Black Holes and their Microstates from the Stringy Perspective

Nick Warner, Kyoto, November 23, 2015

Research supported supported in part by DOE grant DE- SC0011687

Outline

General results (not just BPS)

- The black-hole information problem
- Resolving singularities and removing horizons
- Strong coupling: Solitons and Microstate geometries
- Phases and new scales for black-hole physics

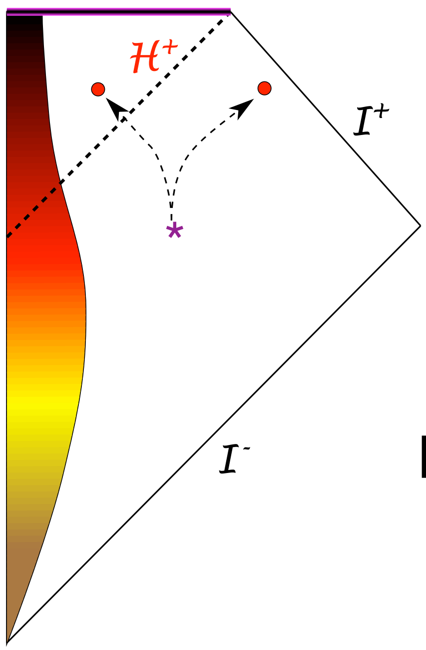
BPS microstate structure

- Phases of microstate structure
- Detailed microstate structure
- Recent Developments: W-branes and hypermultiplets

Beyond BPS

- Non-BPS extremal; Near BPS and Far from BPS
- More speculative ideas

Hawking Radiation and Black-Hole Uniqueness



Black holes polarize the vacuum

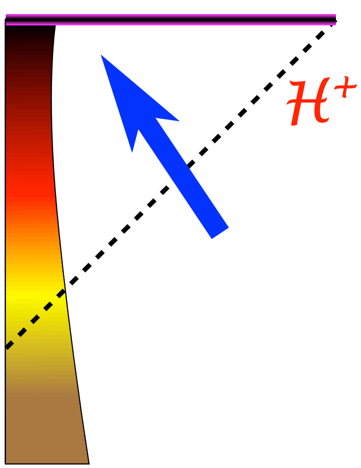
→ Thermal "*Hawking*" radiation at infinity

$$T = \frac{\kappa}{2\pi} = \frac{\hbar c^3}{8\pi G k_B M}$$

Bekenstein-Hawking entropy: $$S = \frac{k_B c^3}{4 G \hbar} A = \frac{1}{4} \frac{A}{\ell_P^2}$$

For Milky Way black hole: **$S \approx 1.8 \times 10^{90}$**

Black-hole uniqueness



Once a black hole forms, matter is swept away from horizon region in the light-crossing time of black hole …

⇒ Horizon region is in in perfect (infalling) vacuum

⇒ Black hole is featureless (unique metric)

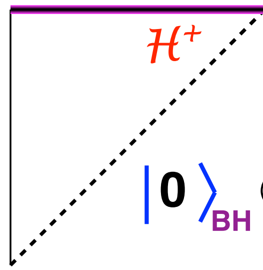
just M, J, + conserved charges

⇒ *Classical entropy:* $S = \log(1) = 0$ ≠ **1.8×10^{90}**

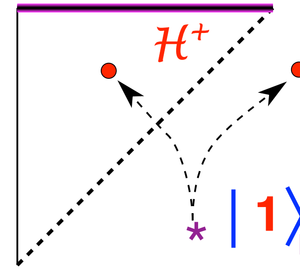
⇒ *Hawking radiation is featureless/universal ..*

Hawking's Original Information Paradox

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

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

Complete evaporation of the black hole ….

