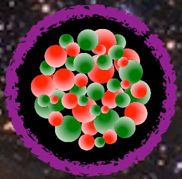
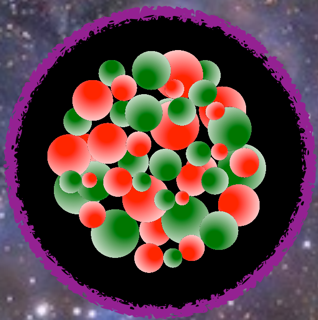
Resolving Black Holes
via
Microstate Geometries





Nick Warner, *Strings `14*, June 24, 2014

Based on Collaborations with:

I. Bena, G. Gibbons, M. Shigemori

arXiv:1305.0957, arXiv:1311.4538 and arXiv:1406.4506

⇒ Two distinct core ideas from *microstate geometries*

1) A string theory ***mechanism*** to support structure at the horizon scale

⇒ Two (at least) new scales for black-hole physics

What does horizon-scale microstate structure look like?

Fuzz/Fire/hybrid… other?

2) A semi-classical description of black-hole microstates?

Arising from fluctuations/moduli of microstate geometries
(in the same regime of parameters in which there is an *actual black hole*)

The ***superstratum*** (BPS): $S_{semi\ class.} \sim \sqrt{N_1 N_5 N_P}$

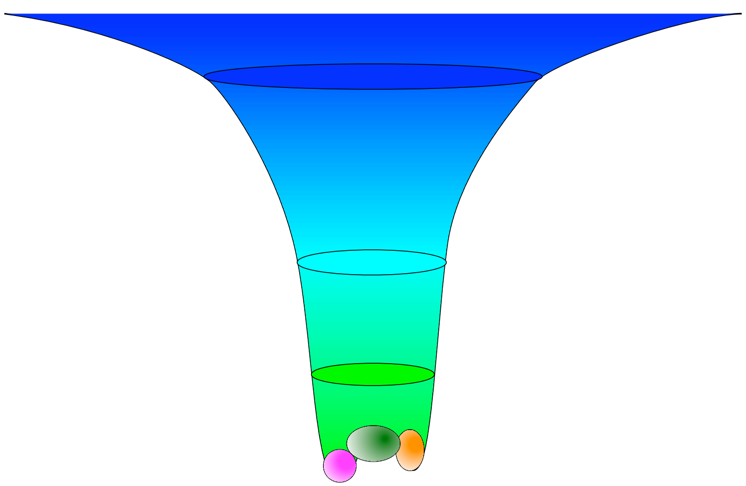
Fixing the information problem: An old conceit

Recover information (and pure quantum state) from small corrections to GR over the evaporation time scale…

e.g. via stringy or quantum gravity (*(Riemann)*^{n}) corrections to radiation?

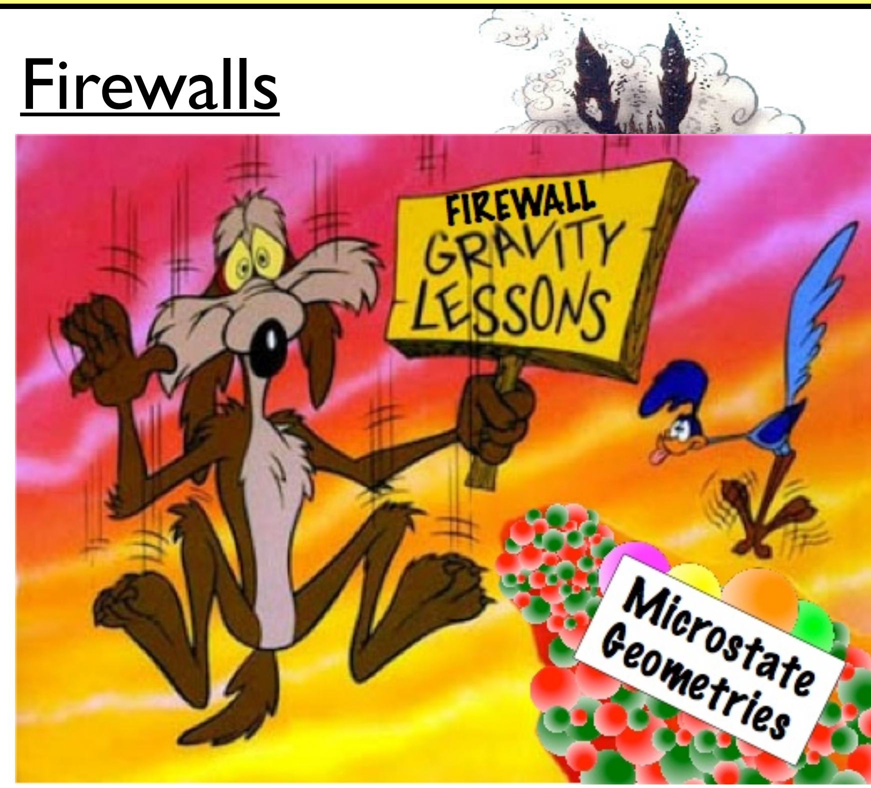
Mathur (2009): *No!* Corrections cannot be small for information recovery
There must be *O(1)* changes to the physics at the horizon scale

