The Smarr Way of Doing Things

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Upshot

Non-extremal black holes

- ▶ Microstates – can we leap ahead?
  - • Isolated stationary examples

- ▶ Use a powerful analogy in string theory
  - • Black holes $\leftrightarrow$ Flux vacua

Upshot

- Two systems in string theory:

$$\text{Vacua:} \qquad e^{2A(y)}ds_4^2 \quad + \underbrace{g_{mn}(y)dy^m dy^n}_{6d}$$

$$\text{Black holes:} \quad -e^{2U(x)}dt^2 \quad + \underbrace{g_{mn}(x)dx^m dx^n}_{3d + 6d}$$
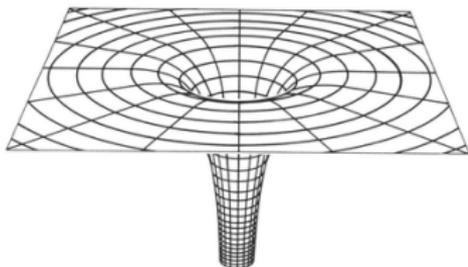
- Break SUSY? Anti-branes in warped flux backgrounds!

Outline

Outline

Chern-Simons couplings in String Theory

▶ Action: topological terms $\int (\star F \wedge F + A \wedge F \wedge F)$

$$\text{IIB:} \qquad d \star F_5 = H_3 \wedge F_2$$
$$\text{5d SUGRA:} \qquad d \star F_2 = F_2 \wedge F_2$$

1. Charge dissolved in flux

S^n

Charge

S^n

Flux

2. Dipole effect


$-$ $+$
$-$ $+$
$-$ $+$

$\vec{E}$

D2
D0
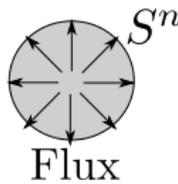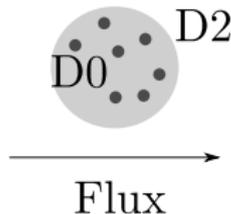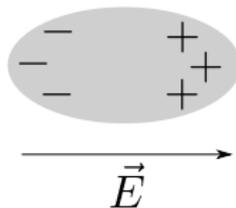
Flux

Supersymmetry = bye bye singularities

Charge dissolved in flux: Topology and new IR phases

S^n

Flux
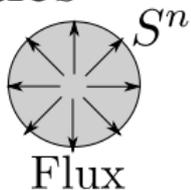
- ▶ RG flow: deformed conifold

  [Klebanov-Strassler '00]

  UV S^2

  r

  IR S^3

  S^2

  A-cycle

  S^3
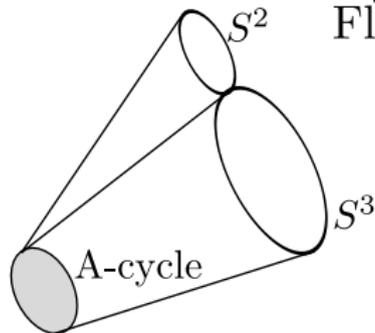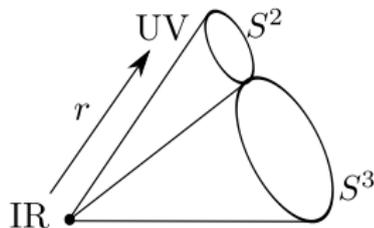
- ▶ Black holes & microstate geometries

  [Denef, de Boer, Lunin-Mathur, Bena, most of the audience...]

  horizon

  singularity

  two-cycles
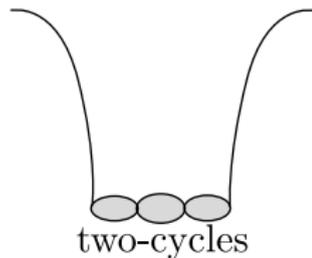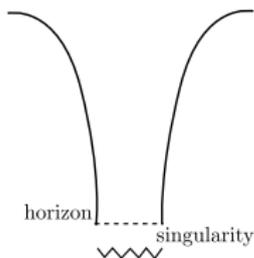
No Supersymmetry = ?

