

Moulting Black Holes

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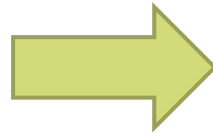
molt †, 《英》 moult/móult/ 【動】 | 自 | 〈鳥が〉 羽毛が生え替る, 〈動物が〉 毛[角]が抜け[生え]替る, 脱皮する // Snakes ~. ヘビは脱皮する.
— | 他 | 〈羽毛・殻など〉 を脱ぐ, 落す.
— 【名】 ㊦㊦ 抜け替り; その時期.
molt·er 【名】 ㊦ 羽[毛, 角]が生え替る時期の鳥[虫, 動物].

Introduction

No hair theorem

Black holes have no “hair”

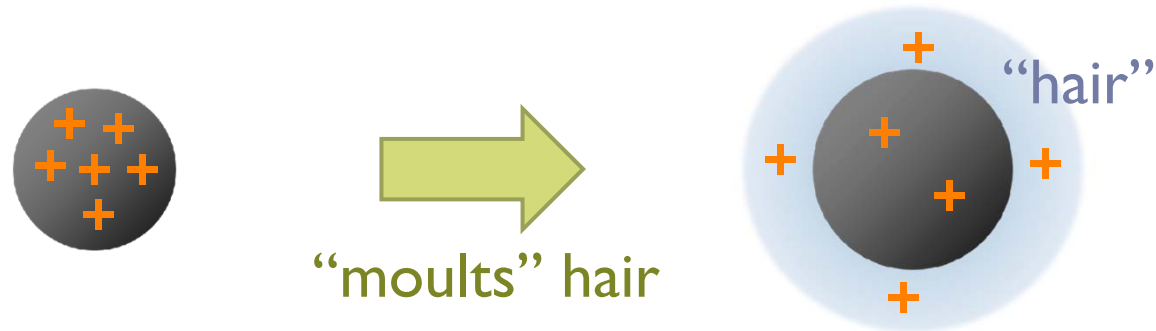
Given charges
 M, J, Q



Unique BH
solution



“Moulting” black holes



- ▶ AdS BH can spit out excessive charges to “hair” and increase entropy
 - ▶ Einstein-Maxwell has BH with charged condensate [Gubser]
 - ▶ AdS₅ BH with R-charge [Bhattacharyya+Minwalla+Papadodimas]
 - ▶ “Enigmatic” BHs in 4d N=2 sugra / MSW [Denef+Moore]

— but not under very good control



AdS₃/CFT₂: ideal arena

- ▶ DI-D5 system

- ▶ Bulk: $AdS_3 \times S^3 \times T^4$ or $AdS_3 \times S^3 \times K3$

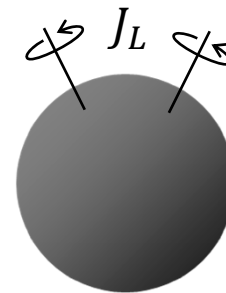
- ▶ Boundary: DI-D5 CFT

- ▶ Pivotal role in micro. understanding of BH in string theory

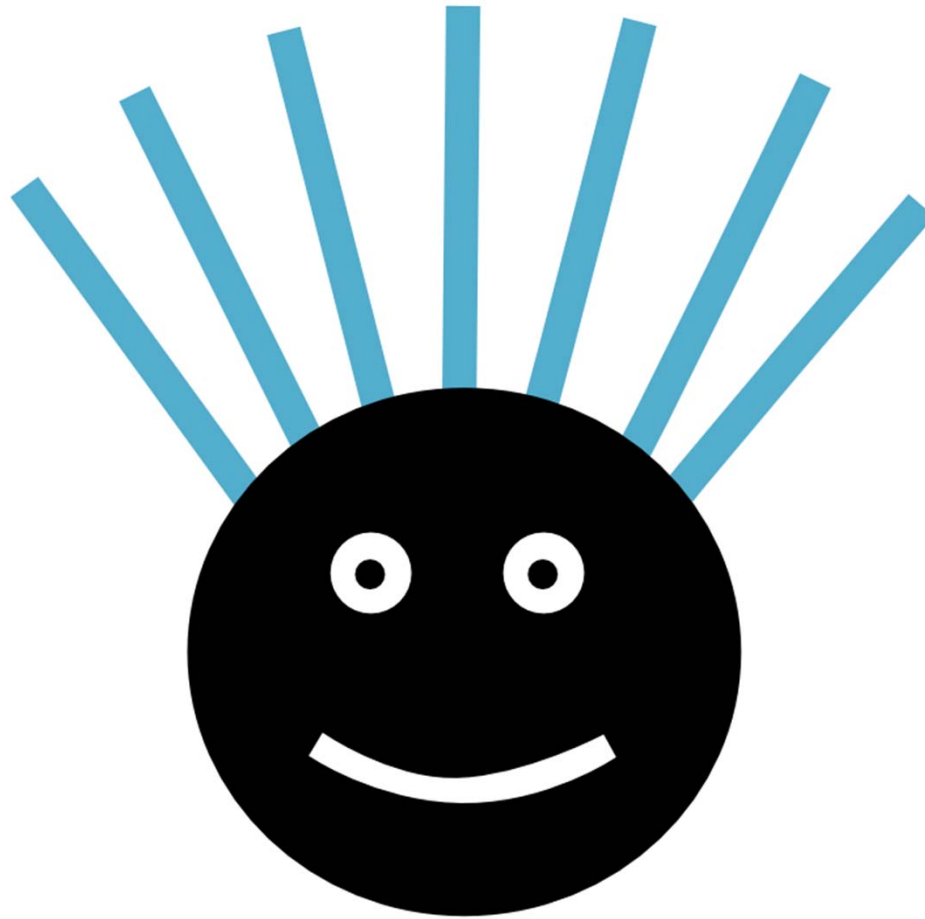
- ▶ Strominger-Vafa: the first microscopic explanation of S_{BH}

- ▶ BMPV black hole

- ▶ Under good control 😊

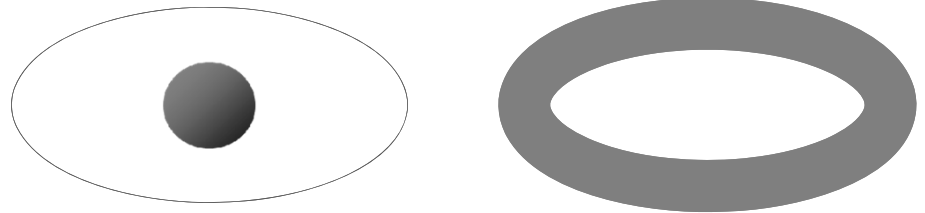


$$J_L \neq 0, J_R = 0$$



What we do

- ▶ **Strategy:** find max entropy config for fixed M, J
- ▶ **Results**
 - ▶ CFT side: found a novel phase
 - ▶ Gravity side: 2-center solution: “hairy BH” and BR
 - ▶ But $S_{\text{CFT}} > S_{\text{grav}}$



