AdS

Expansion in series at the black hole horizon and at infinity. Demand to match in between.
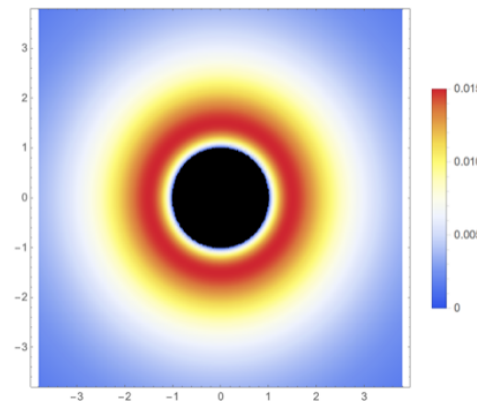
In total there are 14 equations. At the end of the day, 7 free parameters = BH charges

# Black hole solutions [Monten, CT, '17]

Example of electric BH with massive vector and nontrivial scalar profile:



*massive vector field*

Black hole is surrounded by a massive vector "atmosphere", which hovers outside the black hole horizon
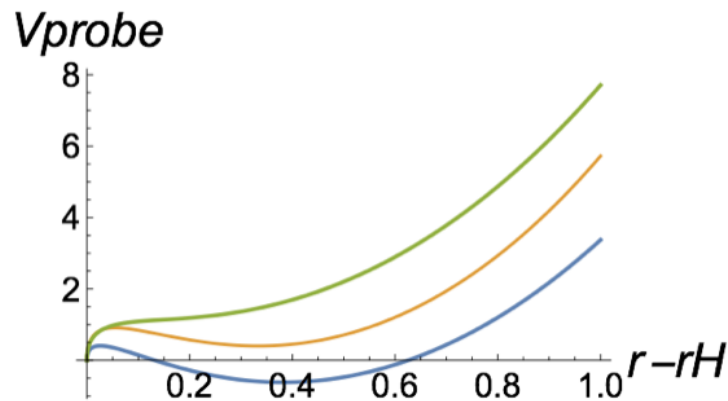


Accuracy of the numerics verified by checking the first law:

$$\delta M = T\delta S + \phi^\Lambda \delta Q_\Lambda - \chi_\Lambda \delta P^\Lambda$$

# Probes

Expectation: at high temperatures the single–center horizon will be thermodynamically favored (liquid phase), probe will enter the black hole



Vprobe is zero at the black hole horizon.

Probes can be <span style="color:green">unstable</span>, <span style="color:blue">stable</span> and <span style="color:orange">metastable</span> depending on the minimum of the potential

- Chart parameter space to see where stable probes arise

- Compare with the previous case of uncharged scalar. Effect of the interaction probes - condensate

# Probe analysis in various cases

Uplift to 11d $SE_7$ manifold $Q^{111} = SU(2)^3/U(1)^2$ **for solutions without axions**:

$$ds_{11}^2 = e^{2V}\mathcal{K}^{-1}ds_4^2 + e^{-V}ds^2(B_6) + e^{2V}(\theta + A_0)^2 \qquad \theta = d\psi + \frac{1}{4}\left(\cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2 + \cos\theta_3 d\phi_3\right)$$

with

$$ds^2(B_6) = \tau_1 ds_{V_1}^2 + \tau_2 ds_{V_2}^2 + \tau_3 ds_{V_3}^2 \qquad ds_{V_i}^2 = d\theta_i^2 + \sin^2\theta_i d\phi_1^2$$

and

$$F_4 = 6\mathcal{K}^{-1}e^{4\phi}\star 1 + d\tilde{B}\wedge(\theta + A_0) + dA^i\wedge\omega_i \qquad \omega_i = \frac{1}{8}\sin\theta_i d\theta_i \wedge d\phi_i$$

- Consider various horizon topologies: planar, spherical, higher genus horizon

- Different kinds of probes: spacetime filling M2 probes or internally wrapped branes

# Spacetime filling probe M2 branes

Consider M2 branes that fill the spacetime directions $t, x, y$

$$S_{M2} = -\tau_{M_2} \int d^3x \sqrt{G} \pm \tau_{M_2} \int A_3 = -\tau_{M_2} \int dt\, dx^1 dx^2 (V_g + V_e)$$

Planar horizons: instability towards nucleation of **space-time filling** M2 branes.