Microstate geometries



A mechanism for resolving the problem in string theory

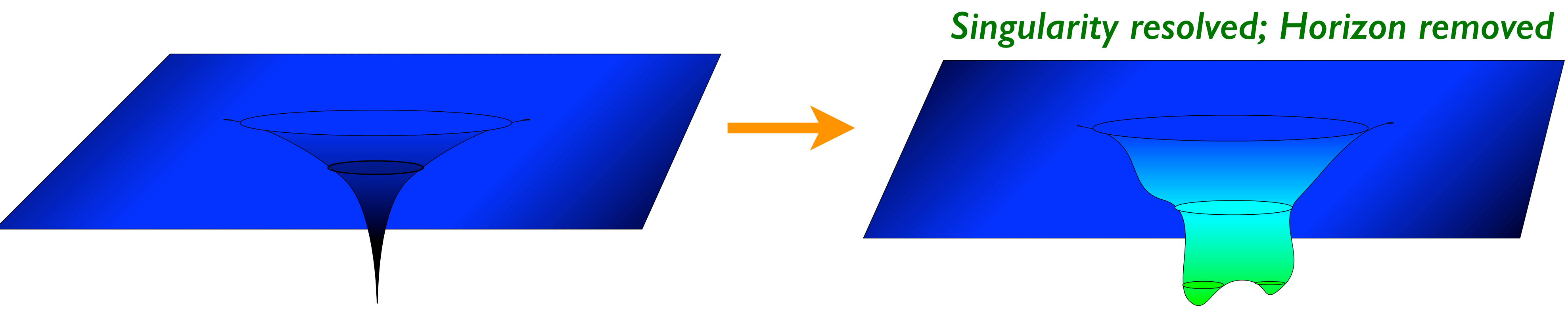
Firewalls



Unsupported superstructure

Microstate Geometry Program

Microstate Geometry ≡ Smooth, horizonless solutions to the bosonic sector of ***supergravity*** with the same asymptotic structure as a given black hole/ring



Supergravity because we seek stringy resolutions on horizon scale

- *Very long-range effects* ⇒ Massless limit of strings …
- Framework within which we can ***actually do calculations***

What is the form of generic, (non-)BPS, time-independent horizonless, smooth solutions in supergravity?

Microstate Geometries/*solitons* long believed ***impossible*** because *only the presence of a **horizon*** can restrict massless fields to a classical lump …

Microstate Geometries exist (how?) … and lead to new physical issues

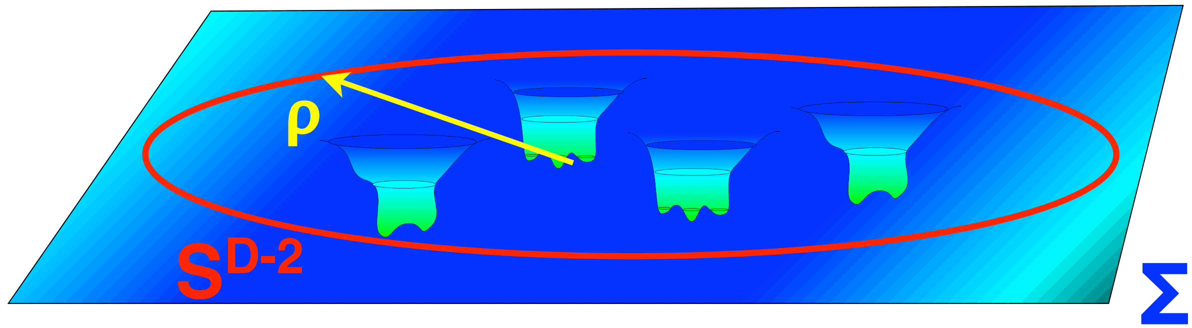
- *New physics/scales will emerge from the resolution*
- What can supergravity tells us about details of microstate structure?