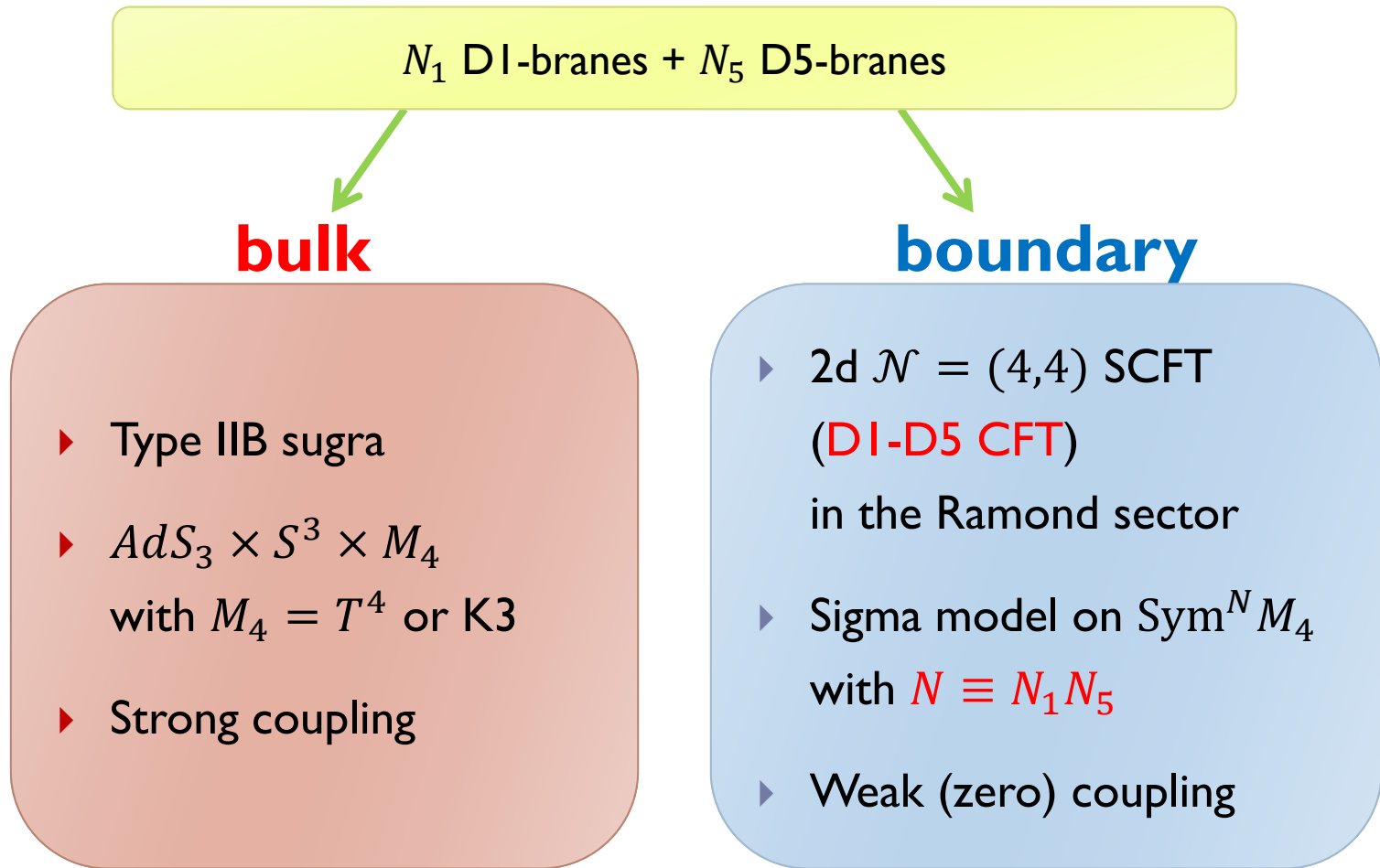
- ▶ **Implications**
 - ▶ Some states lift but some don't?
 - ▶ A new index?

Outline

- ▶ Introduction ✓
- ▶ Boundary CFT side
- ▶ Bulk gravity side
- ▶ Discussion
- ▶ Conclusion

Boundary CFT side of the story

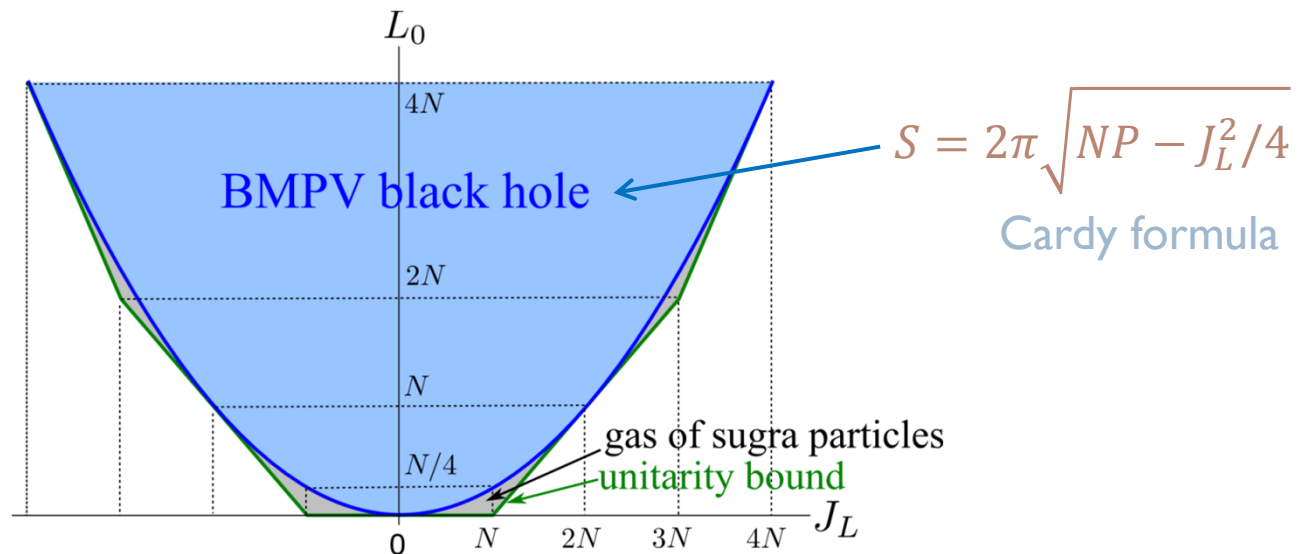
The AdS_3/CFT_2 correspondence



Some facts about D1-D5 CFT

- ▶ Charges: L_0, \bar{L}_0 ; $SU(2)_L \times SU(2)_R$ R-charges J_L, J_R
- ▶ **Supersymmetric** states: $\bar{L}_0 = 0$
 - ▶ $L_0 = P$: momentum; J_L, J_R : angular momenta

“Standard lore” phase diagram

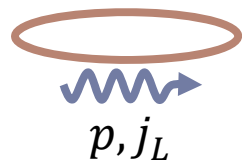
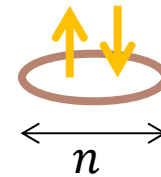


