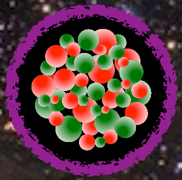
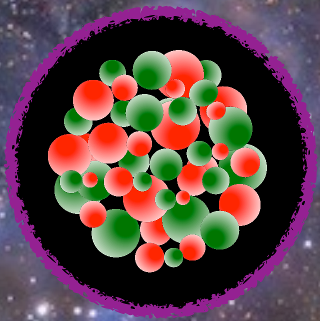
# Universal Ideas from Microstate Geometries





Nick Warner, March 17, 2014

Based on Collaborations with:

**I. Bena, J. de Boer, G. Gibbons, B. Niehoff, M. Shigemori, O. Vasilakis**

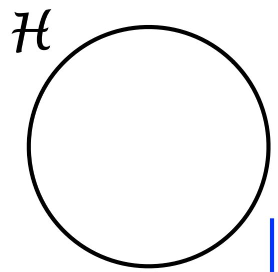
**arXiv:1305.0957 and arXiv:1311.4538**

Outline

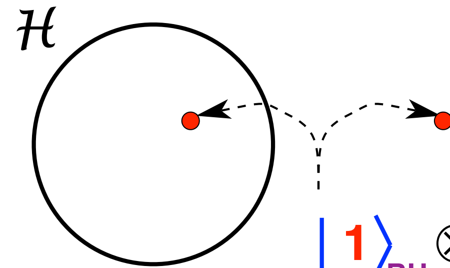
- Motivation for Microstate Geometries
- Solitons, horizonless solutions and topology
  - Microstate geometries as solitons
- Lessons from holographic field theory
  - Two new scales for black-hole physics
- Microstate geometries and microstate structure
- *BPS* Microstate structure visible within supergravity
  - The superstratum
- Current status + Speculative ideas…

# Information Loss via Hawking Radiation

Particle creation near horizon of black hole




$|0\rangle_{BH} \otimes |0\rangle_{\infty}$




$|1\rangle_{BH} \otimes |1\rangle_{\infty}$

After black-hole light-crossing time

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left( |0\rangle_{BH} \otimes |0\rangle_{\infty} + |1\rangle_{BH} \otimes |1\rangle_{\infty} \right)$$

State of quantum of Hawking Radiation

$$\rho = \mathrm{Tr}_{BH}\left( |\psi\rangle\langle\psi| \right) = \frac{1}{2}\left( {}_{\infty}|0\rangle\langle 0|_{\infty} + {}_{\infty}|1\rangle\langle 1|_{\infty} \right)$$

Entanglement entropy of N Hawking quanta: $= N\, \mathit{log}(2)$

After black hole fully evaporates:

Black-hole state $\longrightarrow$ Hawking Radiation

Pure state $|\psi\rangle$ $\longrightarrow$ Density Matrix, $\rho$

Complete evaporation + Entanglement $\Rightarrow$
Cannot be described by unitary evolution in Quantum Mechanics

# An old conceit:

Fix the information problem with small corrections to GR?

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

Entangled State of Hawking Radiation

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left( |0\rangle_{BH} \otimes |0\rangle_{\infty} + |1\rangle_{BH} \otimes |1\rangle_{\infty} \right)$$

$$+ \varepsilon \left( |0\rangle_{BH} \otimes |0\rangle_{\infty} - |1\rangle_{BH} \otimes |1\rangle_{\infty} \right) + \varepsilon_1 |0\rangle_{BH} \otimes |1\rangle_{\infty} + \varepsilon_2 |1\rangle_{BH} \otimes |0\rangle_{\infty}$$

Hawking evaporation is extremely slow ...

$$t_{evap} = \frac{5120\,\pi\, G^2\, M^3}{\hbar\, c^4} \approx 6.6 \times 10^{74} \left(\frac{M}{M_\odot}\right)^3 s \approx 2.1 \times 10^{67} \left(\frac{M}{M_\odot}\right)^3 years$$

Restore the pure state over vast time period for evaporation?

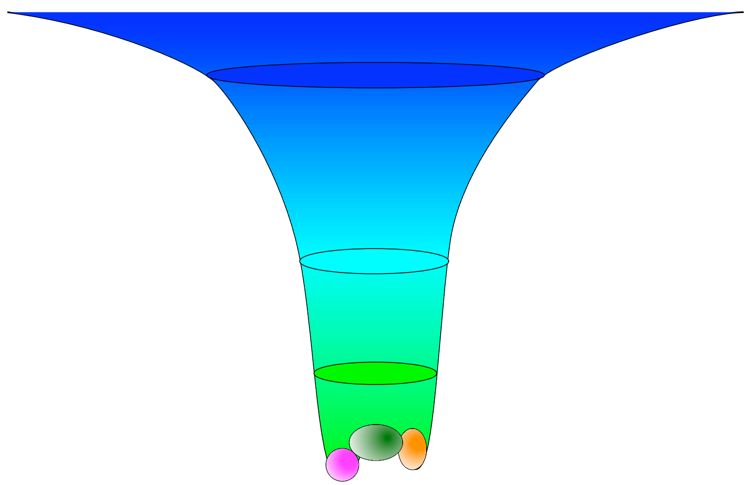
Mathur (2009): *No!* Corrections cannot be small for information recovery

$\Rightarrow$ There must be *O(1)* changes to the Hawking states at the horizon.

# Resolving Black Holes

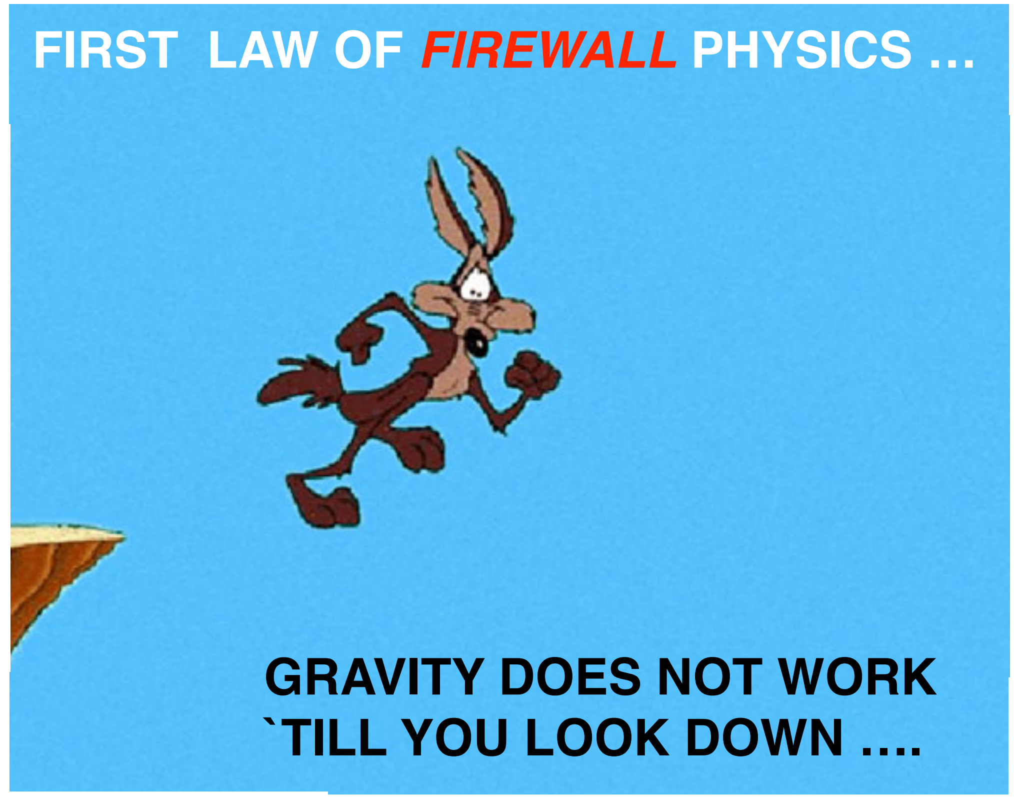
There must be new *O(1)* physics at the horizon scale ….