The Komar Mass/Smarr Formula

If there is time-translation invariance then energy is conserved:
There is a vector field (Killing vector) K generating time translations.

$$K^\mu \frac{\partial}{\partial x^\mu} = \frac{\partial}{\partial t}$$

D-dimensional space-time, sectioned by hypersurfaces, Σ, with Gaussian (D-2)-spheres, S^{D-2}, at infinity



There is then an associated conserved *ADM mass*:

$$K^\mu K^\nu g_{\mu\nu} = g_{00} \approx -1 + \frac{16\pi G_D}{(D-2)\,A_{D-2}} \frac{M}{\rho^{D-3}} + \dots \quad \textit{at infinity}$$

$$\Rightarrow \quad M = -\frac{1}{16\pi G_D} \frac{(D-2)}{(D-3)} \int_{S^{D-2}} *dK$$

If Σ is smooth with *no interior boundaries*: $\quad d * dK = -2 * (K^\mu R_{\mu\nu} dx^\nu)$

$$M = \frac{1}{8\pi G_D} \frac{(D-2)}{(D-3)} \int_\Sigma *_D (K^\mu R_{\mu\nu} dx^\nu)$$

Bosonic sector of a generic *massless* (ungauged) supergravity

- Graviton, $g_{\mu\nu}$
- Scalars, Φ^A
- Tensor gauge fields, $F_{(p)}{}^K$

Bianchi: $d(F_{(p)}{}^K) = 0$

Define: $G_{J,(D-p)} \equiv *\left(Q_{JK}(\Phi)\, F_{(p)}{}^K + \textit{Chern Simons terms}\right)$

$Q_{JK}(\Phi)$ = Scalar matrix in kinetic terms

Equations of motion: $d(G_{J,(D-p)}) = 0$

Assume time-independent matter:

$$\mathcal{L}_K F^I = 0\,, \qquad \mathcal{L}_K \Phi^A = 0 \qquad \Rightarrow \qquad \mathcal{L}_K G_I = 0$$

Cartan formula for forms: $\cancelto{0}{\mathcal{L}_K \omega} = d(i_K(\omega)) + \cancelto{0}{i_K(d\omega)}$

$$d(i_K(F_{(p)}{}^I)) = 0, \qquad d(i_K(G_{J,(D-p)})) = 0$$

Define *harmonic* forms, ***H***:

$$i_K(F_{(p)}{}^I) = H_{(p-1)}{}^I + \textit{exact} \qquad\qquad i_K(G_{J,(D-p)}) = H_{J\,(D-p-1)} + \textit{exact}$$

No Solitons without Topology

Smooth spatial sections with *no interior boundaries*

$$M = \frac{1}{8\pi G_D} \frac{(D-2)}{(D-3)} \int_\Sigma *_D \left(K^\mu R_{\mu\nu} dx^\nu\right)$$

Equations of motion imply

$$\mathbf{M} = const. \int_\Sigma \left[H_{I\,(D-p-1)} \wedge F^I_{(p)} + H^J_{(p-1)} \wedge G_{J\,(D-p)} \right]$$

Gibbons + NPW 1305.0957; Haas 1405.3708

- Mass ***can be*** topologically supported by the cohomology $H^*(\Sigma, R)$

  Stationary end-state of star held up by topological flux ...

  - A new object: *A Topological Star*
  - Black-Hole Microstate?