States of D1-D5 CFT

▶ Building blocks: “effective strings”

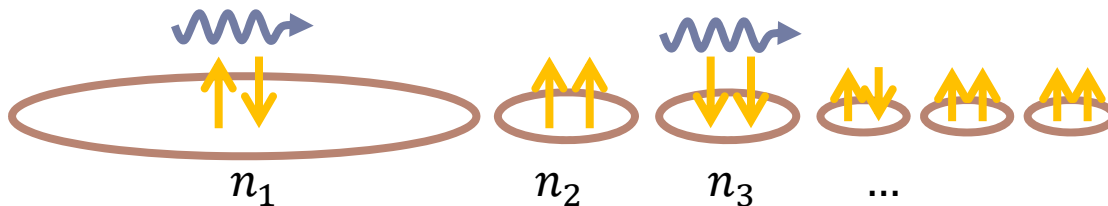
- ▶ Has length n
- ▶ Carries “base” spin $(j_L, j_R)_{\text{base}} = (\pm 1, \pm 1)$
- ▶ Excitations on it can carry momentum p and angular momenta j_L

$$(j_L, j_R)_{\text{base}} = (+1, -1)$$



This has entropy $S = 2\pi\sqrt{np - j_L^2/4}$

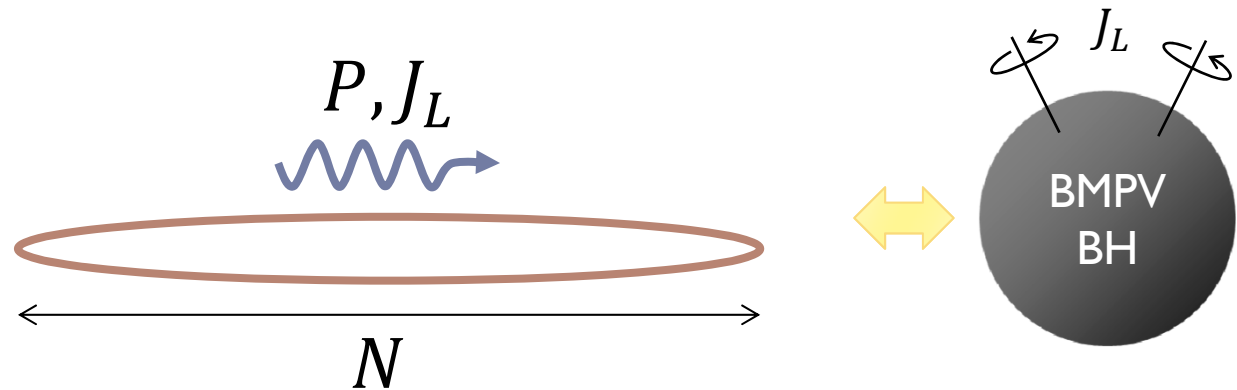
▶ States of the CFT is constructed by combining eff. strings



$$\sum_i n_i = N$$

charges add up

Example: BMPV ensemble

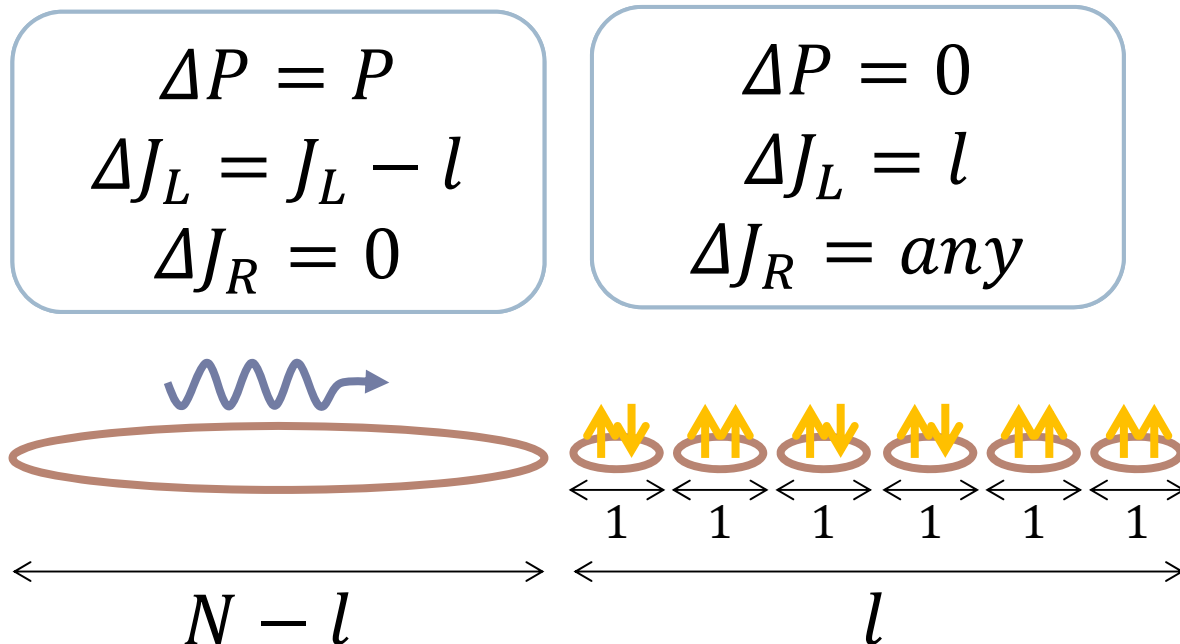


- ▶ A single string carries all charges N, P, J_L
- ▶ Base spin ignorable

$$S_{\text{CFT}} = 2\pi \sqrt{NP - J_L^2/4} = S_{\text{BMPV}}$$

The question

- ▶ What's the max entropy states, for given L_0, J_L ?
 - ▶ Better for P to be carried by a long string
 - ▶ Making the long string carry J_L reduces entropy
 - ▶ It may be better to make some of J_L carried by 'short' strings



Maximizing entropy

$$S(l) = 2\pi\sqrt{(N-l)P - (J_L - l)^2/4}$$



maximize for l

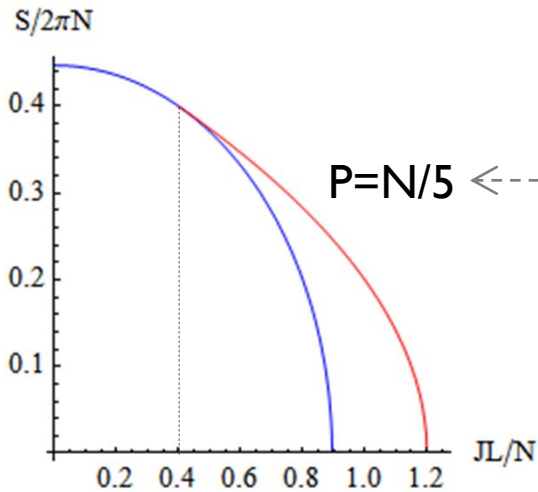
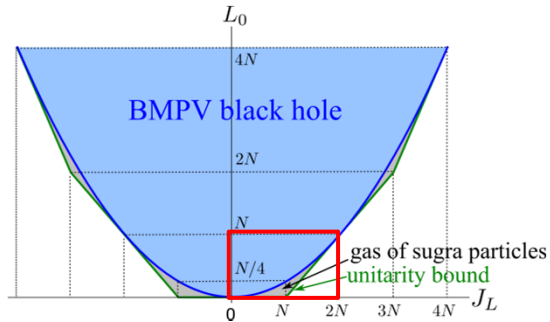
For $2P \leq J_L \leq N + P$, max is

$$S(l_{\max}) = 2\pi\sqrt{P(N + P - J_L)} \equiv S_{\text{CFT}},$$
$$l_{\max} = J_L - 2P$$