Black hole entropy ⟶ Entropy of Hawking Radiation

$|\psi\rangle_{initial}$ ⟶ $\rho = \sum_{\substack{radiation \\ states\ |\psi>}} e^{-\beta E} |\psi><\psi|$

Pure state, $|\psi\rangle$ ⟶ Density Matrix, ρ

Cannot be described by unitary evolution in Quantum Mechanics

An old conceit: Fix 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: For a solar mass black hole

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

Restore the pure state over vast time period for evaporation?

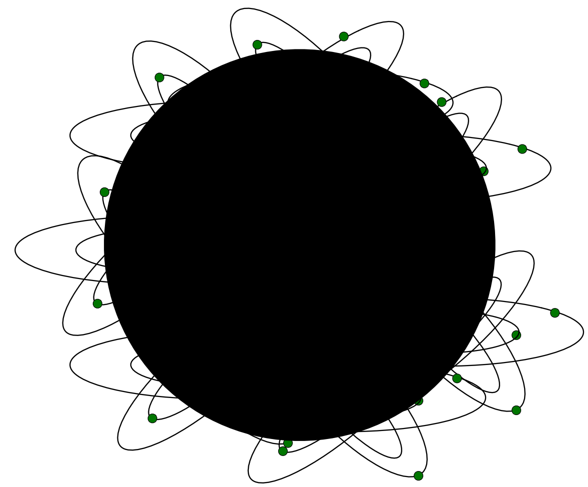
Mathur (2009):

No! Corrections cannot be small for information recovery

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

Microstate Structure at the Horizon Scale: I

Set G_{Newton} = 0 and understand the microstate structure of material that will form a black hole at finite G_{Newton} …   **String theory: Strominger and Vafa: hep-th/9601029**



Increase G_{Newton}, (or string coupling, g_s)

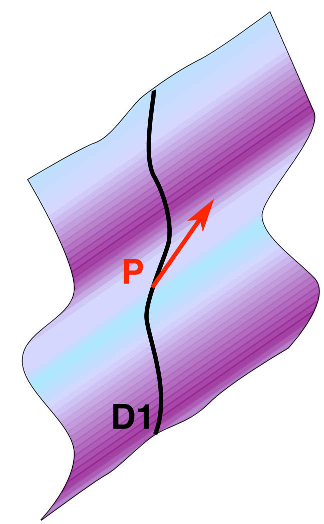
- ★ Matter/microstate structure ***shrink***
- ★ Horizon areas *grow*: $R_S = \frac{2\, G_{Newton}\, M}{c^2}$

The Horowitz-Polchinski Correspondence Principle

As G_{Newton} or g_s increases, whatever microstates you have found disappear behind a horizon: Microstates are Planck scale fuzz deep inside the black hole

The Error: D-brane tension ~ g_s^{-1} + momentum, P

⇒ Branes spread out with increasing g_s



D-branes with shape modes can give structures that grow with g_s at ***exactly the same rate*** as the size of a black hole.

⇒ *D-branes with shape modes can provide microstate structure that can extend to horizon scale*

Includes exactly the system whose states were counted by Strominger and Vafa

Microstate Structure at the Horizon Scale: II

Finite G_{Newton} (or g_s): Stringy resolution at the horizon scale

⇒ *Very long-range effects* ⇒ *Massless* limit of string theory: ***Supergravity***

Microstate Geometry Program: *Find mechanisms and structures that resolve singularities and prevent the formation of horizons in Supergravity*

- Smooth, horizonless solutions to the bosonic sector of supergravity with the same asymptotic structure as a given black hole or black ring

Problems:

★ *Configurations of massive fields shrink as G_{Newton} (or g_s) increase*

★ *Massive fields cannot produce a resolution at the horizon scale: No massive field is stiff enough to prevent collapse to black hole*

(Tolman-Oppenheimer-Volkov for R < 9/4 M)

★ *Massless fields travel at the speed of light ... only a "dark star" or black hole can hold such things into a star.*