No stationary solitons without horizons or **topology** [Gibbons-Warner 13]

$$M_{ADM} = \int_{horizon} (...) + \int_{space} H_2 \wedge F_2$$

horizon

singularity

two-cycles
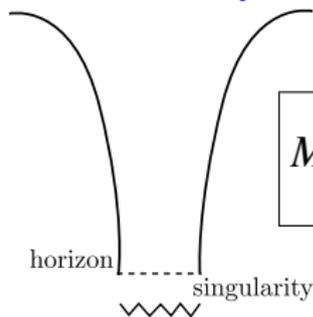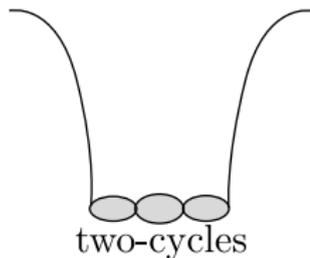
- ▶ 5d/6d/11d [Gibbons-Warner 13; Kunduri-Lucietti 13] [de Lange, Mayerson, BV 15] [Haas 14]

Examples

- ▶ Very few supergravity solutions [JMaRT + extensions: Bena, Bossard, Katmadas, Turton '15; Running-Bolt Bena, Giusto, Ruef, Warner '09]
- ▶ Large classes at probe level [Bena, Puhm, BV 11-12] → dipole effect

D2

D0
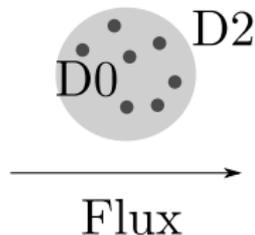
Flux

Outlook for talk (and research)

Black holes		Flux Vacua
in progress	$\longleftarrow$	back-reaction: debate
$\updownarrow$		$\updownarrow$
Smarr relation	$\longrightarrow$	this talk

Outline

# Probe branes in flux backgrounds

1. Compare probe constructions

2. Review anti-brane back-reaction debate

Compare probe constructions

Microstate geometries

M-theory $M_5 \times T^6$

polarization: M2-M2 $\rightarrow$ M5
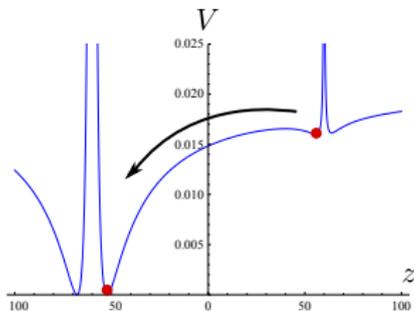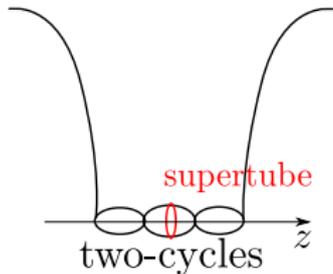
Klebanov Strassler

IIB $M_4 \times X_6$

polarization: $\overline{D3} \rightarrow$ NS5

[Bena, Puhm, BV 11-12]
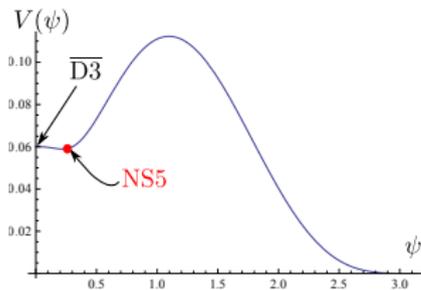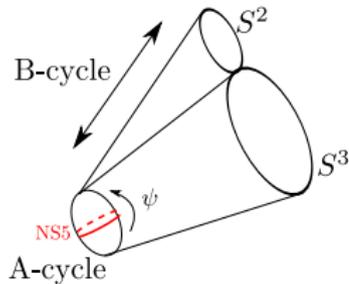
[Kachru, Pearson, Verlinde '01]

Importance

Used for:

- ▶ Klebanov-Strassler and friends:
  - Metastable SUSY breaking
  - de Sitter vacua (KKLT) [Kachru, Kallosh, Linde, Trivedi '03]
- ▶ Black hole microstates
  - Alternative to collapse

Backreaction for p anti-branes unknown!

Review of backreaction debate

Short statement for p anti-branes:

- ▶ Does pathology-free supergravity solution exist ($g_s p \gg 1$)?

  Many no-go results [Saclay,Uppsala,Leuven,Hannover '09-'15...]

- ▶ Does a string theory solution exist ($g_s p$ small)?

  "Yes-go" result from EFT [Polchinski and friends '14-'15

Note: probe limit is $p/M \ll 1$ ($M = \int_A F_3$ background flux)

Black hole microstate geometries?

Supergravity: many no-go results

$g_s p \gg 1$ (supergravity) [Saclay,Uppsala,Leuven,Hannover...]