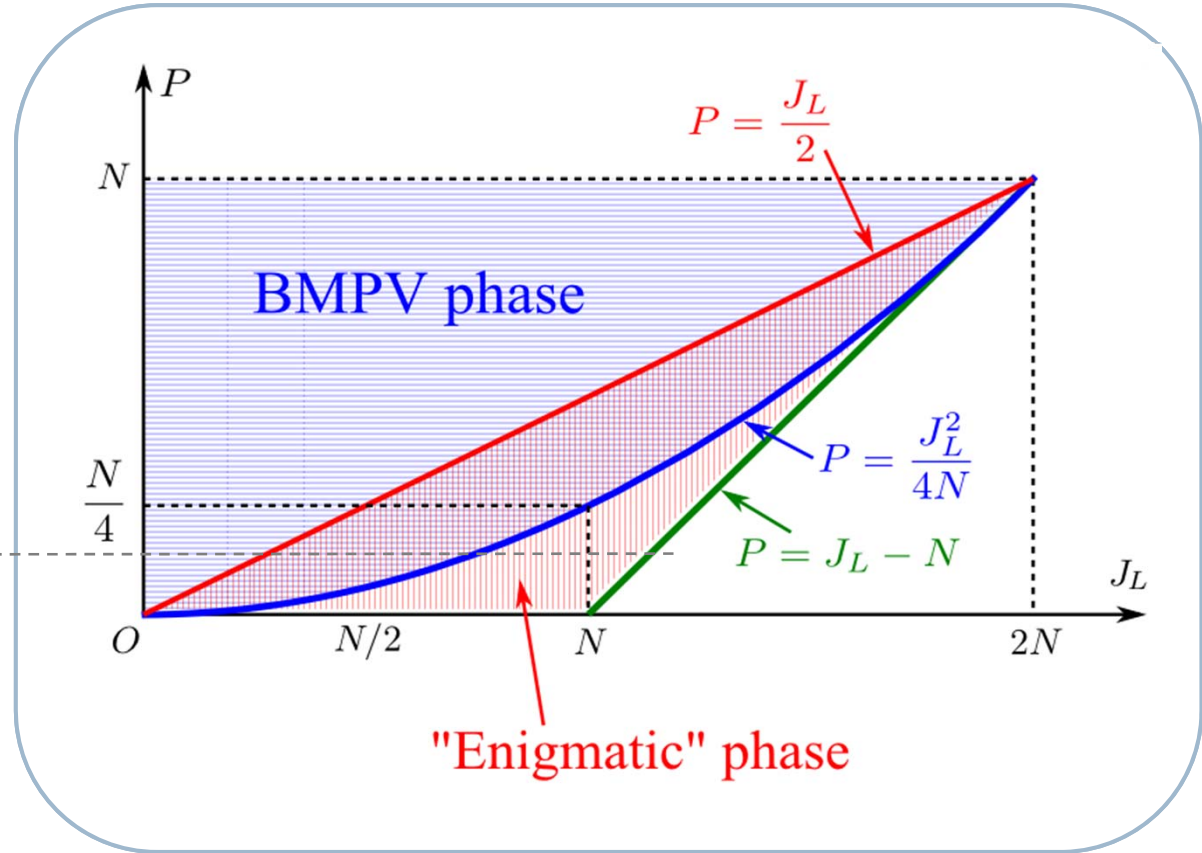
- ▶ Always larger than S_{BMPV}
- ▶ Comes in an $SU(2)_R$ multiplet with $J_R = J_L - 2P$

The new CFT phase diagram

old



new



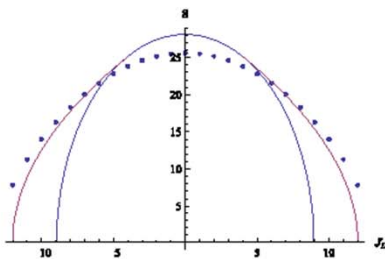
Applies for both T^4 & $K3$



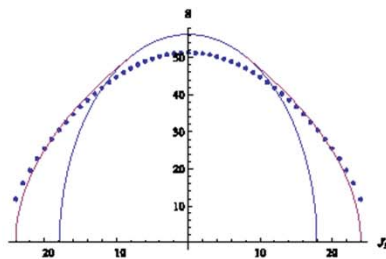
Numerical check

▶ Compare with T^4 partition function

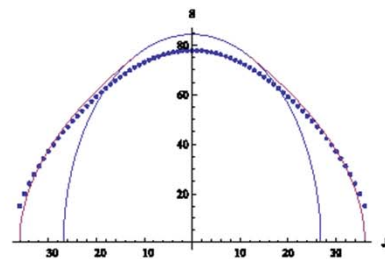
- ▶ Can't use Cardy (which is valid only for $P \gg N$)
- ▶ Use DMVV formula and evaluate by computer



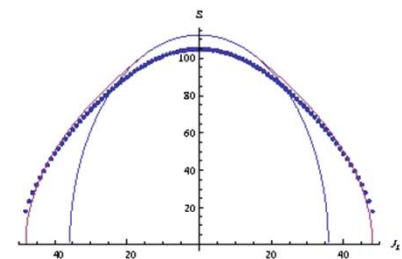
$N = 10, P = 2$



$N = 20, P = 4$



$N = 30, P = 6$



$N = 40, P = 8$

$$S \text{ versus } J_L \text{ for } k = \frac{P}{N} = \frac{1}{5}$$



Confirmed!

Comments

- ▶ Degeneracy (entropy) \neq index (elliptic genus)

$$Z = \text{Tr}_{\text{BPS}}[q^{L_0} y^{J_L}]$$

- ▶ Absolute # of states
- ▶ Not protected

$$\chi = \text{Tr}[(-1)^{J_L + J_R} q^{L_0} y^{J_L}]$$

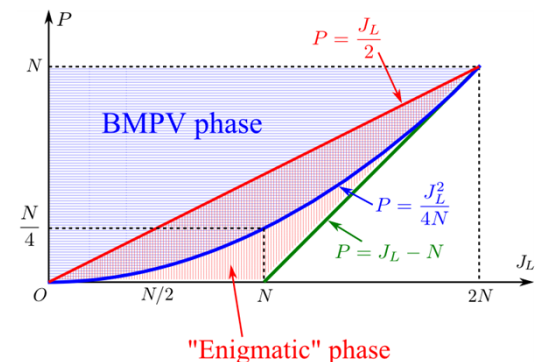
- ▶ Not absolute # of states
- ▶ Protected

- ▶ For enigmatic phase, entropy \neq K3 elliptic genus

- ▶ Elliptic genus always gives BMPV entropy: $\chi \sim \exp(2\pi\sqrt{NP - J_L^2/4})$ even outside the Cardy regime $P \gg N$ [Castro-Murthy]
- ▶ New phase *not* captured by elliptic genus

Summary — CFT side

- ▶ Found an “new phase” in non-Cardy regime
- ▶ Exists even outside the “BMPV parabola”
- ▶ Dominates over BMPV when coexists
- ▶ Comes in an $SU(2)_R$ multiplet with $J_R = J_L - 2P$
- ▶ Not captured by elliptic genus
 - Gets lifted at strong coupling?
 - Zero coupling artifact?