~~"No solitons without horizons"~~

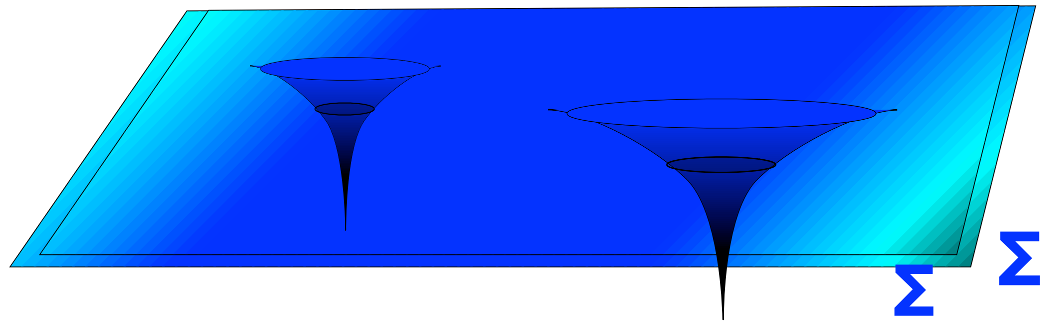
Limitations on *Solitons* = Smooth, Stationary Solutions

Assume time-invariance: and there is a time-like Killing vector, K.

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

Canonical energy-density

$$T_{00} = K^\mu K^\nu g_{\mu\nu}$$



Unlike black-hole space-times, solitonic solutions are sectioned by ***smooth***, space-like hypersurfaces, **Σ.**

Mass/energy is conserved and can be defined through a smooth integration over a regular surface: $M = \int_\Sigma T_{00}\, d\Sigma$

No solitons without horizons:

Equations of motion for *massless* field theory

+ Time-independent matter ⇒ T_{00} = total derivative in Σ

⇒ **M ≡ 0** ⇒ *Space-time can only be globally flat,* $\mathbf{R}^{D-1,1}$

The Error: T_{00} = total derivative in Σ *only locally* …

this argument neglects topology

Solitons can be supported by cohomological magnetic fluxes

…. and this is the only way to support solitons!

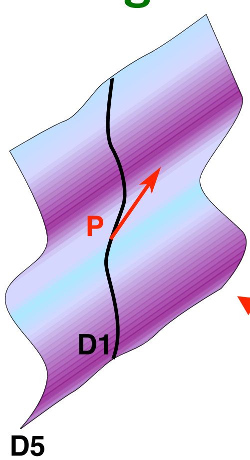
Correct calculation ⇒

$$M \sim \sum_p \int_\Sigma F^{(p)} \wedge H^{(D-p-1)} \quad \text{where} \quad H^{(D-p-1)} \equiv harm(i_K(*_D F^{(p)}))$$

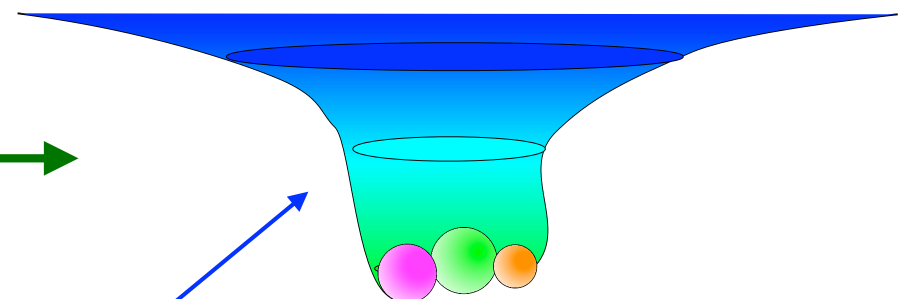
Correct conclusion: ***No solitons without topology***