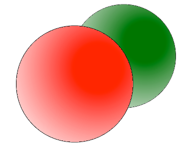
- No spatial topology $\Rightarrow$ **M = 0** $\Rightarrow$ Space-time is flat/empty

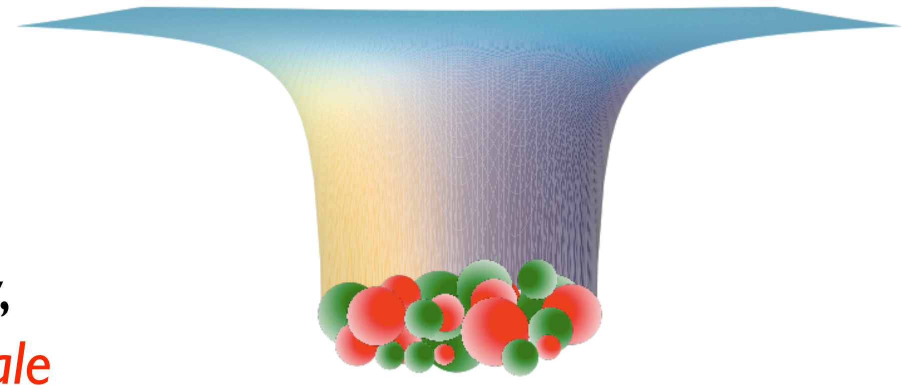
  Only assumed time independence: ***Not simply for BPS objects***

Applies to all time-independent smooth remnants in massless ungaged supergravity

A Decade of *BPS* Microstate Geometries

Bubbled geometries in five or six dimensions ⇒ 2 or 3 cycles





★ There are vast families of smooth, horizonless microstate geometries

★ New physics *at the horizon scale*

⇒ The cap-off and the non-trivial topology, "bubbles," arise at the original *horizon scale*

★ Families of solutions: Large moduli spaces of cycles; fluctuations around cycles

★ Special class: KK reduction yields multi-centered solutions of Denef

★ There are *scaling microstate geometries* with *AdS throats* that can be made *arbitrarily long* but cap off smoothly

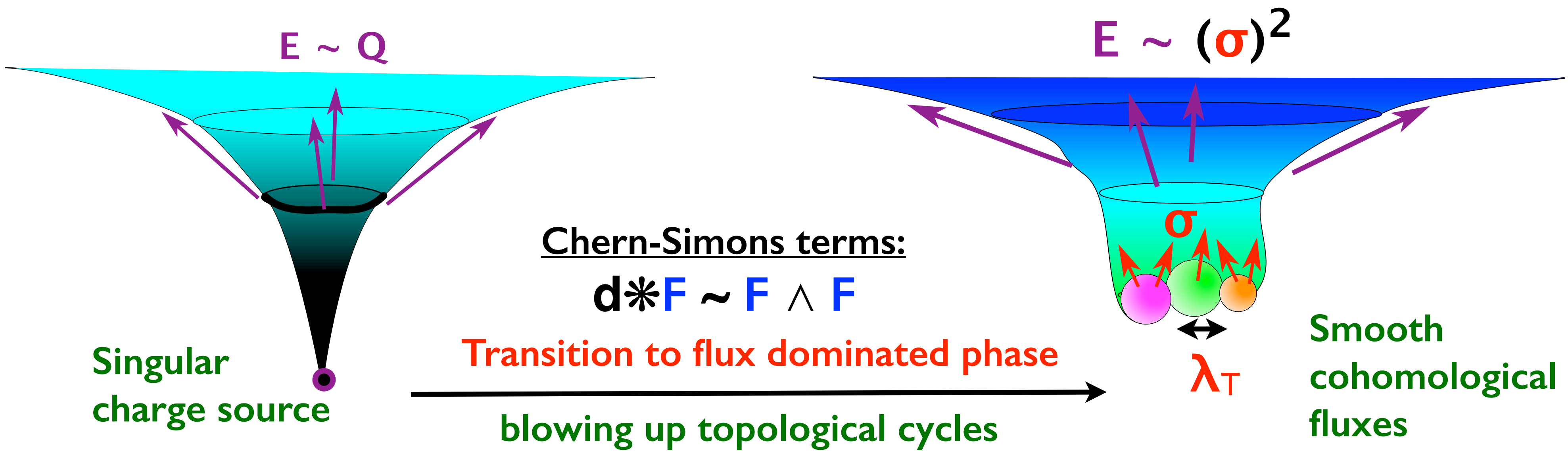
★ Holography in the long AdS throat:
All these solutions represent black-hole microstates

⇒ Semi-classical sampling of black-hole microstate structure

"Topological stars" = coherent microstates of black holes

★ New physical scales …

Scale 1: The Order Parameter of the Geometric Phase



This is an example of a phase/geometric transition in string theory ...

