Black Hole Throats and Large Quantum Fluctuations

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Based on work with J. de Boer, I. Messamah, and D. Van den Bleeken

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Motivation

Puzzles from Black Hole Physics

- Field Theory reasoning fails to explain qualitative features of QG:
    1. Information Loss
    2. Holography
    3. Black hole entropy
- How does standard effective field theory (EFT) break-down in QG?

Potential New Features in Quantum Gravity?

- Failure of locality (at horizon scales)?
- Large scale quantum effects?

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Approach

Deep Throats in String Theory

- Study families of black hole *like* solutions in string theory.
- Soln's support throats of arbitrary depth mimicking horizons of SUSY BHs.
- Throats end in smooth cap and have no large curvature
  $\Rightarrow$ EFT implies quantum corrections negligible.

Quantization

- Geometries are backreaction of system of D-branes.
- D-branes at weak coupling described by SUSY QM $\Rightarrow$ tractable!
- Phase space at strong and weak coupling related by SUSY.
- After quantization throat destroyed by macroscopic quantum fluctuations!

Based On

- *A bound on the entropy of supergravity?* [arXiv:0906.0011]
- *Quantizing $\mathcal{N} = 2$ Multicenter Solutions.* [arXiv:0807.4556]

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D-branes

Setup

- Wrap branes on cycles of 6-d compactification manifold (Calabi-Yau).
- Branes sit at a points $\vec{x}_a \in \mathbb{R}^3$.
- "Integrate out" internal degrees of freedom.

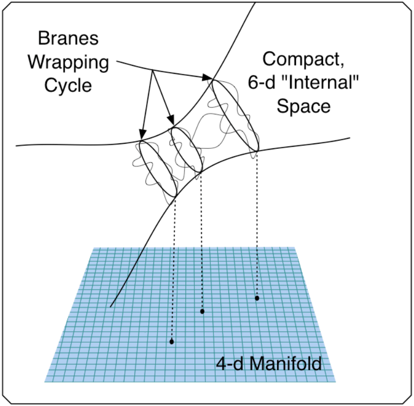

Figure: Positions $\vec{x}_a$ minimize potential.

D-brane Theory (at weak-coupling)

- $\mathcal{N} = 4$, $d = 1$ theory (SUSY QM).
- Coords become world-line fields, $\vec{x}_a(\tau)$, encoding brane dynamics.
- Coupling, g_s, is free parameter from spacetime point of view.
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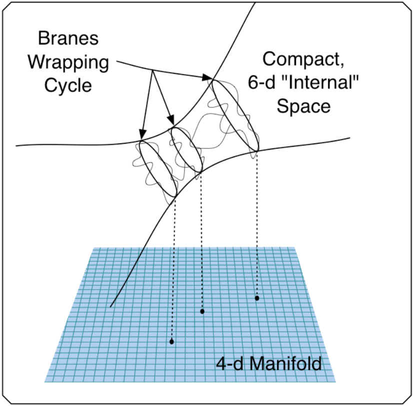

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- Branes have electron-monopole like interactions.
- First order part of Lagrangian fixed by SUSY

$$L^{(1)} = \sum_a \left(-U_a(x)D_a + \vec{A}_a(x)\cdot\dot{\vec{x}}_a\right) + \text{ fermions}$$

- $(x_a^i(\tau), D_a(\tau))$ are bosonic world-line fields.
- $U(x)_a$ and $A_a^i(x)$ functionals fixed by SUSY $\Rightarrow g_s$ independent.
- Protected terms fix SUSY phase space and symplectic form.

Commutators (from symplectic form)

$$[x_{ab}^i, x_{ab}^j] \sim \epsilon^{ijk} x_{ab}^k$$

Note: $\vec{x}_{ab} := \vec{x}_a - \vec{x}_b$ self-conjugate (consistent with electron-monopole interaction).

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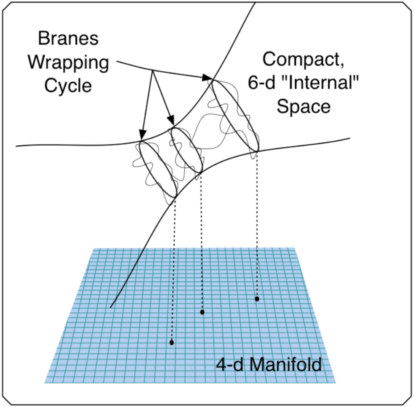
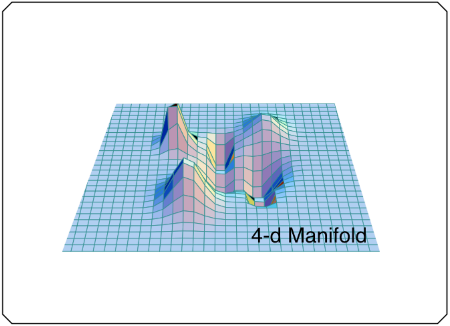
From D-branes to Supergravity

Pictures

- As g_s tuned up D-branes couple to gravity and backreact.
- At strong coupling supergravity is a better effective description than SQM.