<u>Relate the horizon scale resolutions:</u>

Fluctuating branes *Microstate geometries*



Geometric Transition

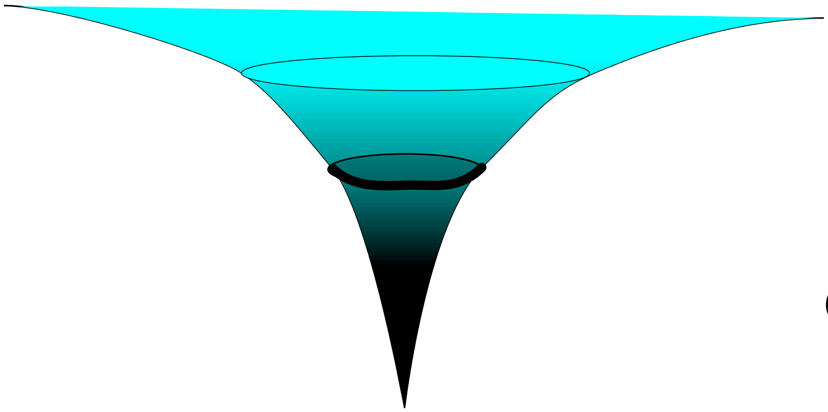


$$d * F^{(p)} \sim \delta^{(D-p)} + \sum_k G^{(k)} \wedge G^{(D-p-k)}$$

A phase transition driven by the Chern-Simons interaction

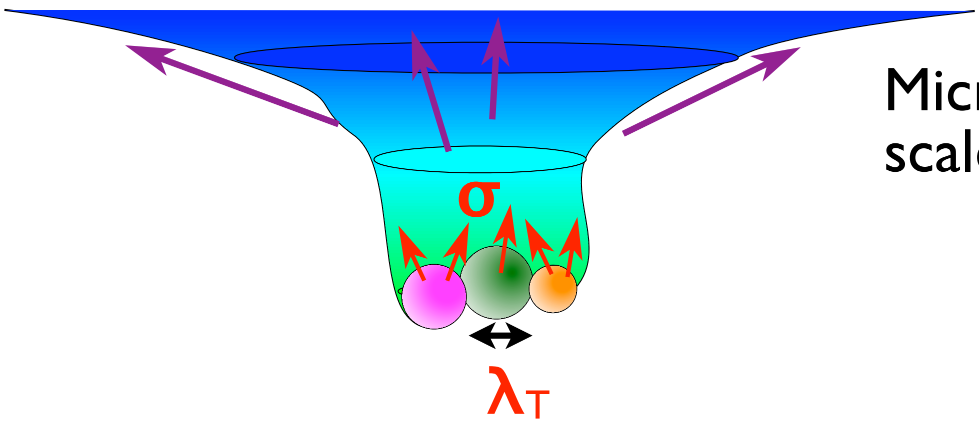
Scale of transition: Size, λ_T, of a typical cycle

Two new scales in black-hole physics



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

Original black hole: $R = \frac{2GM}{c^2}$



Microstate geometry: M, ℓ_P + two new scales

- ★ Scale of a typical cycle, λ_T
- ★ "Depth" of the "throat"

Physical "depth" defined by z_{max} = *maximum redshift between infinity and the bubbles at the bottom that resolve the black hole*

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

Two distinct and independent ideas from *microstate geometries*

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

- *The bubbled geometry provides a background to study other string phenomena, like fluctuations and brane wrapping*

- *Holography: Such geometries describes a phases of the black-hole physics*

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

- *Holography:* Fluctuations/moduli of microstate geometries
  = coherent semi-classical description of detailed microstate structure

- Other structures in microstate geometries **(like W-branes)**
  = description of other microstate structures **(like Higgs branch states)**

Strategy

- Study BPS/Supersymmetric black holes "M = Q" first

  ★ Stable: Hawking Temperature = 0

  ★ Computationally far simpler. Microstates are all BPS states

  ★ Microstates "protected by supersymmetry;" preserved under variation of the string coupling

  ★ Enough supersymmetry ("$\mathcal{N} = 1$") to be computable but not too much to destroy interesting physics. *Parallel with using SQCD to study and understand QCD*

Solve the *information storage problem*:

Allow access microstate structure from infinity

- Use perturbation theory to study "near-BPS"

  BPS states: quasi-static background for such analysis

- Non-extremal, non-BPS ….