$q_1 = 1/500$

$V_{M_2}$

- T = 0.272171
- T = 0.184534
- T = 0.127313
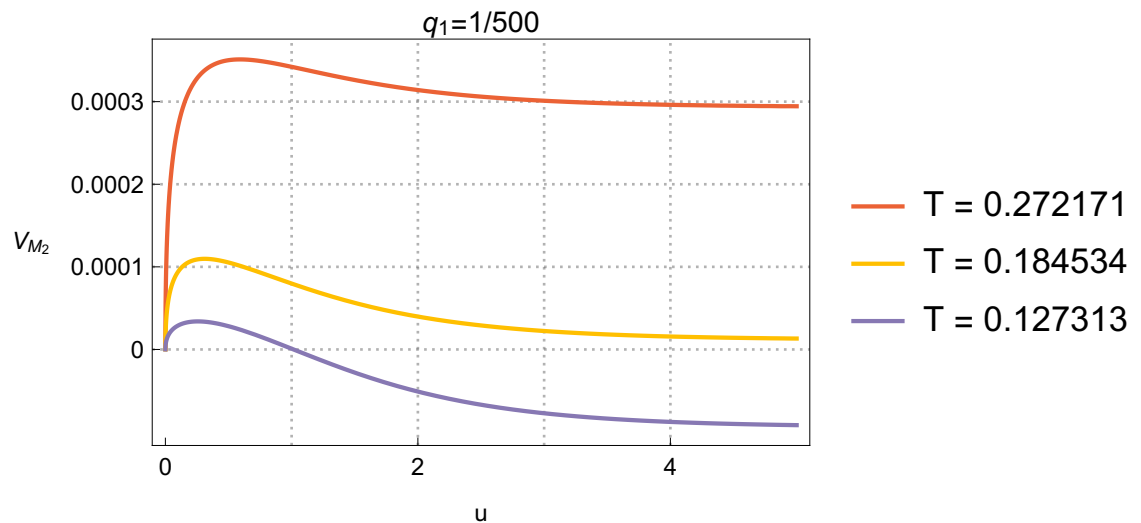
Lower energy by moving away towards the boundary of spacetime (similar to [Henriksson, Hoyos, Jokela '19] for branes in $T^{11}$). Instability is due to nonzero value of R−symmetry.

# More general probes [Monten, CT, '21]

DBI action for Fluxed D6 brane (combination of M2, M5 KK monopole)

$$V_{D6} = -\int m_\gamma(z) - \int (q_I A^I - p^I B_I) \qquad m_\gamma = |Z(\gamma, z, \bar{z})|$$