## Fuzzballs



*A mechanism for resolving the problem in string theory*

## Firewalls

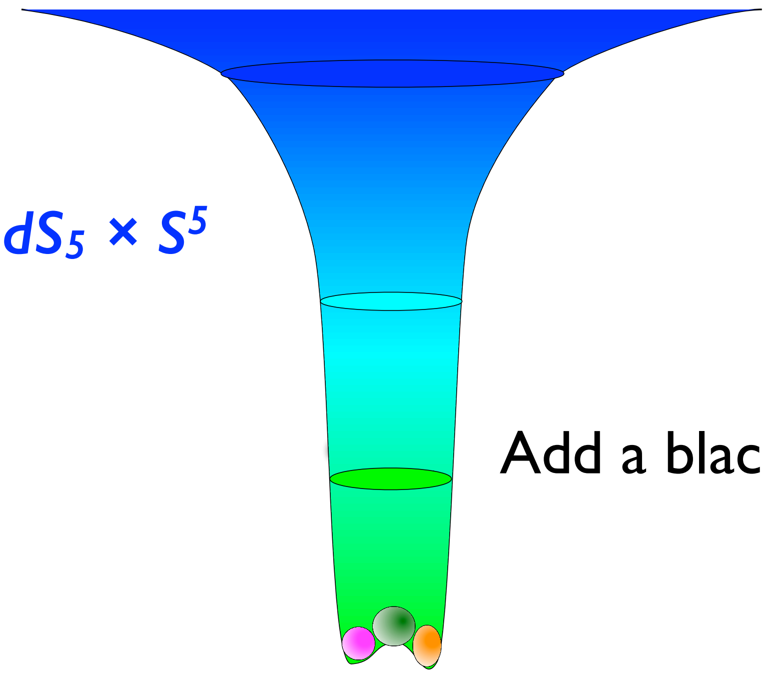



*Unsupported superstructure*

# Unitary Evolution and Black Holes

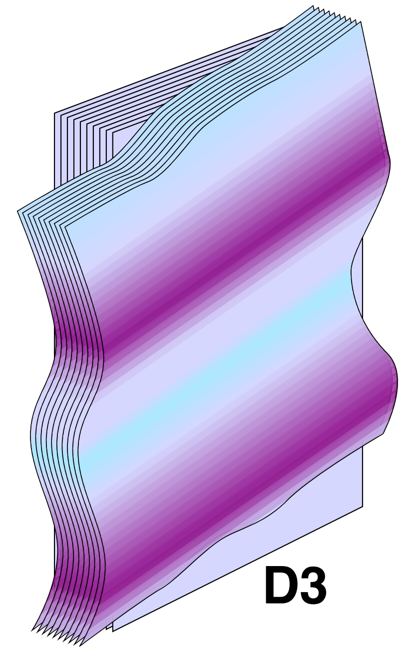
Earliest motivation from AdS/CFT:

*$AdS_5 \times S^5$*



Add a black hole

*$N = 4$ Yang Mills*




⇒ Unitary evolution

What this should involve …

New *IR phase* of the field theory: *Order parameter(s)*; *Energy Gap*

Gravity dual:

- *Smooth geometry*
- *Finite red shift*
- *Fluxes + geometric moduli*

⇒ *Microstate geometries*

# Microstate Geometry Program

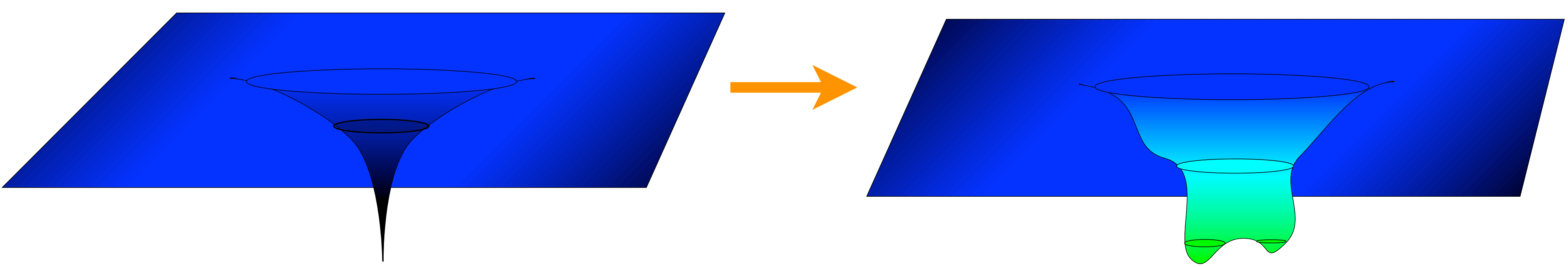
Find mechanisms and structures that resolve singularities and prevent the formation of horizons in the low-energy (*massless*) limit of string theory: *Supergravity*

- Stringy resolutions on horizon scale ⇒ *Very long-range effects* ⇒ Massless fields (only other scale in String theory is the Planck scale)
- *Massless sector means before any compactification scale is introduced*

## Definition

- Solution to the bosonic sector of supergravity as a low-energy limit of string theory
- Smooth, horizonless solutions with the same asymptotic structure as a given black hole or black ring

*Singularity resolved; Horizon removed*



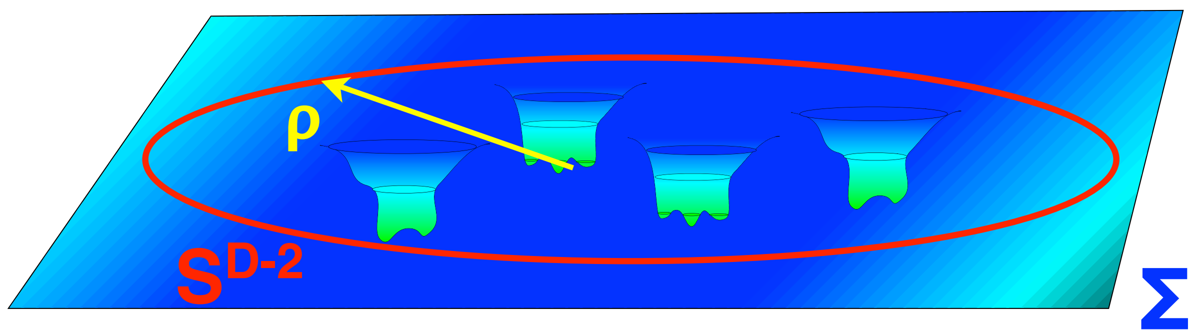
***Are there horizonless, smooth solitons in supergravity?***

# 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, $\Sigma$, with Gaussian (D-2)-spheres, $S^{D-2}$, at infinity




There is then an associated conserved *ADM mass*:

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

Moreover

$$d * dK = -2 * (K^\mu R_{\mu\nu} dx^\nu) \qquad R_{\mu\nu} = 8\pi G_D \left( T_{\mu\nu} - \frac{1}{(D-2)} T\, g_{\mu\nu} \right)$$

If $\Sigma$ is smooth with *no interior boundaries*:

$$\boxed{M = -\frac{1}{16\pi G_D} \frac{(D-2)}{(D-3)} \int_{S^{D-2}} *dK = \int_\Sigma T_{00}\, d\Sigma}$$

# No Solitons without Horizons via the Smarr Formula

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

Strategy:

Assume time-independent matter as well as time-independent metric

Equations of motion for *massless* field theory

$\Rightarrow \quad *(K^\mu R_{\mu\nu} dx^\nu) \quad = \quad d(\gamma_{D-2})$ for some global (D-2)-form, $\gamma$.