BPS Microstate Geometries

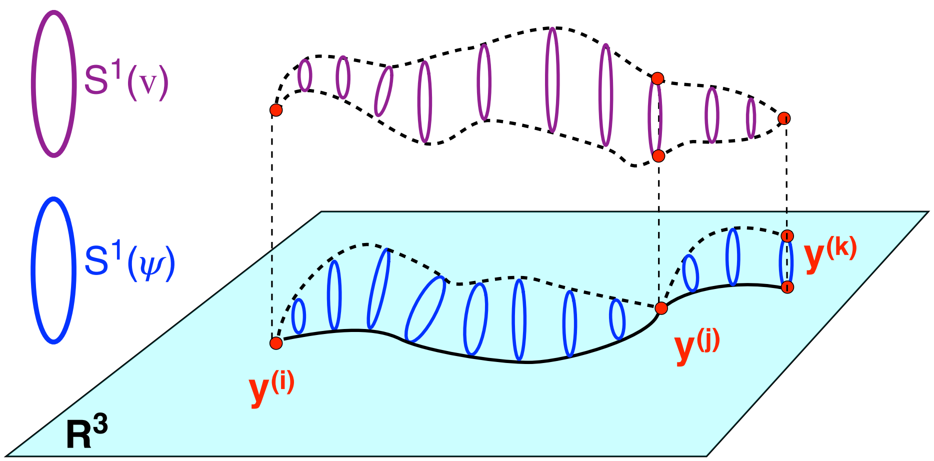
Phase structure and the supergravity ***mechanism***

Building *BPS* Microstate Geometries

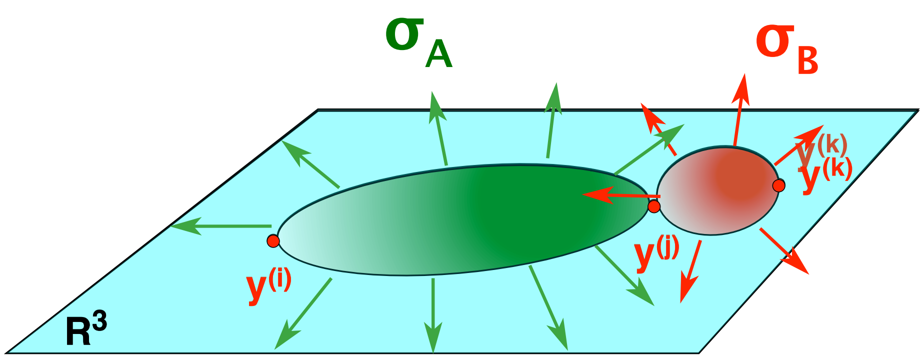
IIB Supergravity on T^4: Supergravity in six-dimensions ⇒ Six dimensional metric ansatz:

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\Big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\Big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double S^1 fibration over a flat R^3 base with coordinates, y.



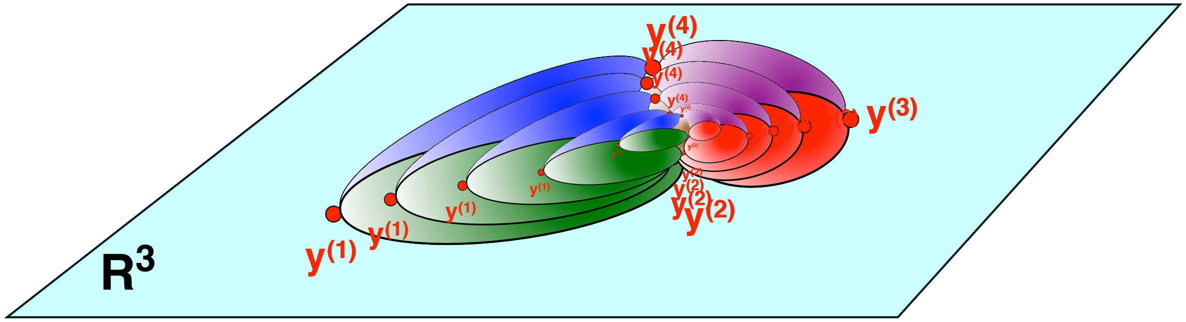
The non-trivial homology cycles are defined through the pinching off of the $S^1 \times S^1$ fibration at special points in the R^3 base.