Analogous to holography of confinement and chiral symmetry breaking.

- ★ Magnitude of fluxes , σ = Order parameter of new phases
- ★ Size of the bubbles, λ_T = *Transition Scale* is a new scale in the topological phase

Supergravity equations ⇒ λ_T ~ Magnitude of fluxes , σ

Balance: *Gravity* ⟷ *Flux expansion force*

Classically: *Freely choosable parameter.* Can have $\lambda_T >> \ell_P$

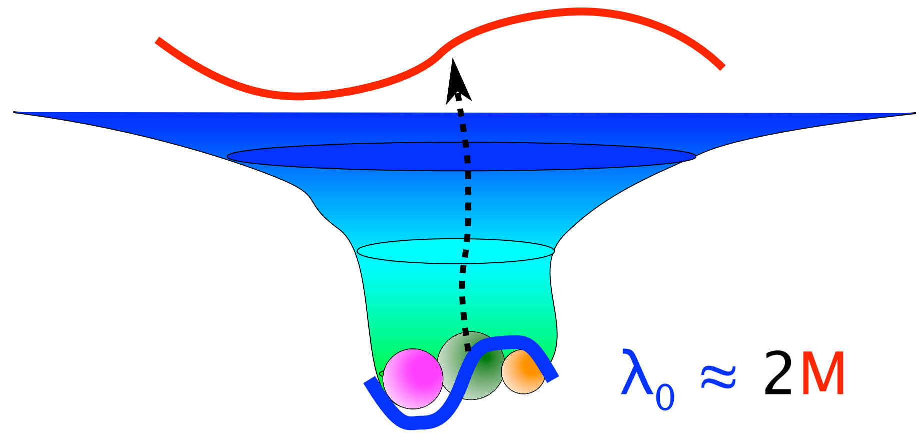
Quantum mechanics: Could λ_T be dynamically generated?

Black holes: Could large λ_T be entropically favored?

Scale 2: The Energy Gap

λ_{gap} = maximally redshifted wavelength, at infinity of lowest collective mode of bubbles at the bottom of the throat.

$$E_{gap} \sim (\lambda_{gap})^{-1}$$



★ The gap is determined by "maximum redshift," z_{max}, and size of black hole

Traditional black holes: $E_{gap} = 0$

★ E_{gap} determines where microstate geometries begin to differ from black holes

BPS black holes

Semi-classical quantization of the moduli of the geometry:

- ★ The throat depth, or z_{max} , is *not* a free parameter
- ★ E_{gap} is determined by the flux structure of the geometry

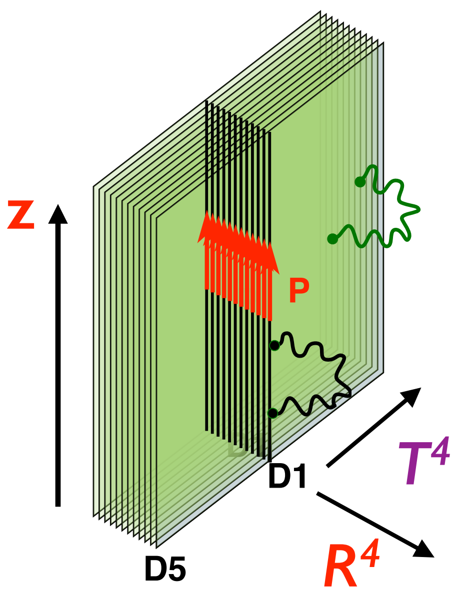
Exactly matches E_{gap} for the stringy excitations underlying the original state counting of Strominger and Vafa .....