$\Rightarrow \quad \mathbf{M \equiv 0}$

$\Rightarrow$ *Space-time can only be globally flat,* $\mathbf{R}^{D-1,1}$

*Intuition*: *Massless fields travel at the speed of light ... only a black hole can hold such things into a star.*

How do you show that: $*(K^\mu R_{\mu\nu} dx^\nu) \quad = \quad d(\gamma_{D-2})$ ?

# Bosonic sector of a generic massless (ungauged) supergravity

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

Scalar matrices in kinetic terms: $Q_{JK}(\Phi)$, $M_{AB}(\Phi)$

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

Equations of motion: $d{*}(Q_{JK}(\Phi)\, F_{(p)}{}^K) = 0$ *Ignoring Chern Simons terms*

Define: $G_{J,(D-p)} \equiv {*}\,(Q_{JK}(\Phi)\, F_{(p)}{}^K)$ and $Q^{JK}$ by $Q^{IK} Q_{KJ} = \delta^I{}_J$

then: $d(F_{(p)}{}^K) = 0$ and $d(G_{J,(D-p)}) = 0$ *Ignoring Chern Simons terms*

Einstein equations:

$$
\begin{aligned}
R_{\mu\nu} &= Q_{IJ}\left[F^I{}_{\mu\rho_1\ldots\rho_{p-1}}\, F^J{}_\nu{}^{\rho_1\ldots\rho_{p-1}} - c\, g_{\mu\nu}\, F^I{}_{\rho_1\ldots\rho_p} F^{J\,\rho_1\ldots\rho_p}\right] \\
&\quad + M_{AB}\left[\partial_\mu \Phi^A\, \partial_\nu \Phi^B\right] \\
&= a\, Q_{IJ}\, F^I{}_{\mu\rho_1\ldots\rho_{p-1}}\, F^J{}_\nu{}^{\rho_1\ldots\rho_{p-1}} + M_{AB}\left[\partial_\mu \Phi^A\, \partial_\nu \Phi^B\right] \\
&\quad + b\, Q^{IJ}\, G_{I\,\mu\rho_1\ldots\rho_{D-p-1}}\, G_{J\nu}{}^{\rho_1\ldots\rho_{D-p-1}}
\end{aligned}
$$

for some constants a,b and c

# Time Independent Solutions

Killing vector, K, is time-like at infinity

Assume time-independent matter: $\mathcal{L}_K F^I = 0\,, \quad \mathcal{L}_K \Phi^A = 0$

$$\Rightarrow \quad \mathcal{L}_K G_I = 0$$

$$K^\mu R_{\mu\nu} = a\,Q_{IJ}\,K^\mu\,F^I{}_{\mu\rho_1\ldots\rho_{p-1}}\,F^J{}_\nu{}^{\rho_1\ldots\rho_{p-1}} + M_{AB}\left[\cancelto{0}{K^\mu\,\partial_\mu\Phi^A}\,\partial_\nu\Phi^B\right]$$
$$+ \; b\,Q^{IJ}\,K^\mu\,G_{I\,\mu\rho_1\ldots\rho_{D-p-1}}\,G_{J\nu}{}^{\rho_1\ldots\rho_{D-p-1}}$$

- $\mathcal{L}_K\Phi^A = 0 \;\Leftrightarrow\; K^\mu\partial_\mu\Phi^A = 0 \;\Rightarrow$ Scalars drop out of $R_{\mu\nu}K^\mu$
- Cartan formula for forms: $\cancelto{0}{\mathcal{L}_K\omega} = d(i_K(\omega)) + \cancelto{0}{i_K(d\omega)}$

  $d(F_{(p)}{}^I) = 0$, $d(G_{J,(D-p)}) = 0 \;\Rightarrow\; d(i_K(F_{(p)}{}^I)) = 0$, $d(i_K(G_{J,(D-p)})) = 0$
- Ignore topology: $i_K(F_{(p)}{}^I) = d\alpha_{(p-2)}{}^I$, $i_K(G_{J,(D-p)}) = d\beta_{J,(D-p-2)}$
- Define (D-2)-form, $\gamma_{D-2} = a\,\alpha_{(p-2)}{}^J \wedge G_{J,(D-p)} + b\,\beta_{J,(D-p-2)} \wedge F_{(p)}{}^J$

  Then: $*(K^\mu R_{\mu\nu}\,dx^\nu) = d(\gamma_{D-2})$

$\Rightarrow$ **M = 0** $\Rightarrow$ "No Solitons Without Horizons" ....

# Omissions:

- Chern-Simons terms
- Topology

Equations of motion in generic massless supergravity:

$$d{*}(Q_{JK}(\Phi)\, F_{(p)}{}^{K}) \;=\; \textit{Chern-Simons terms}$$

$$\Rightarrow\; d(G_{J,(D-p)}) = \textit{Chern-Simons terms}$$

$$\Rightarrow\quad *(K^{\mu} R_{\mu\nu} dx^{\nu}) \quad=\quad d(\gamma_{D-2}) \quad + \textit{Chern-Simons terms}$$

$$i_{K}(F_{(p)}{}^{I}) \;\neq\; d\boldsymbol{\alpha}_{(p-2)}{}^{I}\,, \quad i_{K}(G_{J,(D-p)}) \;\neq\; d\boldsymbol{\beta}_{J,(D-p-2)}$$

$$\Rightarrow\; \mathbf{M} \;\sim\; \textit{Topological contributions} + \textit{Chern-Simons terms}$$

# Five Dimensional Supergravity

N=2 Supergravity coupled to two vector multiplets

Three Maxwell Fields, $F^{\mathrm{I}}$, two scalars, $X^{\mathrm{I}}$, $X^{1}X^{2}X^{3} = 1$

$$S = \int \sqrt{-g}\, d^5x \Big( R - \tfrac{1}{2} Q_{IJ} F^{I}_{\mu\nu} F^{J\mu\nu} - Q_{IJ} \partial_\mu X^I \partial^\mu X^J - \tfrac{1}{24} C_{IJK} F^{I}_{\mu\nu} F^{J}_{\rho\sigma} A^{K}_{\lambda} \bar{\epsilon}^{\mu\nu\rho\sigma\lambda} \Big)$$

$$Q_{IJ} = \frac{1}{2} \operatorname{diag}\left( (X^1)^{-2}, (X^2)^{-2}, (X^3)^{-2} \right)$$

Three forms: $G_J \equiv *_5 \left( Q_{JK}(X)\, F^K \right)$

Four-dimensional spatial base slices, $\boldsymbol{\Sigma}$:

- Assume simply connected $\Rightarrow$ $i_K F^J = d\lambda^J$
- Topology of interest: $H_2(\boldsymbol{\Sigma}, Z) \neq 0$

$$i_K(G_I) - \tfrac{1}{2} C_{IJK} \lambda^J F^K = d\beta_I + \boxed{H_I}$$

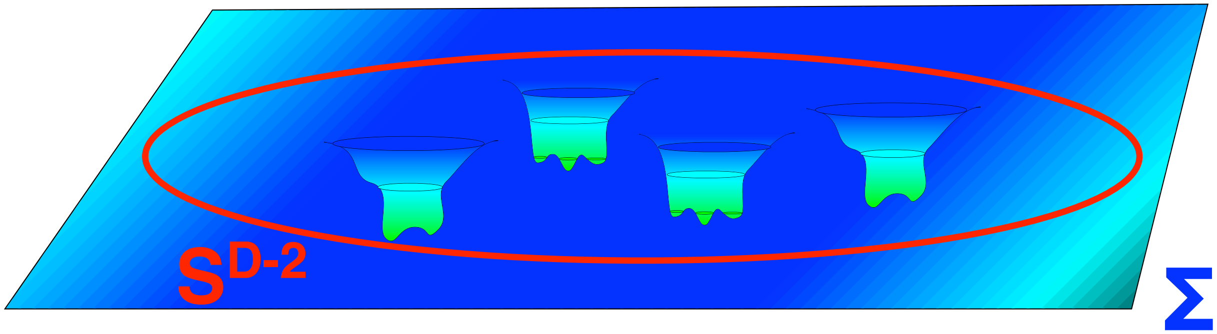
***Harmonic***

Chern-Simons terms cancel in the Smarr Formula …

*Only topology contributes via the $H_I$…*

# No Solitons without Topology

If $\Sigma$ is a smooth hypersurface with no interior boundaries




$$M = \frac{3}{16\pi G_5}\int_\Sigma K^\mu R_{\mu\nu}\, d\Sigma^\nu = \frac{1}{16\pi G_5}\int_\Sigma H_J \wedge F^J$$

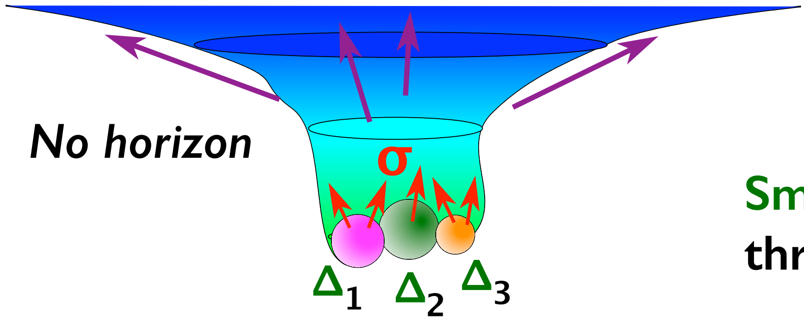
**The mass can be topologically supported by the cohomology $H^2(\Sigma,R)$**

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

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

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

# Topological Stars




**Smooth 2-cycles threaded by fluxes**

$$\sigma_a^{\;J} = \int_{\Delta_a} F^J$$

$$\widehat{\sigma}_J^{\;a} = \int_{\Delta_a} H_J$$

Mass, **M** ~ Magnetic fluxes $\hat{\sigma}_{\mathbf{J}} \wedge \sigma^{\mathbf{J}}$

*Chern-Simons Interaction:* $\nabla_\rho F^{J\rho}{}_{\mu} \sim C_{IJK}\, \epsilon_{\mu\alpha\beta\gamma\delta}\, F^{J\,\alpha\beta}\, F^{K\,\gamma\delta}$

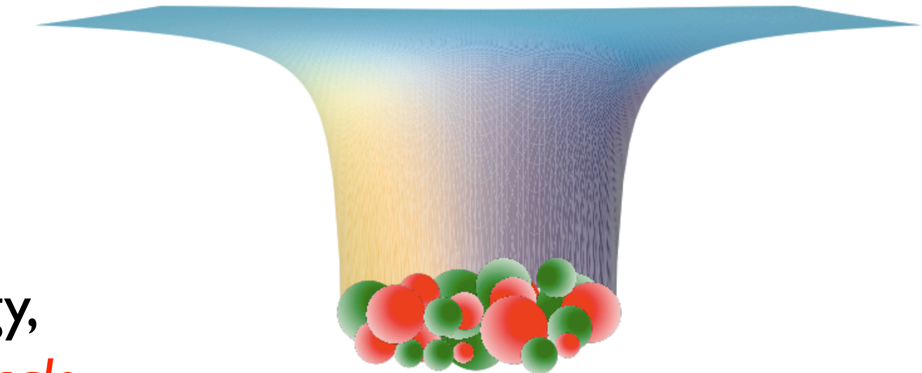
Electric Charge, $\mathbf{Q_I}$ ~ Magnetic fluxes $\sigma^{\mathbf{J}} \wedge \sigma^{\mathbf{K}}$

On **Σ: F** *fluxes* have *self-dual* and *anti-self-dual* parts $\sigma = \sigma^+ + \sigma^-$

Mass, **M** ~ $|\sigma^+|^2 + |\sigma^-|^2$ Charge, **Q** ~ $|\sigma^+|^2 - |\sigma^-|^2$

BPS topological stars $\sigma = \sigma^\pm$

# The Status of *BPS* Microstate Geometries in Five Dimensions



★ 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*

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

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

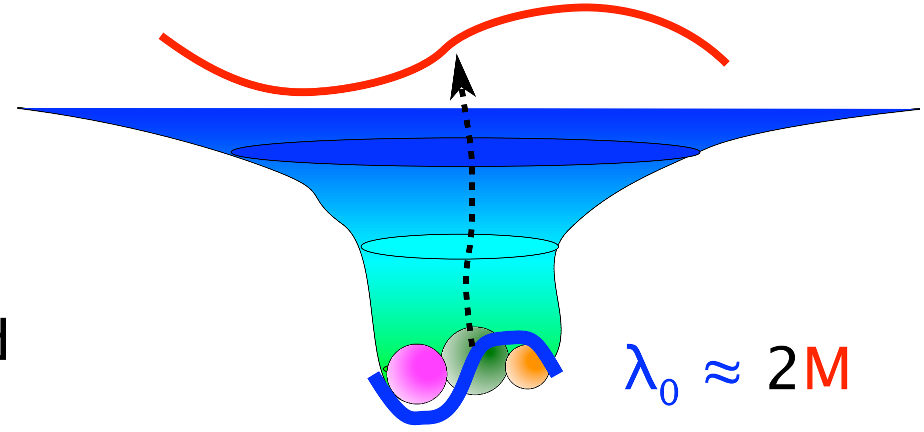
★ Holography in the long AdS throat: *All these solutions represent black-hole microstates*

⇒ Semi-classical sampling of black-hole microstate structure

***“Topological stars” = coherent microstates of black holes***

# Scale 1: The Energy Gap

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




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

★ The spectrum is black hole is now gapped

★ The gap is determined by "depth," $z_{max}$

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

## BPS black holes

Classical microstate geometries: *AdS throats* that can be made *arbitrarily long*

$\Rightarrow$ $z_{max}$ *arbitrarily big* $\Rightarrow$ $E_{gap}$ *arbitrarily small*

Semi-classical quantization of the moduli of the geometry:

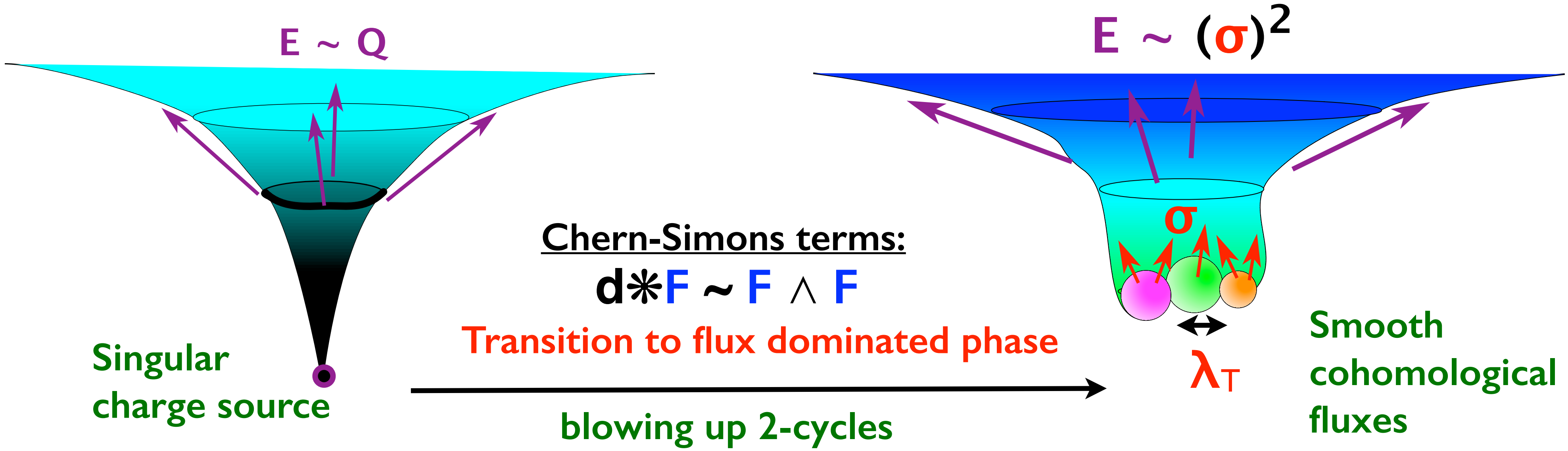
★ The throat depth, or $z_{max}$ , is ***not*** a free parameter

★ $E_{gap}$ is determined by the charge 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

# Scale 2:  The Order Parameter of the Geometric Phase




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

- ★ Magnitude of fluxes , $\sigma$ =  Order parameter of new phases
- ★ Size of the bubbles, $\lambda_T$ = *Transition Scale* is a new  scale in the topological phase

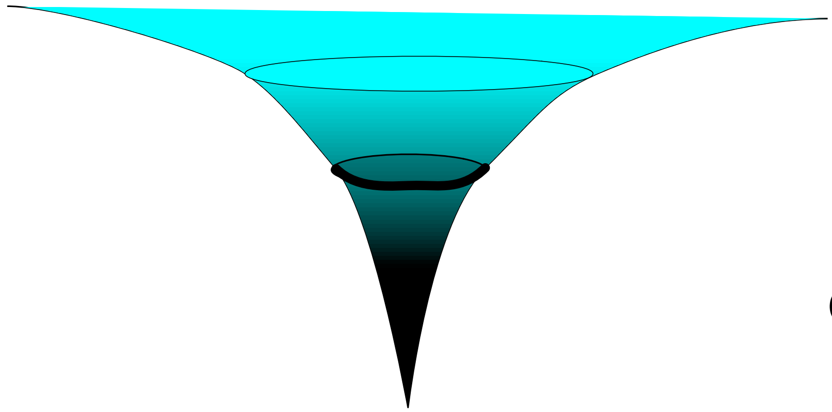
Supergravity equations  $\Rightarrow$  $\lambda_T$  ~  Magnitude of fluxes , $\sigma$

Balance:  *Gravity* $\longleftrightarrow$ *Flux expansion force*

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

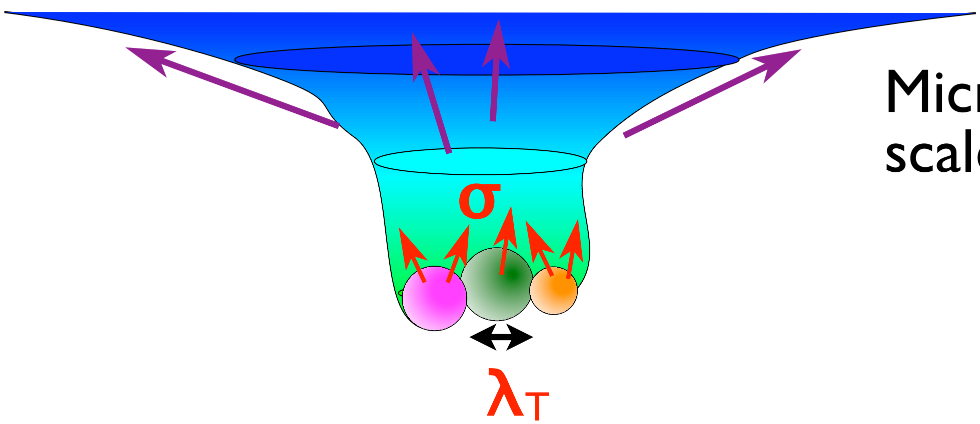
Quantum mechanics: Could $\lambda_T$ be dynamically generated?

# Two new scales in black-hole physics



Quantum mechanics + gravity: $\ell_P = \sqrt{\dfrac{G\,\hbar}{c^3}}$

Original black hole: $R = \dfrac{2\,G\,M}{c^2}$



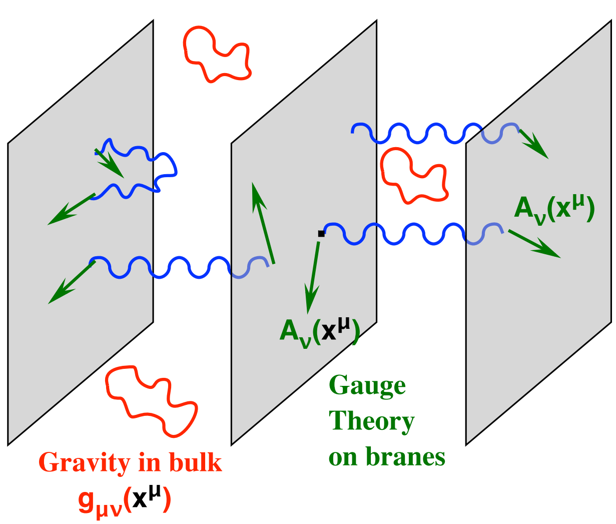

Microstate geometry: $M$, $\ell_P$ + two new scales

- ★ Scale of a typical cycle, $\lambda_T$
- ★ "Depth" of the "throat"

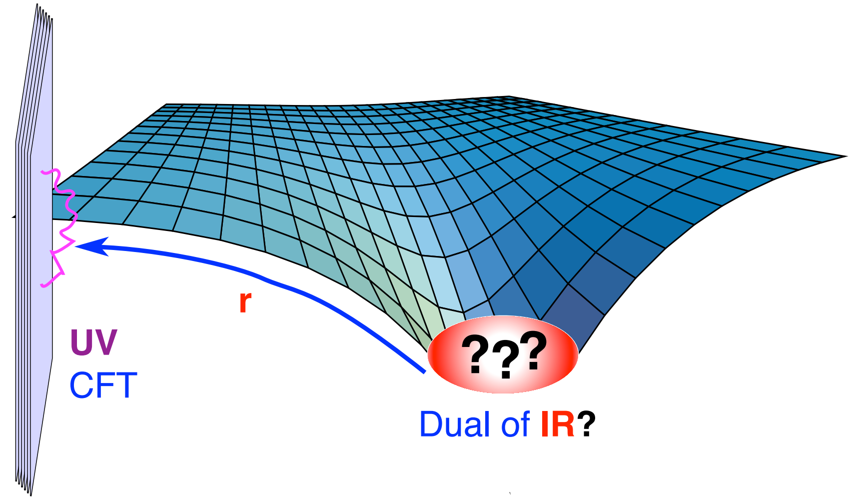
Physical "depth" defined by $z_{max}$ = *maximum redshift between infinity and the bubbles at the bottom of the throat*

