Microstates of black branes as interacting elementary branes

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JHEP **1307** (2013) 100 [arXiv: 1305.0789 [hep-th]],
Class. Quant. Grav. **31** (2014) 085001 [arXiv: 1311.6540 [hep-th]],
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(Famous) D1-D5-P system

[Strominger-Vafa '96]

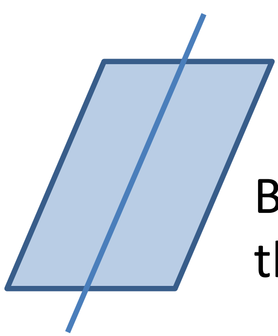
- One of the most remarkable achievements in the superstring theory.

- This discussion successfully reproduces the (near-) extremal blackhole entropy.
- We believe that it provides the microscopic description of blackhole in terms of string theory as quantum gravity.
- It is based on CFT calculation where we assume that the branes are coincident in the transverse directions.
- In order to retain this coincidence, we turn on NS-NS B-field. This is justified using the non-renormalization theorem.

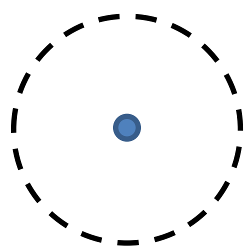
Our proposal

[Morita-SS-Wiseman-Withers ’13]

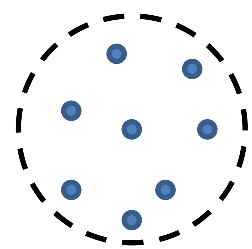
- Recently we proposed that the thermodynamics of near-extremal black branes are explained by an effective theory of gravitationally interacting elementary branes.
- In this description, branes are separately located and moving. They may compose a bound state (with no extra field).
- In this talk, I’d like to show you that our proposal can also reproduce the blackhole entropy and other quantities.



Branes expand in the same directions.



SV: Higgs phase



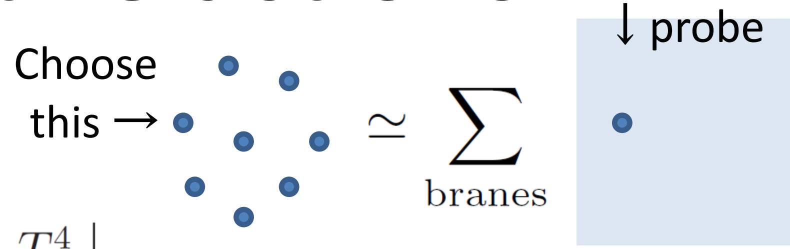
Ours: Coulomb phase

Our procedure

- ➢ Obtain the effective action of gravitationally interacting branes.
- Unfortunately it is difficult to discuss the details of graviton exchange interactions. *Ref. [Okawa-Yoneya '96]*
- Instead we estimate them using the probe brane actions for all the branes in the system.
- ➢ Evaluate the action in a natural manner for interacting systems.
- A kind of virial theorem for a system confined in a finite region.
- The relation $v \sim \pi T r$ for a thermal field. Here r is a scalar field for transverse direction and expanded in Matsubara modes.

$$v = \partial_t r \qquad \vec{r}_i(t) = \sum_n \vec{r}_{i(n)} \exp\left(i\frac{2\pi n}{\beta}t\right)$$

Obtain effective actions



➢ Ex.) intersecting D1-D5 system

	t	1	2	3	4	(5)	T^4
Q_1 D1-brane	$-$					$-$	
Q_5 D5-brane	$-$					$-$	$-$

[Morita-SS '14, '15]

- Choose one of the branes as a probe and regard all the other branes as the background geometry of D1-D5 black brane itself. $Q_1,\ Q_5 \gg 1$
- Write its probe brane action on black brane background:

$$S_{\mathrm{D1}}^{\mathrm{probe}} = -m_1 \int dt \left(\frac{1}{H_1}\sqrt{1 - H_1 H_5 \vec{v}^2} - \left(\frac{1}{H_1} - 1 \right) \right),$$

$$H_1 = 1 + \frac{r_1^2}{\vec{r}^2}, \quad H_5 = 1 + \frac{r_5^2}{\vec{r}^2}, \quad r_1^2 = \frac{4 m_1 G_5 Q_1}{\pi}, \quad r_5^2 = \frac{4 m_5 G_5 Q_5}{\pi}.$$