At $g_s \sim 0$ brane lives on $\mathbb{R}^{1,3}$.



For $g_s \gg 1$ branes warp spacetime
$\Rightarrow$ generate geometry.

- Branes backreact giving SUSY solutions to 4d, $\mathcal{N} = 2$ sugra.
- Also lift to soln of 5d, $\mathcal{N} = 1$ sugra (but will not discuss).

4-d fields

$$ds^2 = -\frac{1}{\Sigma(x)}(dt + \omega(x))^2 + \Sigma(x)\, dx^i dx^i \,,$$

$$t^A = B^A + i\,J^A \,, \qquad \mathcal{A}^A = \ldots$$

- Original brane coords $\vec{x}_a$ parameterize soln's via dependence of $\Sigma(x)$ and $\omega(x)$ on $H(x)$.

Solutions specified in terms of:

$$H(x) = \sum_{a=1}^{N} \frac{\Gamma_a}{|x - x_a|} + h$$

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Angular Momentum of Solutions

- $\omega(x)$ in metric implies solutions are stationary but *not static*.
- Angular momentum carried between *each pair* of centers $\vec{J}_{ab}$.

Intrinsic Angular Momentum

$$\vec{J} = \sum_{a<b} \vec{J}_{ab} = \frac{1}{2} \sum_{a<b} \frac{\langle \Gamma_a, \Gamma_b \rangle \, \vec{x}_{ab}}{r_{ab}} \,.$$

- Asymptotic value of $\omega(x)$.
- $\langle \Gamma_a, \Gamma_b \rangle$ electric-magnetic pairing $\Rightarrow$ crossed EM fields.

- Brane commutator $[x^i_{ab}, x^j_{ab}] \sim \epsilon^{ijk} x^k_{ab}$ corresponds to quantizing $\vec{J}_{ab}$.

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SUSY Phase Space

BPS Constraint Equations

$r_{ab} = |\vec{x}_a - \vec{x}_b|$ must satisfy:

$$\sum_{a,\, a \neq b} \frac{\langle \Gamma_a, \Gamma_b \rangle}{r_{ab}} = \langle h, \Gamma_a \rangle$$

- Constraint eqns minimize potential from gravity and scalars.
- For N centers solution space to above $2N - 2$ dim.
- Dimension even $\Rightarrow$ good because sol space is phase space!
- This is because $\{\vec{x}_a\}$ parameterizing soln's are self-conjugate.

Weak-Strong Equivalence

Constraint eqns exactly match min of brane ($g_s \sim 0$) potential!

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Scaling Solutions

Special Family of Solutions

Consider a family of solutions parameterized by λ such that $x_{ab} \sim \lambda$.

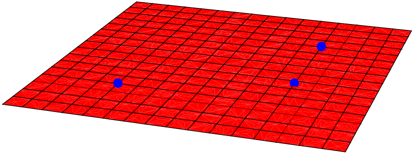
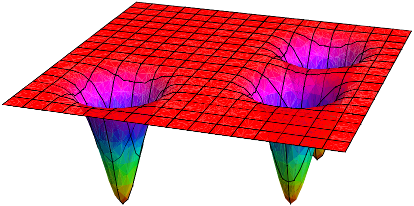


Figure: D-brane QM Regime ($g_s \sim 0$)

- Brane wavefn's have little overlap.
- Approximately semi-classical.



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- Smooth multicentered sugra solution.

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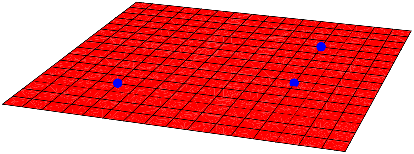

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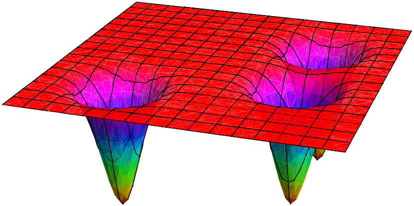

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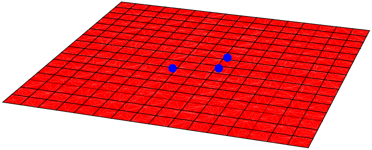
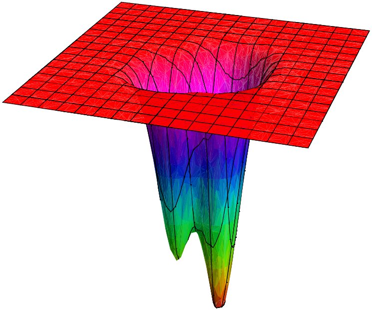
Scaling Solutions

$\lambda \ll 1$

As $\lambda \to 0$ centers meld to long but smooth throat ending in a cap.