Bena, Wang and Warner, arXiv:0706.3786

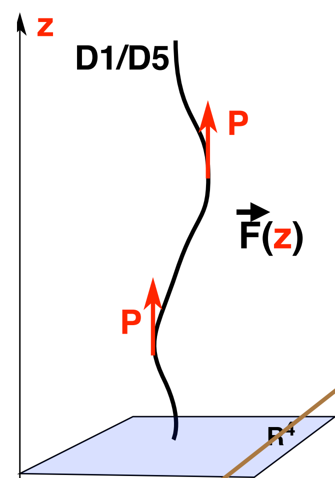
de Boer, El-Showk, Messamah, Van den Bleeken, arXiv:0807.4556 arXiv:0906.0011

Semi-classical Microstate Structure: *Superstrata* on $R^{5,1} \times T^4$

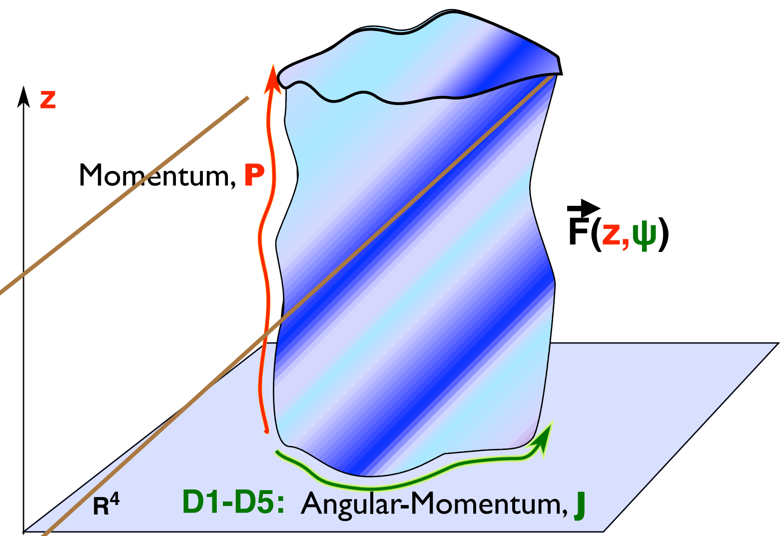
IIB: D1-D5-P system compactified on T^4 (or K3)



Six Dimensions: Profile in $R^{5,1}$

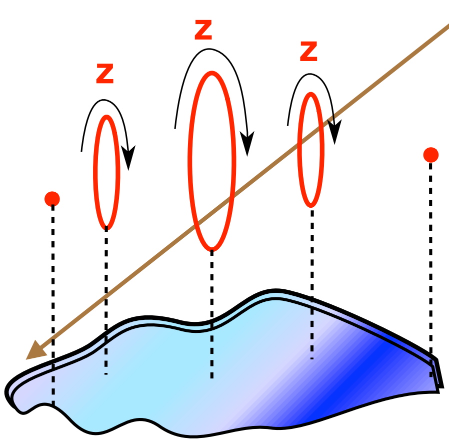


Add KKM dipole and Angular Momentum



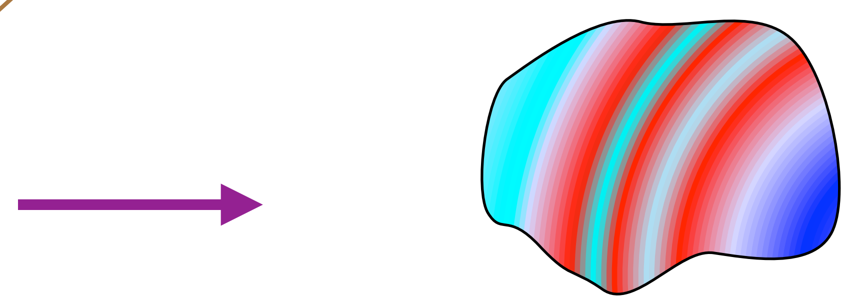
Smooth BPS configurations that depend upon *functions of two variables:* $\vec{F}(z,\psi)$