Bulk supra side
of the story

The goal

- ▶ We found CFT phase with more entropy than BMPV
- ▶ What's the bulk dual configuration?
 - Find max entropy configuration given N, P, J_L

Supersymmetric sugra solutions

- ▶ Assume two isometries → reduces to 4d N=2 sugra
- ▶ Most general timelike susy solutions in 4D known
[Bates-Denef] [Gauntlett-Gutowski] [Bena-Warner]

$$ds_{11}^2 = -Z^{-2/3}(dt + k)^2 + Z^{1/3}ds_{HK}^2 + Z^{1/3}(Z_1^{-1}dx_{12}^2 + Z_2^{-1}dx_{34}^2 + Z_3^{-1}dx_{56}^2)$$

$$\mathcal{A} = A^1 \wedge dx_1 \wedge dx_2 + A^2 \wedge dx_3 \wedge dx_4 + A^3 \wedge dx_5 \wedge dx_6$$

$$Z = Z_1 Z_2 Z_3, \quad A^I = B^I - Z_I^{-1}(dt + k)$$

$$ds_{HK}^2 = V dy_{123}^2 + V^{-1} \sigma^2, \quad \sigma = d\psi + A,$$

$$\vec{\nabla} \times \vec{A} = \vec{\nabla} V, \quad \text{or} \quad dA = *_3 dV.$$

$$Z_I = L_I + \frac{1}{2} C_{IJK} V^{-1} K^J K^K,$$

$$\Theta^I = dB^I = d(V^{-1} K^I) \wedge \sigma - V *_3 d(V^{-1} K^I),$$

$$B^I = V^{-1} K^I \sigma + \xi^I, \quad \vec{\nabla} \times \vec{\xi}^I = -\vec{\nabla} K^I$$

$$k = \mu \sigma + \omega,$$

$$\mu = M + \frac{1}{2} V^{-1} K^I L_I + \frac{1}{6} C_{IJK} V^{-2} K^I K^J K^K = \bar{M} + \frac{1}{2} V^{-1} Z_I K^I,$$

$$\vec{\nabla} \times \vec{\omega} = V \vec{\nabla} M - M \vec{\nabla} V + \frac{1}{2} (K^I \vec{\nabla} L_I - L^I \vec{\nabla} K_I)$$

Solution determined given harmonic functions on \mathbb{R}^3

$$V, K^I, L_I, M \quad (I = 1, 2, 3)$$

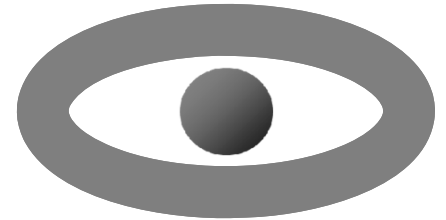
Ansatz

CFT states came in an $SU(2)_R$ multiplet with $J_R = J_L - 2P$

$J_R \leftrightarrow$ 4d angular momentum



2-center configs.



$$V = \frac{1+T}{r} - \frac{T}{\Sigma} \qquad L_I = -\frac{Q_I}{4r} - \frac{Q'_I}{4\Sigma}$$
$$K^I = -\frac{q^I}{2r} - \frac{q'^I}{2\Sigma} \qquad M = m_0 + \frac{m}{r} + \frac{m'}{\Sigma}$$

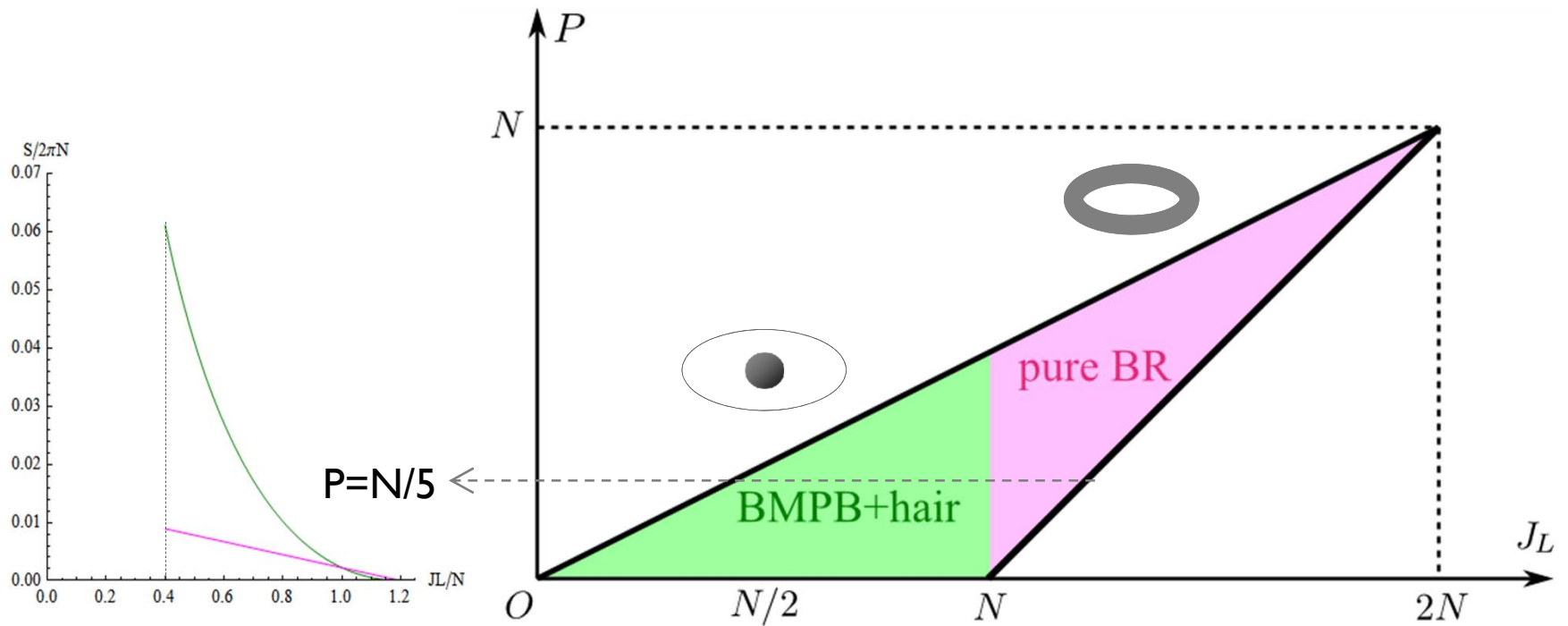
$$r = |\vec{x}|, \qquad \Sigma = |\vec{x} - \vec{a}|$$

Parameters constrained to give desired total charges



Play with parameters and maximize BH entropy

Result: max-entropy 2-center configs.