Traditional black holes: $\lambda_T = 0$, $z_{max} = \infty$

# Lessons from Holographic Field Theory



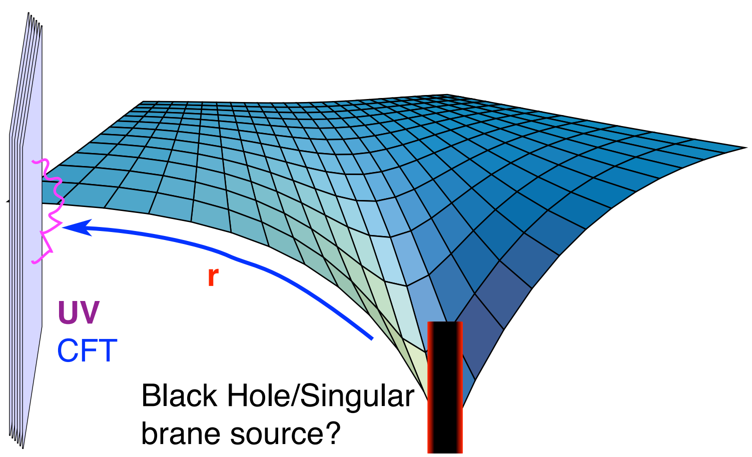

gravitational
back-reaction

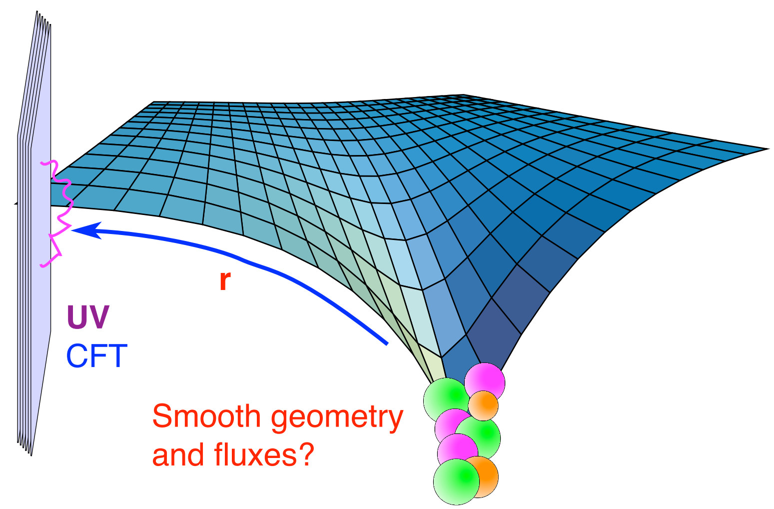



*N=2* SCFT + relevant perturbation  —  *RG flow* →  *N=1** gauge theory

Wrong solutions: Missing IR physics

Right solutions: Correct IR physics

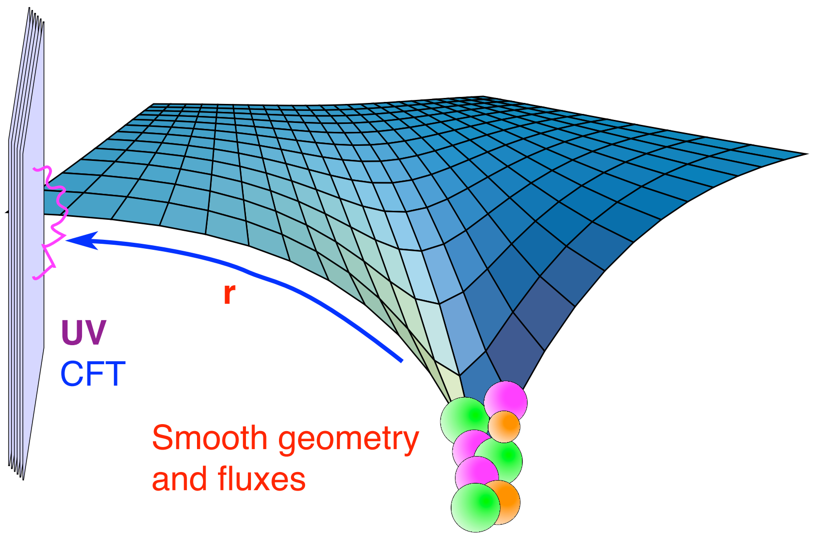



e.g. Klebanov-Tseytlin flow;
Girardello, Petrini, Porrati, Zaffaroni flow …

e.g. Klebanov-Strassler flow;
Polchinski-Strassler flow …

# Infra-red limits of Holographic Flows




- Klebanov-Strassler
- Polchinski-Strassler
- Dijkgraaf-Vafa ….
- Lin, Lunin, Maldacena

★ IR geometry: Branes undergo phase transition to "bubbled geometry"

★ IR phase of field theory ⇔ Fluxed IR geometry:
Fluxes dual to order parameter of IR phase

★ Transition scale, $\lambda_T \sim \lambda_{SQCD}$

★ Singular IR Geometry: wrong IR phase of theory …

★ Black-hole IR Geometry: all vevs vanish …

*Microstate geometries*: Same principles applied to black-hole field theory…

From holographic perspective the new scales in black-hole physics closely parallel the emergence of confining IR phase and scale in QCD...

# Microstate Structure

Microstate geometries *provide a mechanism* to replace singularities and horizons within string theory and support structure where the horizon would be located in a conventional black hole …

In the supegravity approximation microstate geometries represent *the only possible time-independent mechanism: topology and cohomological fluxes*

***Separate issue from mechanism of support***:

- What structures do you want to support in place of a classical horizon?
- How can this represent these microstates of a black hole?

★ The complete description of all microstates will be intrinsically stringy ..

★ Schwarzschild Microstates are intrinsically hot …

*finite temperature* firewall?

Follow-up question within geometries …

To what extent is the microstate structure visible from semi-classical analysis within the supegravity approximation?

# BPS Fluctuating Bubbled Geometries

Bubbled geometries can have *BPS shape fluctuations* that depend upon "transverse/internal dimensions." These shape fluctuations can go down to $E_{gap}$ and/or the Planck scale, $\ell_p$.

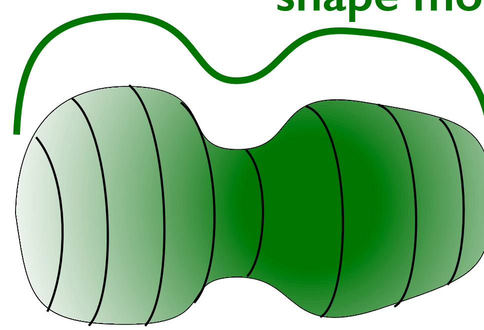
*Most of the semi-classical entropy probably lies in the shape fluctuations...*

Extensive work in five-dimensions:

*BPS shape fluctuations* on 2-cycles depend upon functions of ***one variable***:

Expect entropy like that of a supertube

$$S \sim \sqrt{Q_1 Q_2} \sim Q$$




If fluctuations localized at the bottom of a scaling solution then one can get *entropy enhancement*: Magnetic dipole-dipole interactions can make supertube much floppier than in flat space $\Rightarrow$ $\mathbf{S \sim Q^{5/4}}$