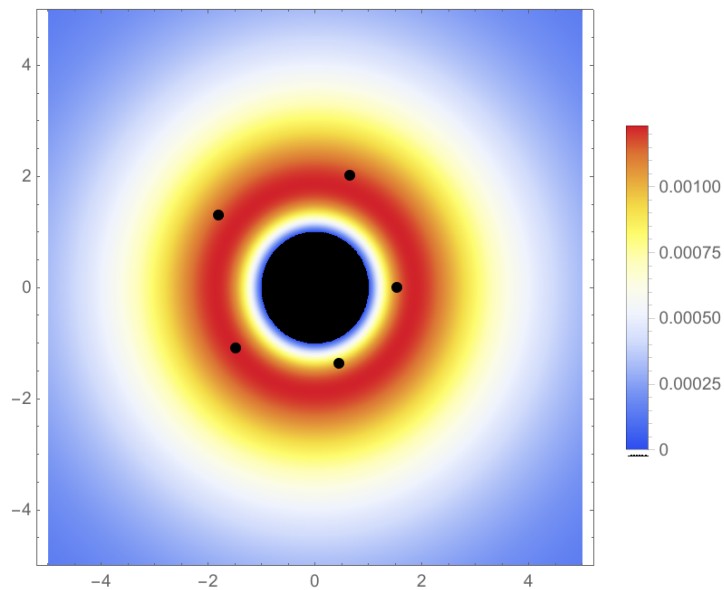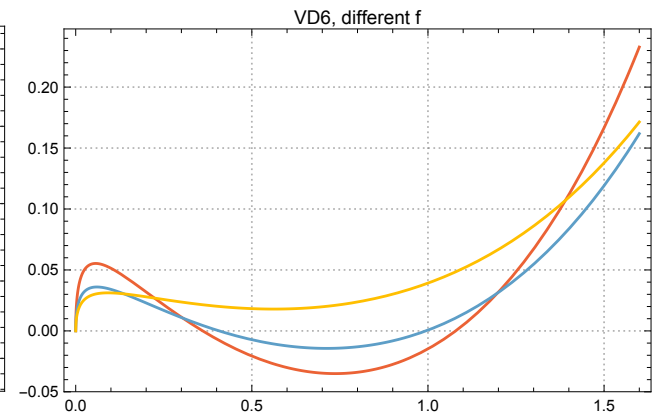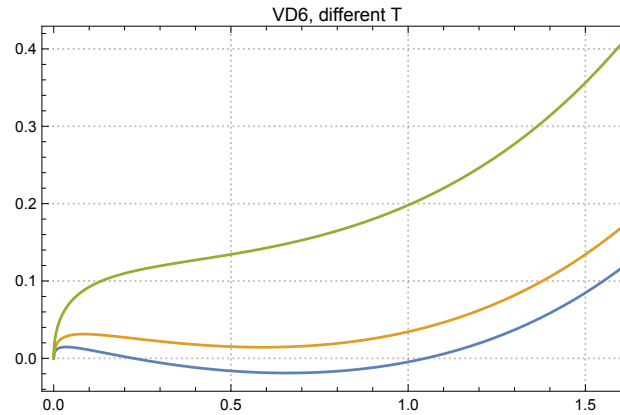Same form for the probe action from the DBI in [Asplund, Denef, Dzienkowski '15]
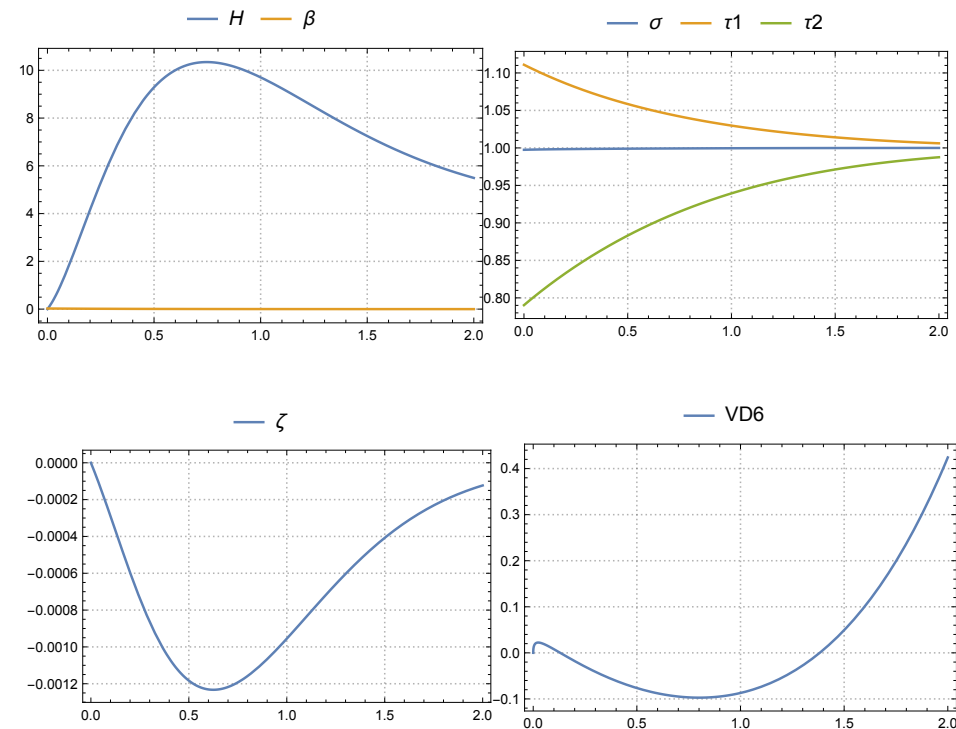
Where to look for stable probes?
Intuition from the FI case [Denef et al.'13]

# More general probes



T = 0.38 (green)

T = 0.16 (orange)

T = 0.08 (blue)



Metastable probes are closer to horizon.