H_3-density has an unphysical singularity at brane

$$\boxed{|H_3|^2 \to \infty}$$

- Tachyonic instabilities
- Time-dependence?
- Singularity not cloaked by a horizon

Caveats:

- Mostly for smeared solutions
- NS5 polarization for $p/M \ll 1$? (the true metastable state!)

String theory: positive arguments

$g_s p \ll 1$ (single anti-brane)

- ▶ EFT: match string perturbation theory
  [Michel,Mintun,Polchinski,Puhm,Saad]
- ▶ Anti-D3 on orientifold: nilpotent superfields
  [Kallosh+ Quevedo, Uranga; Bergshoef,Freedman,Van Proeyen,Wrase]

Caveats:

- ▶ EFT for NS5 polarization?
- ▶ Validity of 4d supergravity model with nilpotent superfield?

Outline

Our work: Match near and far solutions

IR/UV matching:

- **No-go results:**
  - IR/UV matching: singular anti-D3 brane, even at finite T
    [Gautason,Junghans,Zagermann '13] [Blaback, Danielsson, Van Riet, Vargas '14]

- **Our result:**
  - $|H_3|^2$ singularity could become self-energy of NS5!
    [Cohen-Maldonada, Diaz, Van Riet, BV '15]
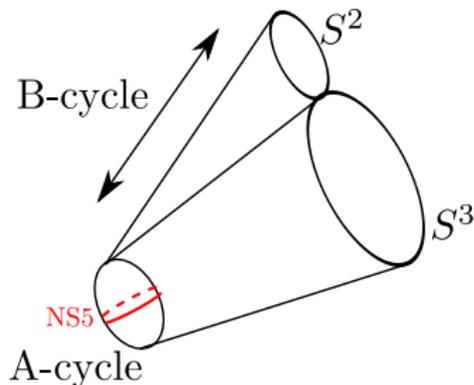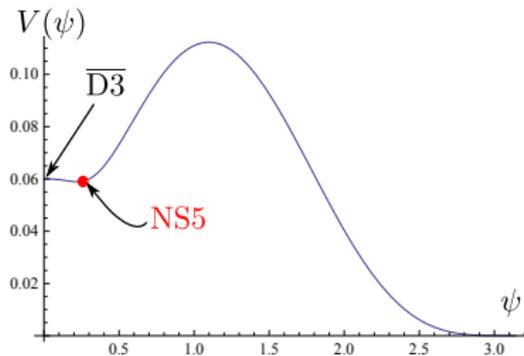
Smarr relation in five dimensions

- K timelike Killing vector $\rightarrow$ ADM mass in flat space:
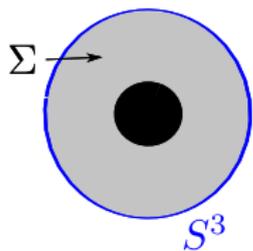
$$\int_{\infty} \star dK = \int_{H} \star dK + \int_{\Sigma} d \star dK .$$

$$M_{ADM} = TS + \Phi Q + \phi q + \int_{\Sigma} H_2 \wedge F_2$$

[Emparan'04, Copsey-Horowitz '05, Gibbons-Warner '13, Kunduri-Lucietti '13]

- Electric monopole charge Q, dipole charge q:

$$Q = \int_{S^3} \star F$$

$$q = \int_{S^2} F$$
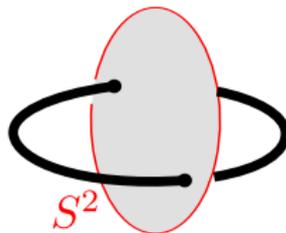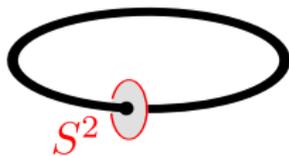
- Dipole charge can support mass: NS5 polarization?