Back-reacted geometry: 3 homology



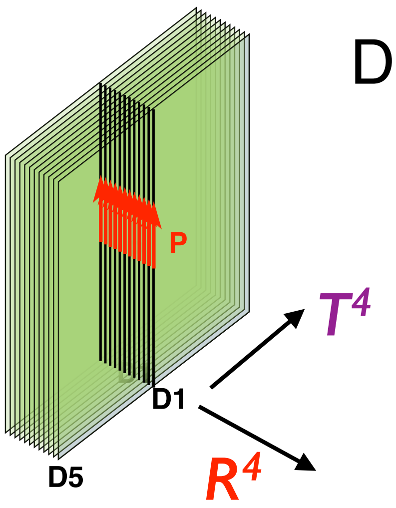
⇒ BPS shape modes on 3 cycles

functions of two variables



D1-D5-P System: Microstate Counting

Strominger-Vafa



D1-D5 SCFT Fields $X^{\dot{A}A}_{(r)}(z,\bar{z})$ $\psi^{\alpha\dot{A}}_{(r)}(z)$ $\widetilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})$

$r = 1, \ldots, N = N_1 N_5$

$$\frac{(T^4)^N}{S_N}$$

$c = 6N = 6 N_1 N_5$ (4,4) supersymmetry

$(A, \dot{A})$ = spinor indices on the T^4

$(\alpha, \dot{\alpha})$ = spinor indices on R^4 transverse to branes

R-symmetry = Rotations in R^4 transverse to branes

= SO(4) = $SU(2)_L \times SU(2)_R$

Define: $J^{\alpha\beta}_{(r)}(z) \equiv \frac{1}{2}\psi^{\alpha\dot{A}}_{(r)}(z)\,\epsilon_{\dot{A}\dot{B}}\,\psi^{\beta\dot{B}}_{(r)}(z)\,,$ $\tilde{J}^{\dot{\alpha}\dot{\beta}}_{(r)}(\bar{z}) \equiv \frac{1}{2}\tilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})\,\epsilon_{\dot{A}\dot{B}}\,\tilde{\psi}^{\dot{\beta}\dot{B}}_{(r)}(\bar{z})$

= CFT Degrees of freedom "visible" in R^4

$$= \frac{(SU(2)_{(1),L} \times SU(2)_{(1),R})^N}{S_N}$$

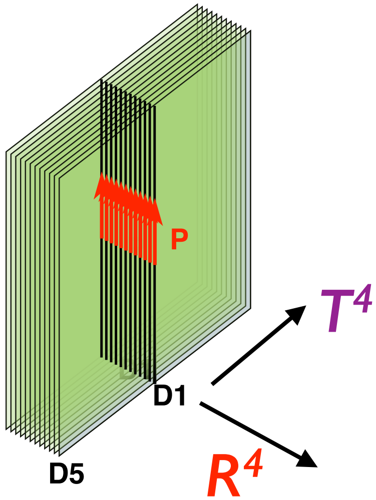
$c = N = N_1 N_5$

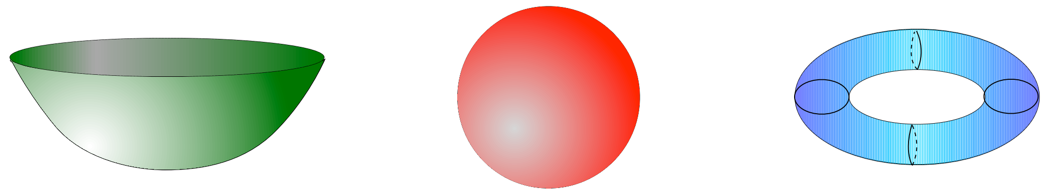
¼ BPS states = (R,R)-ground states

⅛ BPS states = (*any left-moving state*, R ground state) ***Momentum, $P = L_{0,left}$***

The left-handed currents, $J_{(r)}^{\alpha\beta}(z)$, ($c = N_1 N_5$) create left-moving momentum states visible in R^4 ⇔ ***BPS Shape modes*** of the *superstratum/S^3*

The Holographic Dual: $AdS_3 \times S^3 \times T^4$





$AdS_3 \times S^3 \times T^4$

Modes: ***$SU(2)_L \times SU(2)_R$ quantum numbers $(j,m;\hat{j},\hat{m})$***

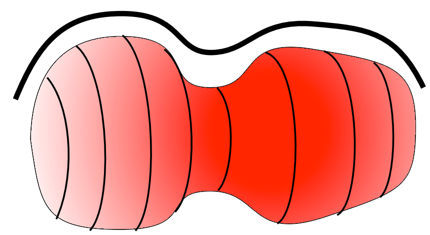
$| j - \hat{j} |$ **= space-time spin of underlying field**