Semi-classical quantization of five-dimensional BPS solutions: $S \sim Q^{5/4}$

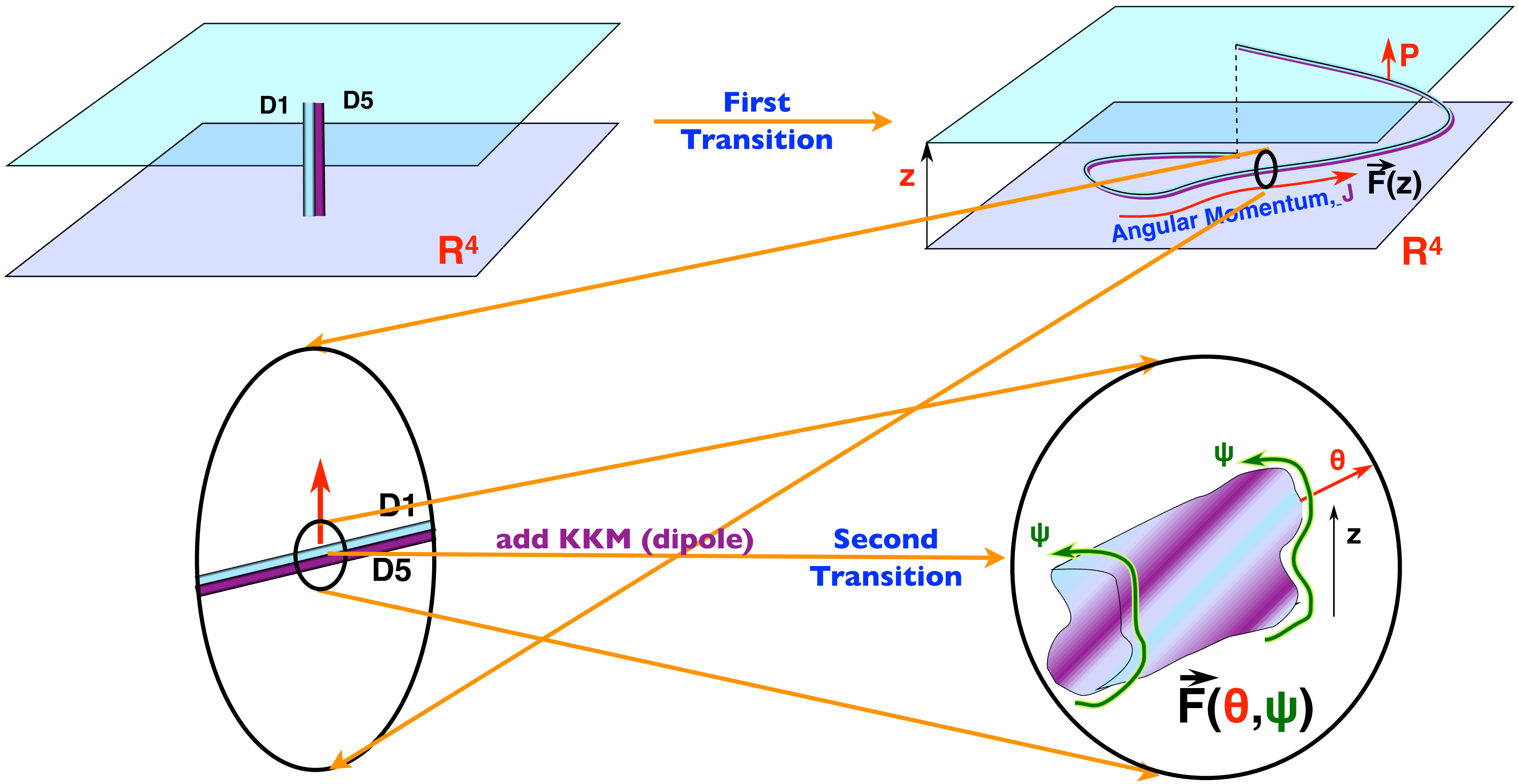
de Boer, El-Showk, Messamah, Van den Bleeken, arXiv:0807.4556, arXiv:0906.0011

Black hole entropy: $S \sim \sqrt{Q_1 Q_2 Q_3} \sim Q^{\frac{3}{2}}$

# The Superstratum:

Bena, de Boer, Shigemori and Warner, 1107.2650

An intrinsically new BPS bound state/microstate geometry in six dimensions.

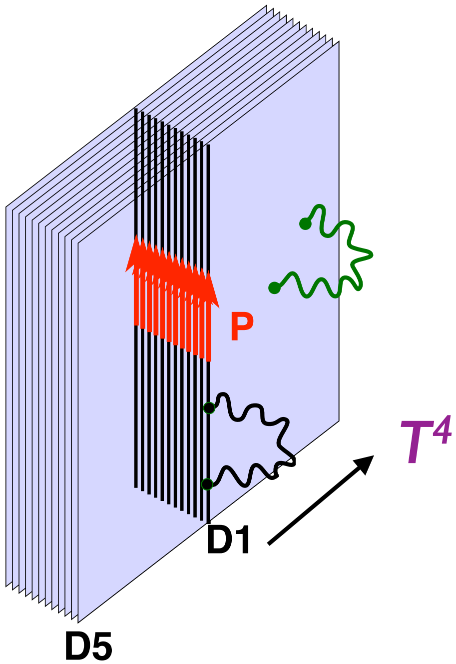



⇒ BPS configurations that depend upon *functions of two variables*

Preserves the 4 supersymmetries if the D1-D5-P system

Smooth in the D1-D5-P duality frame: ***A microstate geometry.***

# The Superstratum: Another Perspective




The D1-D5-P system was the basis of the original counting by Strominger and Vafa …

The underlying CFT is the orbifold $S_N(T^4)$ …

$N = N_1\, N_5$ c = $6N = 6N_1\, N_5$

Carry momentum $P$ ⇒ $S = 2\pi\sqrt{N_1 N_5 P}$

Transverse motions *appear* only involve the internal $T^4$

However the *chiral primaries* of the D1-D5 theory are the twist fields of $S_N$

Fundamental twists: Pairwise interchanges $\sigma_{ij}$ i,j = $1,\ldots,N$

Carry the fundamental representation = vector of SO(4) of the *R-symmetry* group = Rotation group in space-time

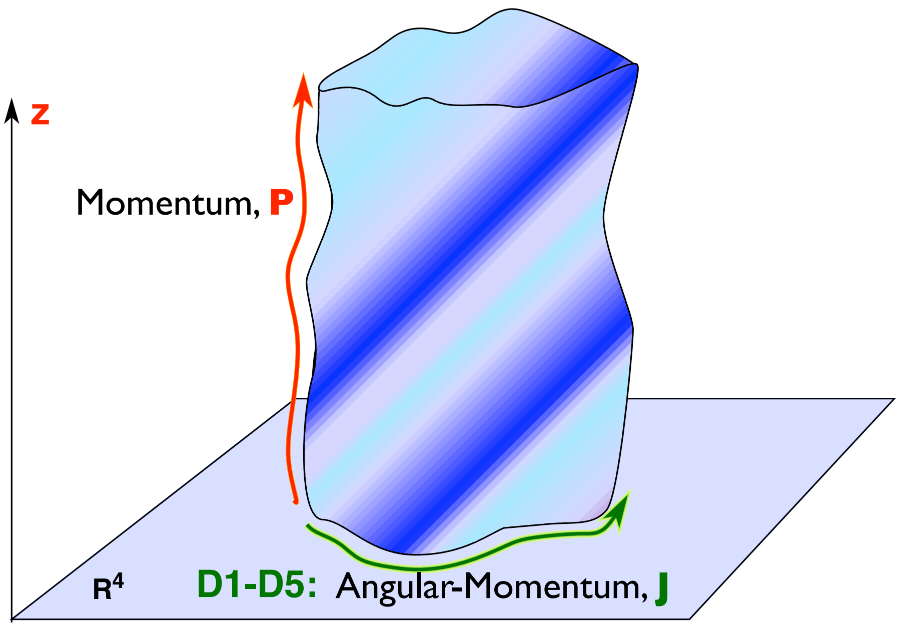
⇒ *Chiral primaries* of the D1-D5 theory carry *space-time* polarizations