Stable probes lie roughly at the peak of the massive vector halo

Notice that we set to zero the magnetic component of the Higgsed U(1)

# Supersymmetric limit

1/4 BPS black holes with NH geometry $AdS_2 \times \Sigma_g$ in [Halmagyi, Petrini, Zaffaroni '13].

We solved EOMs for solutions to $T = 0$ and managed to get "close" to extremal configuration

$$R_2 \sim 1.0012\, R_{2,\text{BPS}} \qquad \tau_i \sim 1.02\, \tau_{i,\text{BPS}} \qquad\qquad T \sim 0.0003$$

Potential shows no signs of inflection.

For these magnetic BPS solutions we do not find stable probes.
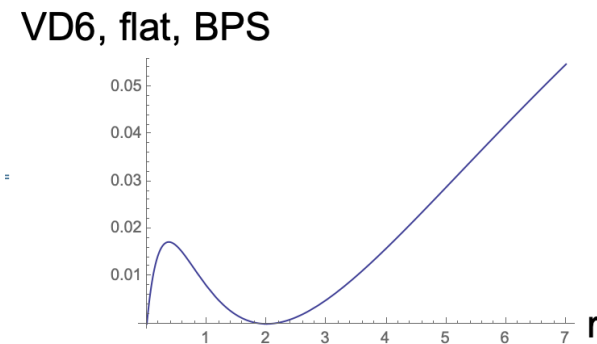

VD6, magnetic
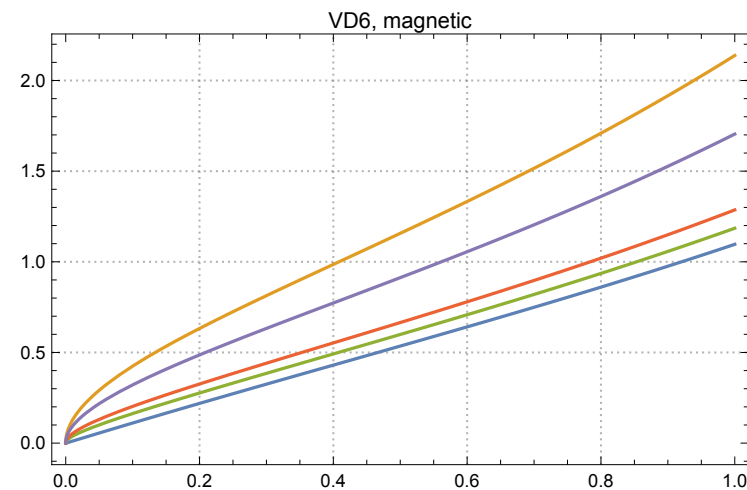
# Caged wall crossing and microstate counting

Small black hole / asymptotically flat limit reproduces the BPS equilibrium separation formula.
"Caged wall crossing" due to AdS asymptotics [Denef et al '13]: radius cannot diverge.

$$r_{\mathrm{BPS}} = \frac{q_0 - q_1 f^2 - q_2 f^2 - q_3 f^2}{3f^2 - 1}$$



VD6, flat, BPS

Status of microstate counting:

- Entropy counting for single–center BH in $Q^{111}$ with baryonic charges still problematic.

- Large N superconformal index for ABJM in [Choi, Hwang, Kim '19]. Need to understand complex fugacities (progress in [Cabo–Bizet et al '18])

# Conclusions and perspectives

We have found

- Instability for black branes towards nucleation of spacetime M2 filling probes

- Stable D6 probes on electric BHs: upon backreaction give black hole bound states. No stable probes on susy backgrounds.

*Multi-center black hole*
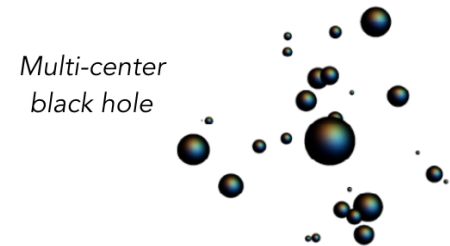


Future directions:

- transport coefficients via AdS/CFT. High viscosity?

- more general 5d supersymmetric solutions? e.g. wrapped branes on solutions from $T^{1,1}$

- exotic horizons i.e. susy black saturns in 5d [Armas, Gnecchi, CT, in progress]