- Expand it at small gravity coupling G_5 and small curvature of branes. (Condition for SUGRA description) $v = \partial_t r \ll 1$

- The condition $v = \partial_t r \ll 1$ means the low energy region and the near-extremal region $r^2 \ll r_1^2, r_5^2$. Then the dominant terms are

$$S_{\rm D1}^{\rm probe} = \int dt \left[-m_1 + \frac{m_1}{2}\vec{v}^2 + \frac{m_1}{2}\frac{r_5^2}{r^2}\vec{v}^2 + \frac{m_1}{8}\vec{v}^4 + \frac{m_1}{8}\frac{r_1^2}{r^2}\vec{v}^4 + \frac{m_1}{8}\frac{r_1^2 r_5^4}{r^6}\vec{v}^4 + \cdots \right]$$

$$S_{\rm D5}^{\rm probe} = \int dt \left[-m_5 + \frac{m_5}{2}\vec{v}^2 + \frac{m_5}{2}\frac{r_1^2}{r^2}\vec{v}^2 + \frac{m_5}{8}\vec{v}^4 + \frac{m_5}{8}\frac{r_5^2}{r^2}\vec{v}^4 + \frac{m_5}{8}\frac{r_5^2 r_1^4}{r^6}\vec{v}^4 + \cdots \right]$$

- Put together all the probe brane actions for all the branes, then we can write down the effective action (of graviton exchanges).

$$S_{\rm D1D5} = \int dt \sum_{n=1}^{\infty} L_n, \quad L_n \sim \sum_{i_1,\ldots,i_n}^{Q_1} \sum_{j_1,\ldots,j_n}^{Q_5} \left(G_5^{2n-1} \frac{m_1^n m_5^n}{\pi^{2n-1}} \prod_{k=2}^{n} \prod_{l=1}^{n} \frac{1}{\vec{r}_{i_1 i_k}^{\,2}\, \vec{r}_{i_1 j_l}^{\,2}} \vec{v}^{2n} + \cdots \right)$$

(2n-1)-graviton exchange interactions

- In this discussion we cannot determine the coefficient of each term. (To do this, we need to discuss the details of graviton exchanges.)
- Various generalizations are straightforward: parallel D/M-branes, intersecting Dp-Dq-P (momentum) system, ...

Evaluate effective actions

- First, we set the characteristic scale of the brane system. This simplifies the effective action very much.

$$\boxed{\vec{r}_i - \vec{r}_j \sim r\,, \quad \vec{v}_i - \vec{v}_j \sim v\,.}$$

- Next, we impose a kind of the virial theorem.

$$\boxed{L_1 \sim L_2 \sim \cdots \sim \sum_n L_n}$$

- It says all terms of graviton exchanges are of the same order. This means we look at the strong coupling region.
- Then the free energy can be evaluated. For the D1-D5(-P) case,

$$F \sim L_1 \sim \frac{\pi r^2}{G_5} \qquad F = -\frac{\pi r_H^2}{8G_5} \quad \text{(SUGRA)}$$

- Finally, we use the relation of velocity and temperature

$$\boxed{v \sim \pi T r}$$

- Then the size of horizon and the entropy can be estimated as

$$r \sim T G_5 \sqrt{Q_1 Q_5 m_1 m_5}$$

$$S_{\text{entropy}} = -\frac{\partial F}{\partial T} \sim \pi m_1 m_5 Q_1 Q_5 G_5 T$$

$$r_H = 8 G_5 T \sqrt{m_1 m_5 Q_1 Q_5}$$

$$S_{\text{entropy}} = 16\pi m_1 m_5 G_5 Q_1 Q_5 T$$

(SUGRA)

- In this way, we can reproduce various physical quantities of black brane systems up to rational factors.
- Interestingly, this discussion can explain the dynamics of general parallel and intersecting branes in a unified way.
- We call this model "warm p-soup model," since the branes are separated and strongly interact at finite temperature.

Summary

- We propose “warm p-soup model”. It may be a new picture of black brane systems.
- In this model, the branes are in Coulomb phase.
- This model can explain the dynamics of various black brane systems (parallel/intersecting D/M-branes) in a unified way.
- We don’t need to introduce extra fields like NS-NS B-field in the previous discussions (in Higgs phase).
- We don’t need to use some UV structure of gravity.
(Ex. duality relations, gauge/gravity correspondence, ...)
- We can’t reproduce rational factors, so we must improve it.