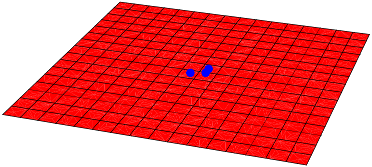
- Centers very close together.
- Less phase space with $|\vec{x}_{ab}| \sim \lambda$.
- Non-commutative nature of coords becomes relevant.

- Throat depth scales inversely to λ.
- Solutions smooth for all $x_{ab} > 0$.

Scaling Solutions

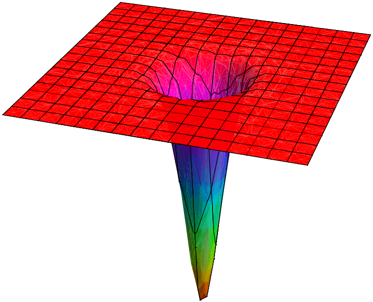
$\lambda \sim 0$

In this regime throat depth very λ-sensitive.



- Outside semi-classical regime.
- ~ 1 unit of phase space in this region.
- Quantum fluctuations large.

$$\langle x_{ab} \rangle \sim \mathcal{O}(\hbar), \qquad |\delta \vec{x}_{ab}| \sim |\vec{x}_{ab}|$$



- Metric scale $g_{ij}(x) \sim \lambda^{-2}$ as $x_{ab} \sim \lambda$.
- Geodesic distance between centers remains finite and large.

Large Quantum Fluctuations

$\lambda \sim 0$ at weak-coupling ($g_s \sim 0$)

- Brane system very quantum when $\lambda \sim 0$ because

$$[x^i, x^j] \sim \epsilon^{ijk} x^k$$

- Define $\lambda_{\rm crit}$ such that $|x_{ab}| < \lambda_{\rm crit}$ occupies less than one unit of phase space.
- States localized near $x_{ab} \sim \lambda_{\rm crit}$ cannot be semi-classical:

$$\sigma_x \sim \sqrt{\langle x_{ab}^2 \rangle - \langle x_{ab} \rangle^2} \sim \langle x_{ab}^i \rangle$$

$\lambda \sim 0$ at strong coupling ($g_s \gg 1$)

- Throat depth very sensitive to x_{ab}.
- As $x_{ab} \to 0$ throat deeper but geometry stays smooth.
- Geometries corresponding to $x_{ab} < \lambda_{\rm crit}$ necessarily quantum!!

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Phase Space

Phase Space Density

Solutions corresponding to $\lambda \sim 0$ occupy very little phase space volume.

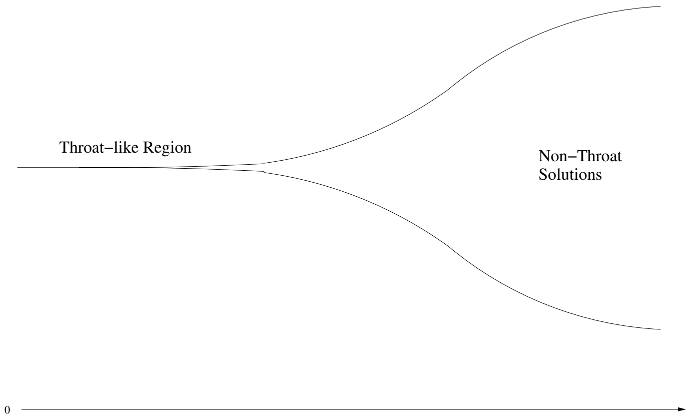

Figure: Phase space as a function of λ (schematically).

Conclusions

Main Result:

Plank size cells in phase space contain soln's that differ on macroscopic scales!

What have we learned?

- Supersymmetric non-renormalization implies phase space volume fixed even if spacetime volume increases.
- Black hole like throats can look quantum near horizon (where spacetime is smooth).
- Supersymmetry gives us control and intuition but result is not totally unexpected and should be more general.

Not Unexpected:

- Consistent with Holography: phase space in QG scales with area not volume.
- This is the kind of effect that *might* help resolve information loss.

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