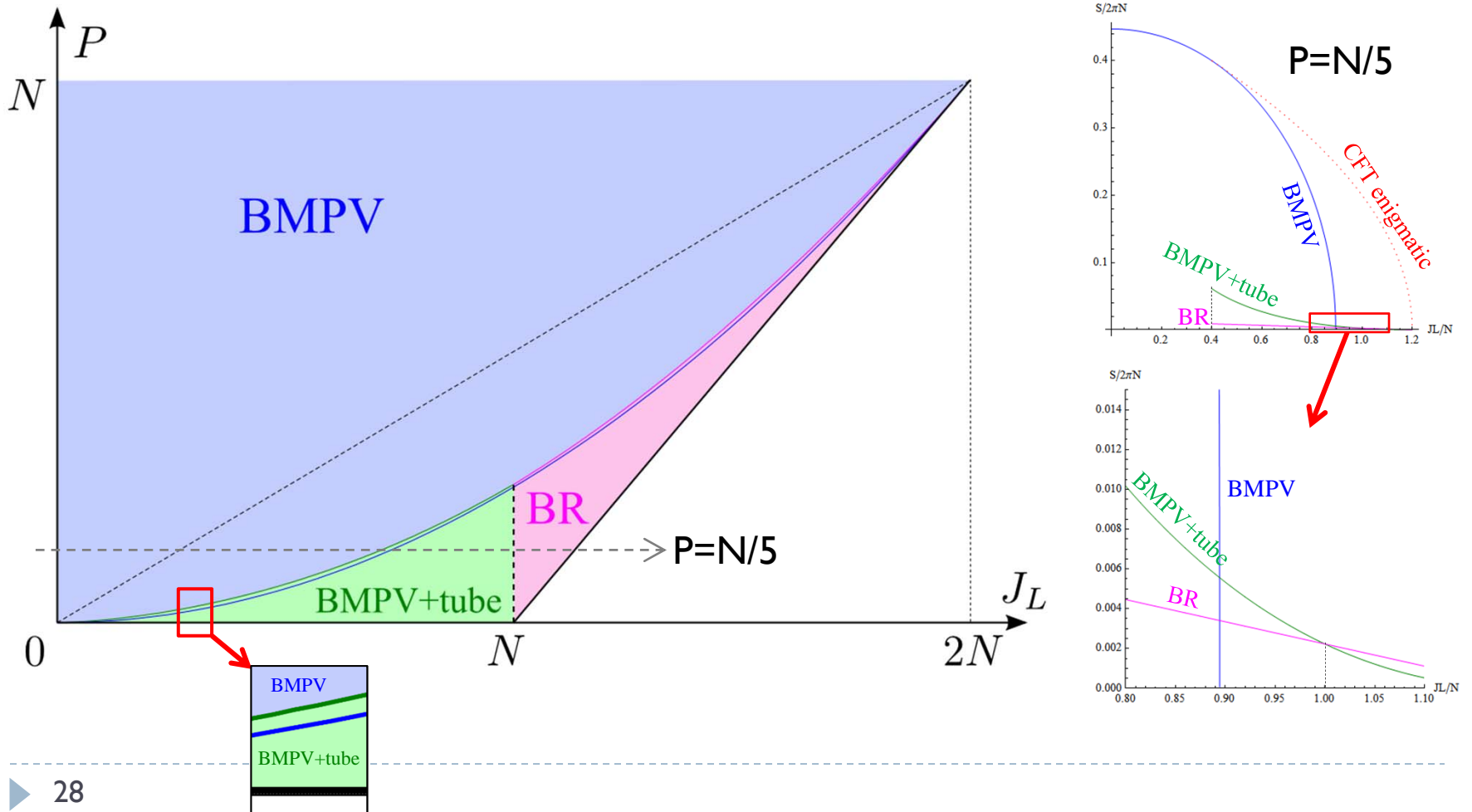
$$S_{\text{BMPV+hair}} = 2\pi(\sqrt{N} - \sqrt{J_L - P})\sqrt{P}$$

$$S_{\text{BR}} = 2\pi(\sqrt{N} - \sqrt{N - P})\sqrt{P - J_L + N}$$

$< S_{\text{CFT}}$

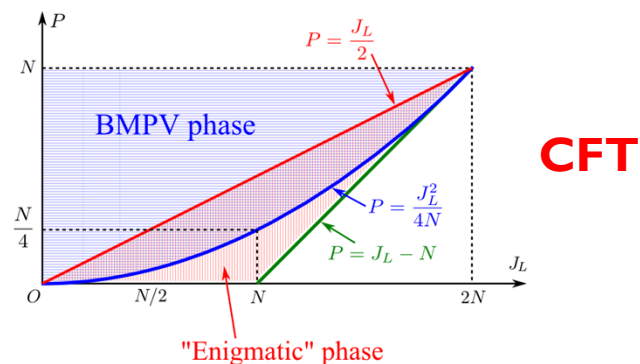
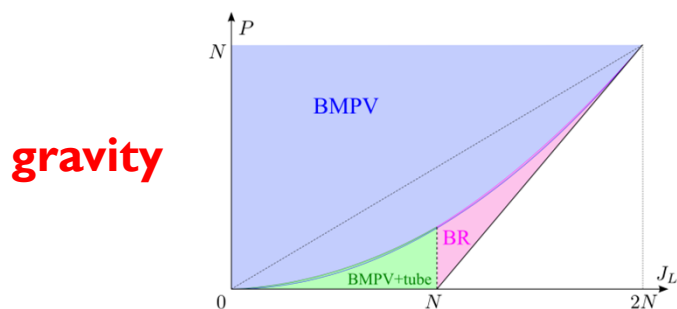
Bulk phase diagram

- ▶ 2-center configs very barely dominates over BMPV



Summary — gravity side

- ▶ Found 2-center configs for $P \sim J_L \sim N$
- ▶ Exists even outside the “BMPV parabola”
- ▶ Exists in the same region as CFT enigmatic phase does
- ▶ Dominates over BMPV partly in coexisting region
- ▶ Entropy strictly smaller than CFT enigmatic phase