⇒ *Back-reaction visible as angular momentum shape modes in space time*

**Generators of $S_N$** are $\sigma_{j\,j+1}$ j = $1,\ldots,N-1$

*$N-1$ independent momentum carriers: angular momentum shape modes*

# How the quantization of the superstratum might work ….




BPS configurations that depend upon *functions of two variables*

- Shape modes in $R^4$ directions arise from quantization of D1-D5 system
- There are $N = N_1\, N_5$ independent angular shape modes, each of which can carry z-momentum

- Each angular shape mode carries a polarization vector in $R^4$ and has four fermonic counterparts $\Rightarrow$ $c = 6\, N_1\, N_5$ *visible as space-time fluctuations*

When semi-classically quantized *we hope* that each of these modes acts as an independent momentum carrier …

If so then: **S =** $2\pi\sqrt{N_1 N_5 P}$

*would follow from semi-classical quantization of supergravity!*

# The Overall Picture

- 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:* $\lambda_T$ = *Transition Scale*
- Extra-dimensions of space-time are crucial:
  $\lambda_T \sim$ *Scale of extra dimensions near topological star*
- The new phase smoothly caps-off the space-time before a horizon forms:
  → *Limits the red-shift; makes the spectrum of fluctuations gapped,* $E_{gap}$
- The new phases represent new "*infra-red*" *vacua* of string theory
- *Fluctuations* about these new phases represent the *microstate structure*
- Vast families of BPS examples explicitly constructed
  *Semi-classical description of black-hole microstate structure/thermodynamics?*

*This viewpoint is a natural and direct outgrowth of holographic field theories ....*

# Current Issues in Microstate Geometries:

## BPS solutions

- Vast families of classical solutions, with huge moduli spaces ...

  → *Semi-classical description of black-hole entropy?*

  *Superstratum: quite possibly yes!*

- Quantum fluctuations about these backgrounds

  → *Complete description of black-hole microstate structure?*

  *Promising but still subject to debate*

## Non-BPS extremal solutions

*Similar to BPS story: but technically much harder*

## Non-BPS, non-extremal solutions

*Very little known but near-BPS picture seems very promising:*

*BPS microstate structures are perturbatively stable*

# More Speculative Ideas…

Other "more stringy" mechanisms have been proposed for changing the physics at the horizon scale.

- Brane polarization effects: e.g. angular momentum; Myers effect
- Non-Abelian degrees of freedom: *e.g. pure Higgs branch fields*

These are generically in corners of the moduli space of the background in which the gravitational back-reaction is minimized/ignored because the string coupling is weak or the number of quanta is small …

Increasing the string coupling or the number of quanta creates a strong back-reaction and Higgs branch fields condense. Then one can use supergravity …

*.. and in supegravity the only possible mechanism is that of **microstate geometries** and based on topological fluxes.*

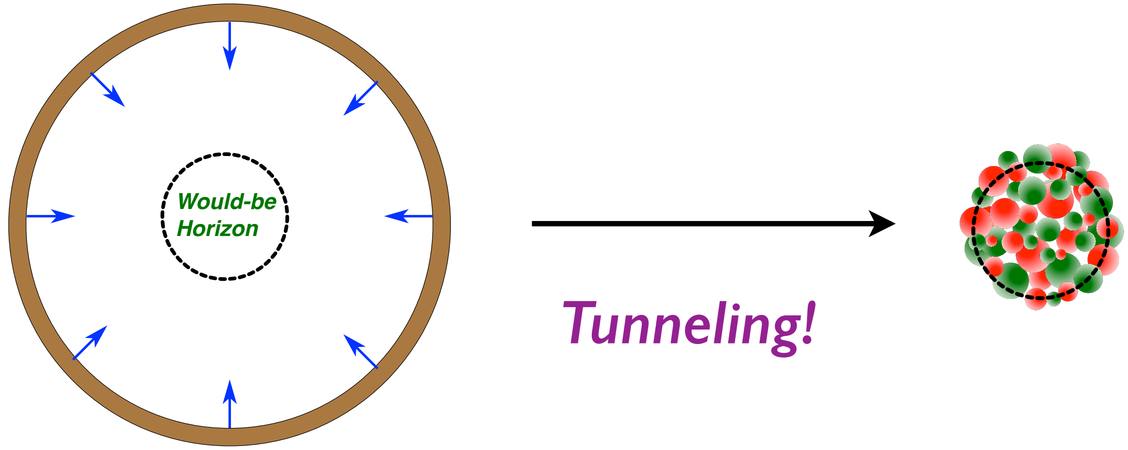
Conversely, one can view such brane-polarization or non-Abelian effects as limiting behavior of *microstate geometries* and thus these other mechanisms can be understood as more general classes of *microstate solutions* that can be linked to *microstate geometries* by tuning parameters.

# More Speculative Ideas: Collapse to a Black Hole

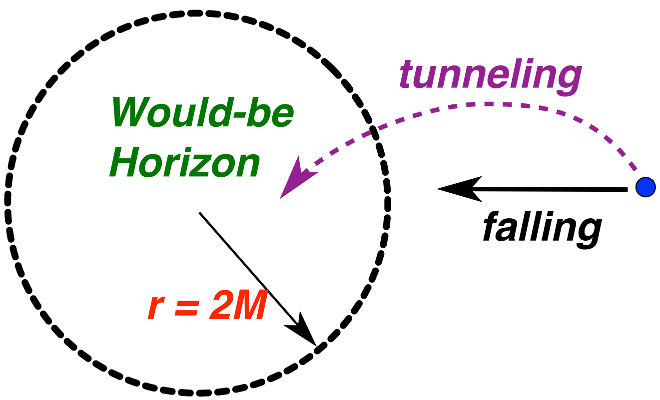
Mathur: 0805.3716; 0905.4483; Mathur and Turton: 1306.5488

A shell of spherically symmetric matter collapses to a *microstate geometry*…

How can this happen?




Consider a particle falling into a black hole ...




Amplitude to tunnel directly into a black hole from nearby $\sim\ e^{-\alpha M^2/m_P^2}$

$\alpha \sim O(1)$

Number of states inside black hole $\sim\ e^{+16\pi M^2/m_P^2}$

Probability of tunneling during infall time ~ *O(1)!*

Black hole formation is intrinsically a quantum tunneling transition!

# Final thought...

Maybe in spite of its macroscopic size, the near-horizon properties of black holes are dominated by quantum effects ... and this is what makes the *O(1)* changes to horizon-scale physics

So then what good is all this classical supergravity analysis?

*It identifies the long-range, large scale degrees of freedom that control physics at the horizon scale ... and maybe we only have to perform the semi-classical quantization of all these relatively simple degrees of freedom to get a good picture of what is really happening at the horizon of a black hole ..*

# Conclusions

- Microstate Geometries: Classify and study ***smooth, horizonless*** solutions to supergravity

  Miraculous existence through spatial ***topology*** and ***Chern-Simons terms***

- Emerge from geometric phase transitions:
  Singular brane sources → Smooth cohomological fluxes

- ***Mechanism*** for supporting matter before a horizon forms
  - ★ *New "flux-dominated" phases of string theory*
  - ★ *Support the microstate structure of black holes in whatever stringy form*
  - ★ *Topological stars in Nature?*

- Semi-classical technique for understanding the detailed microstate structure of black holes

- New scales in black-hole physics: Transition scale, $\lambda_T$, and maximum red-shift, $z_{max}$; related to $E_{gap}$ of fluctuation spectrum

- For BPS microstate geometries, supergravity modes of the ***superstratum*** may be sufficient to provide a semi-classical description of the black-hole entropy