Smarr relation for anti-D3 in KS

- Ansatz
$$ds_{10}^2 = e^{2A} ds_4^2 + ds_6^2$$
$$C_4 = \alpha \, \text{vol}_4$$
$$e^{-\phi} \star_{10} H_3 = C_4 \wedge F_3 + dB_6 \, .$$

- Boundary term from EOM [Gautason, Junghans, Zagermann '13]

$$\int_\infty \mathcal{B} = \int_H \mathcal{B} \, , \qquad \mathcal{B} = C_4 \wedge F_5 - B_2 \wedge dB_6$$

- Asymptotically: mass! [Blaback, Danielsson, Van Riet, Vargas '14]

$$M = \int_\infty \mathcal{B} \qquad \text{with } M \propto p$$

- NO-GO: If anti-D3, $e^{-\phi}|H_3|^2 \to \infty$

Smarr relation for NS5 polarization
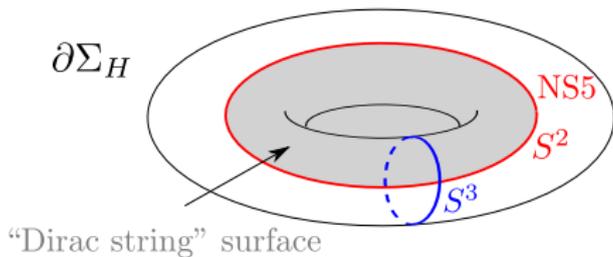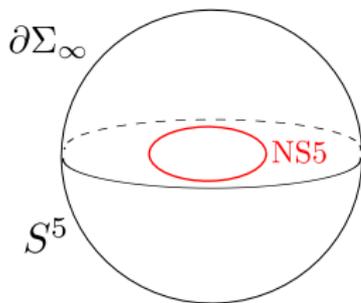
$$\int_\infty \mathcal{B} = \int_H \mathcal{B}\,, \qquad \mathcal{B} = C_4 \wedge F_5 - B_2 \wedge dB_6$$

▶ Just like in flat space:

$$\boxed{M = \Phi Q_{D3} + \phi q_{NS5} V_{S^2}}\,, \quad Q_{D3} = \int_{S^5} F_5\,, \quad q_{NS5} = \int_{S^3} H_3\,,$$

▶ Near-horizon

$$C_4 = \Phi\,\mathrm{vol}_4\,, \quad B_6 = \phi\,\mathrm{vol}_4 \wedge \mathrm{vol}_{S^2}$$

Interpret singularity as NS5 self-energy?

▶ Near solution for NS5: specific divergence
$$e^{-\phi}|H_3|^2 \sim e^{-2A} \quad \Rightarrow \quad e^{-\phi} \star_{10} H_3 = dB_6 + C_4 \wedge F_3 \sim e^{4A}$$

▶ With $C_4 = \Phi \, \mathrm{vol}_4$, $\quad B_6 = \phi \, \mathrm{vol}_4 \wedge \mathrm{vol}_{S^2}$:
$$d\phi + \Phi \to 0$$

▶ Mass is number of anti-branes:
$$M = \Phi Q_{D3} + \phi q_{NS5} V_{S^2} > 0$$

Bye-bye no-go theorem

▶ If anti-D3: $\phi = const.$, $Q_{NS5} = 0 \to$ inconsistency
▶ If NS5: no problem to avoid singularity!

Outline

Summary

Vacua with hierarchies and black holes very similar

- Warped throats

- Topology and flux resolves singularities

- Polarized branes $\leftrightarrow$ metastable solutions

Smarr relation: fate of polarized state!

Outlook for vacua

For vacua:

- Confront NS5 result with probe: discrepancy!

$$R \sim \sqrt{p/M} \qquad \text{vs} \qquad R \sim p/M$$

S^2

R
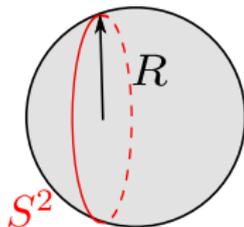
- Redo EFT for NS5? [Michel-Mintun-Puhm-Polchinski-Saad '14]

- Cosmological fuzzballs?

Outlook for non-extremal microstates

▶ Back-reaction of probe constructions

$$M_{ADM} = \Phi Q + \phi q + \int_\Sigma H_2 \wedge F_2$$

▶ Stability $\leftrightarrow$ time-dependence?
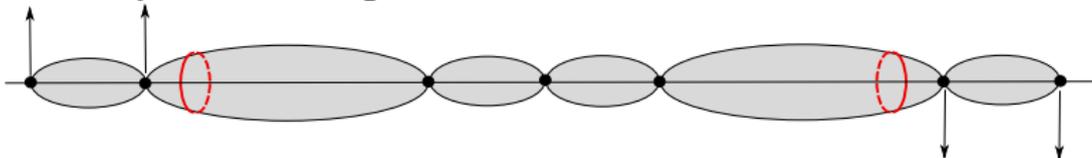
[Bena, Pasini '15]

▶ Are microstate geometries property of AdS$_3$/CFT$_2$?