Cycles support non-trivial cohomological fluxes …

The scale of everything is set by the "warp factors:" *V, P* and Z_3

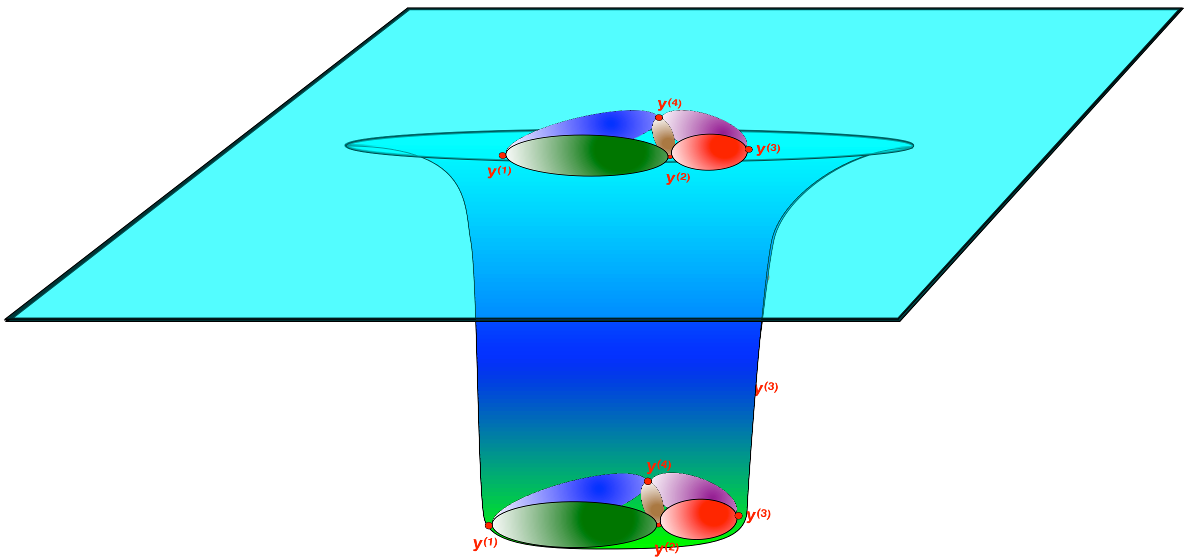
Scaling solutions



One can tune the orientation of the homology cycles and fluxes so that the configuration ***scales to an arbitrarily small size*** in the R^3 base …

This can be done while keeping the fluxes and charges large.

In the full six-dimensional geometry this *scaling process:*

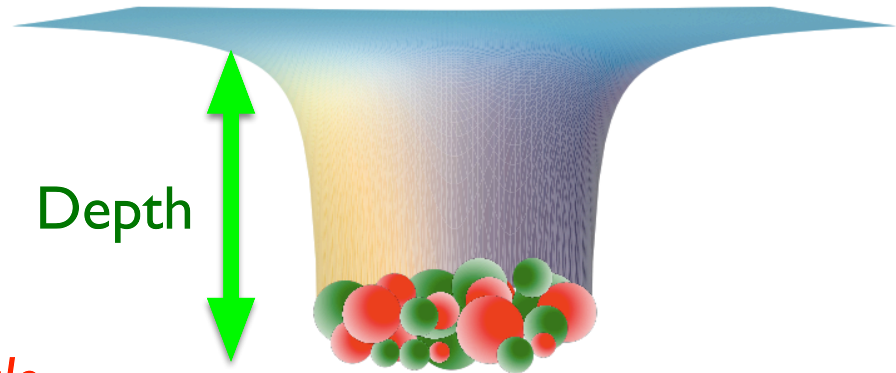


- ★ The bubbles descend and AdS throat
- ★ The bubbles retain their physical size
- ★ The diameter of the throat limits to a fixed size determined by the charges and angular momentum of the configuration