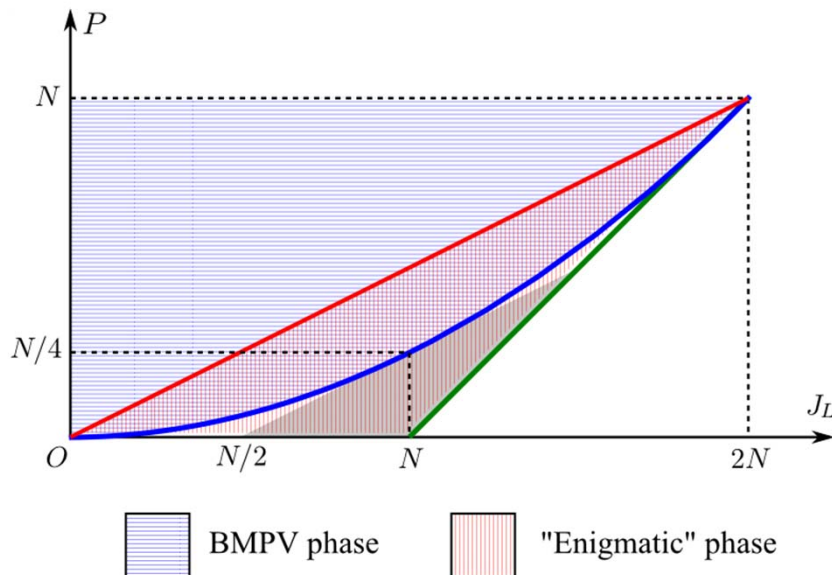


Discussion

Discussion

- ▶ Found configs whose entropy is larger than BMPV
 - ▶ BMPV is unstable, in spite of susy
- ▶ BH configs exist even outside the BMPV parabola!
 - ▶ Elliptic genus doesn't capture this BH

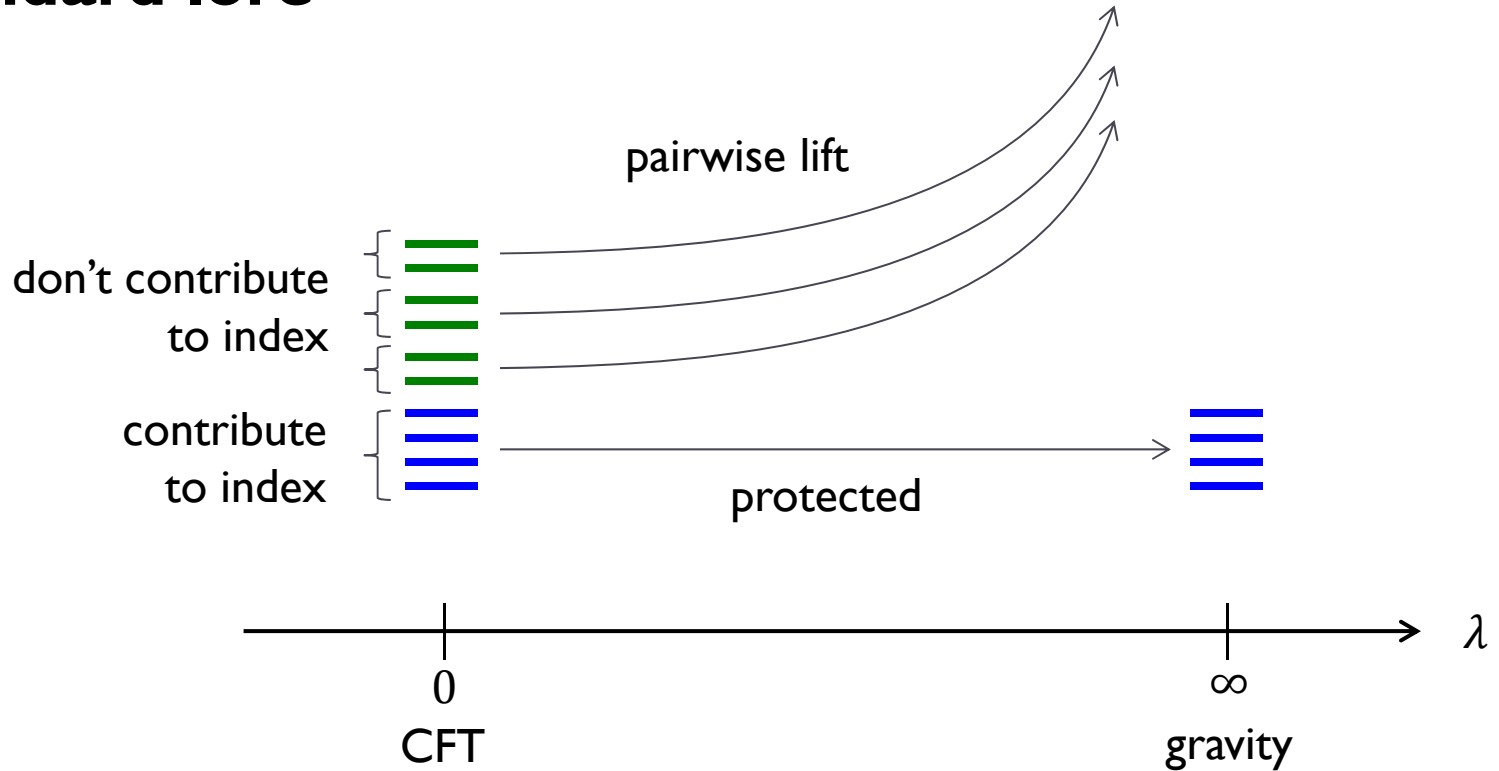
Cf. Matching of CFT and sugra elliptic genera [de Boer]



It was believed that there are no BHs in the gray region, but there *are*!