¼ BPS states = (R,R)-ground states ↔ quantum numbers $(j, j\, ; \hat{j}, \hat{j}\,)$

→ D1-D5 supertube shape modes on S^3

↔ ***one arbitrary function, Fourier modes, j***

Lunin and Mathur; Lunin, Maldacena and Maoz; Mathur; Skenderis and Taylor …



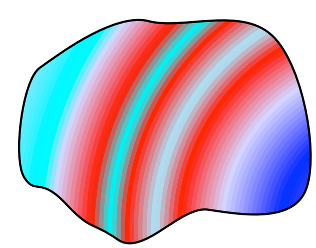
⇒ Semi-classical entropy of a supertube: $S \sim \sqrt{Q_1 Q_2} \sim Q$

⅛ BPS states: Act with modes of $J_{(r)}{}^{\alpha\beta}(z)$ ↔ quantum numbers $(j, m\, ; \hat{j}, \hat{j}\,)$

→ D1-D5 *superstratum* shape modes on S^3

↔ ***two arbitrary functions, Fourier modes, (j,m)***

Bena, Shigemori and NPW 1406.4506

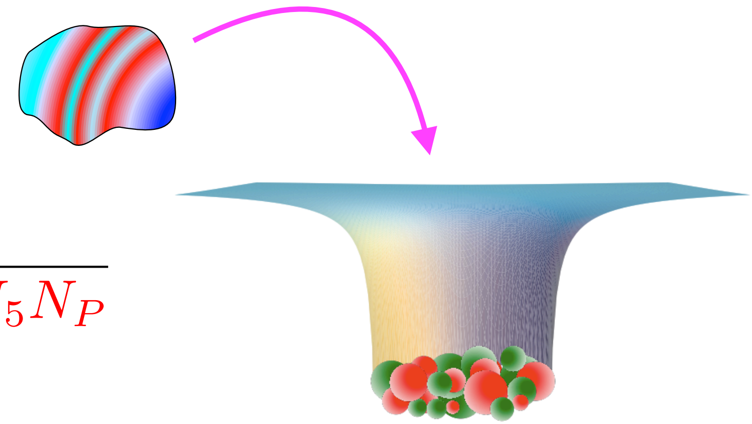


Semi-classical black-hole microstate structure

★ Linearized supergravity modes can *at least* capture, semi-classically, the momentum excitations corresponding to the CFT currents, $J_{(r)}^{\alpha\beta}(z)$.

★ Deep, scaling microstate geometries have $E_{gap} \sim (N_1 N_5)^{-1}$

Add momentum charge N_P using $J_{(r)}^{\alpha\beta}(z)$



$$\Rightarrow \quad S_{semi\ class.} = 2\pi \sqrt{\frac{1}{6} N_1 N_5 N_P} \sim \sqrt{N_1 N_5 N_P}$$

★ Semi-classical quantization gives a dense enough sampling of microstate structure to recover entropy corresponding to a macroscopic horizon scale

⇒ *Typical microstates must have the scale of the original black-hole horizon?*

Summary

- String theory has new phases dominated by topological fluxes that can *prevent the formation of black holes* → *Topological Stars/Black-hole microstates*
- Transition to new phase ⟷ Formation of bubbles supported by flux → *Order parameter and new scale in Nature:* λ_T = *Transition Scale*
- The new phase smoothly caps-off the space-time before a horizon forms: → *Limits the red-shift and the lowest-energy states:* $E_{gap} > 0$
- The new phases represent new "*infra-red*" *vacua* of string theory

  This viewpoint is a natural and direct outgrowth of holographic field theories ....
- Discussion of near-horizon physics, *like the infall problem and even firewalls*, will be enriched/clarified by separating λ_T and E_{gap} from the Planck scale.

  Ignoring this possibility is probably a serious mistake …
- Vast families of BPS examples explicitly constructed
- Superstrata/BPS fluctuations as functions of two variables give *semi-classical entropy with correct growth as a function of the charges*
- These ideas can be extended to non-BPS, extremal and near-extremal …