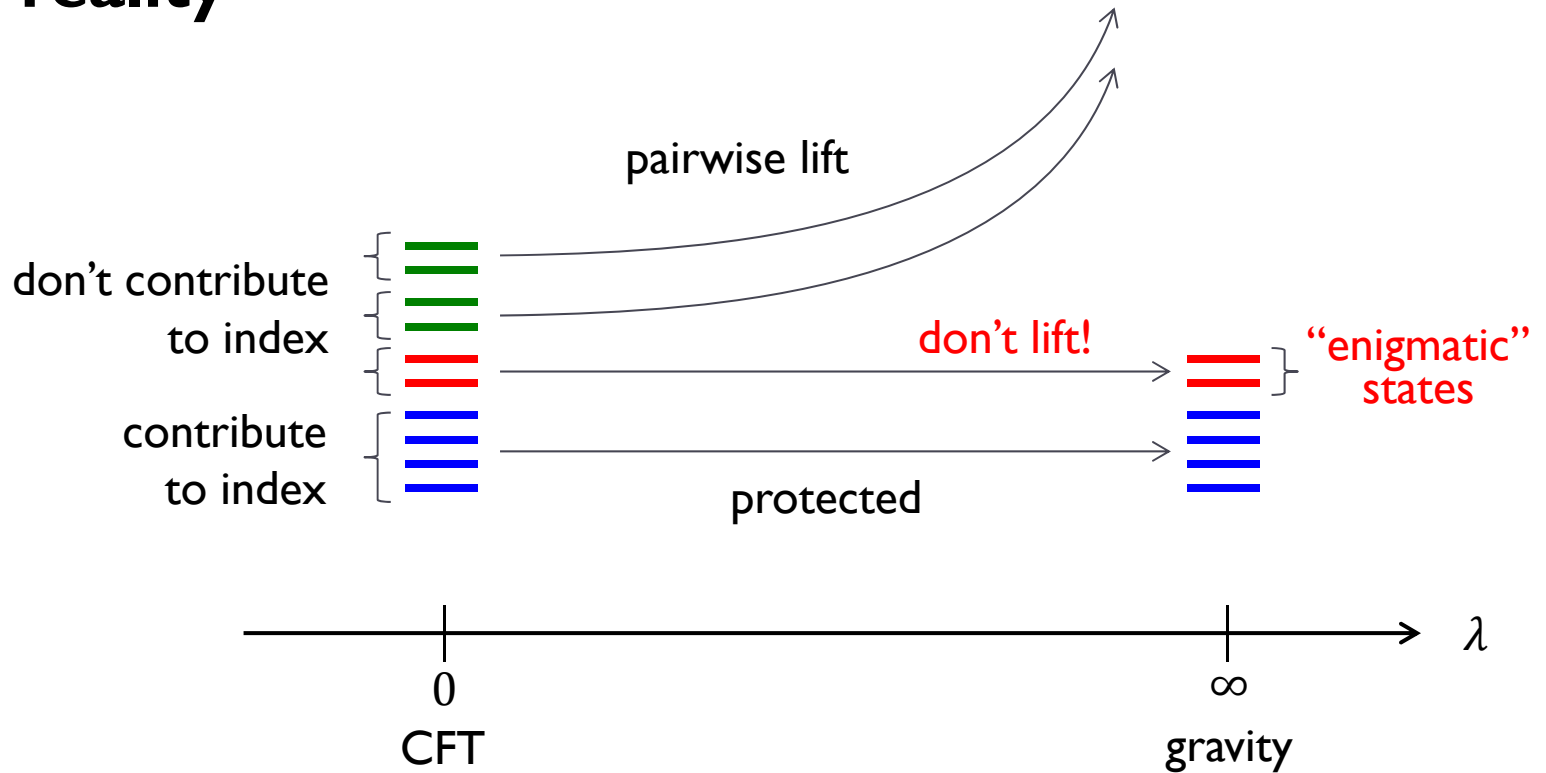
Partial lifting (1)

Standard lore



Partial lifting (2)

The reality



Protected for dynamical reasons, not susy?

Conclusion

Conclusion

- ▶ Studied phases of D1-D5 system for given N, P, J_L
- ▶ Found new phases both in CFT & gravity
 - *Controlled* example of “hairy” BH
- ▶ New phases dominate over BMPV
- ▶ Some states survive strong coupling, although not protected by susy!
 - *Dynamical* protection? A new index??
- ▶ Further investigation needed

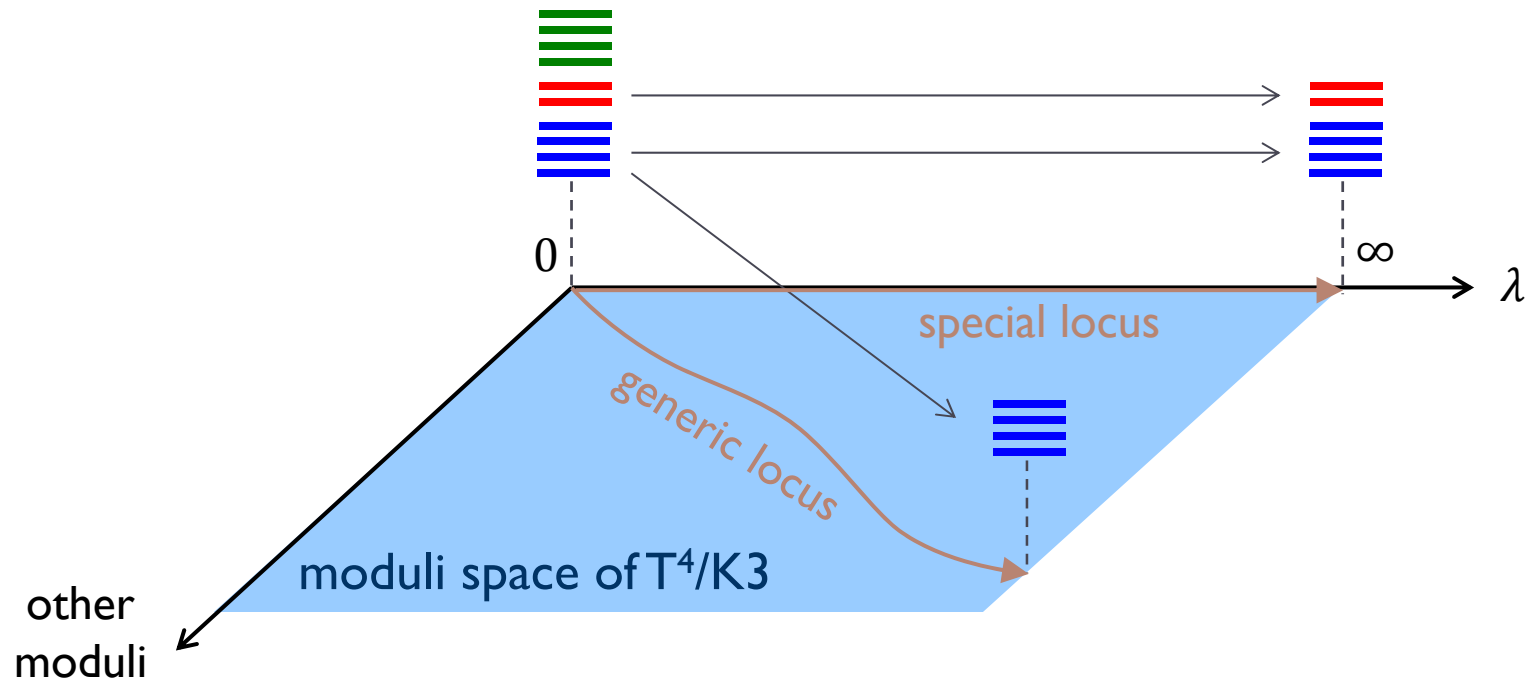
Thanks!



A new index?

We are not turning on generic moduli

— There may be an index protected only on special loci

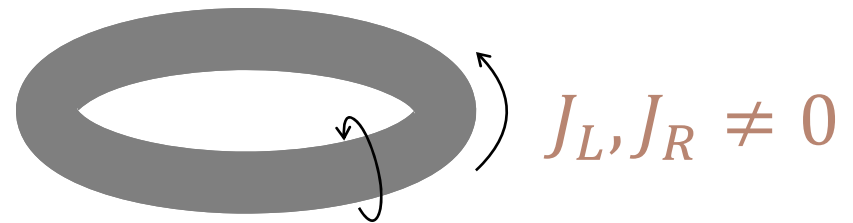


Unsolved issues

- ▶ **Black rings (susy)**

- ▶ Microscopics (CFT state) not understood [Bena+Kraus]

- ▶ Dipole charge?



- ▶ **Multi-center solutions**

- ▶ Zoo of solutions, no organizing principle

- ▶ Microscopics unclear

- ▶ Fuzzballs / gravity microstate