End result: Looks almost exactly like a BPS black hole to as close to the horizon as one likes … but then it caps off in a smooth microstate geometry.

A Decade of *BPS* Microstate Geometries

★ There are vast families of smooth, horizonless BPS microstate geometries



★ New physics *at the horizon scale*

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

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

Look exactly like a BPS black hole as close as one likes to the horizon

Length/depth is classically free parameter

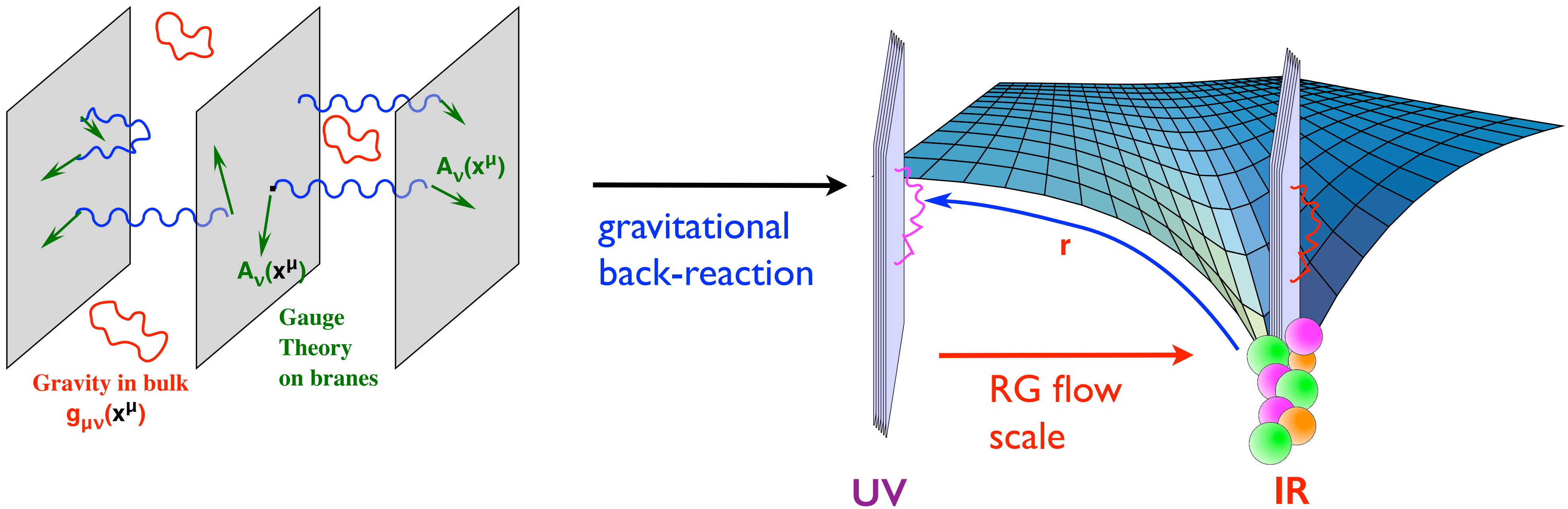
Long AdS throat: *One can do holography in the AdS throat*

⇒ BPS black-hole physics/microstate structure described by a CFT

Precise map: *Bubbled geometry* ⟷ *Phase of CFT*

Geometric fluctuations ⟷ *Coherent combinations of microstates*

Invoke Principles of Holographic Field Theory



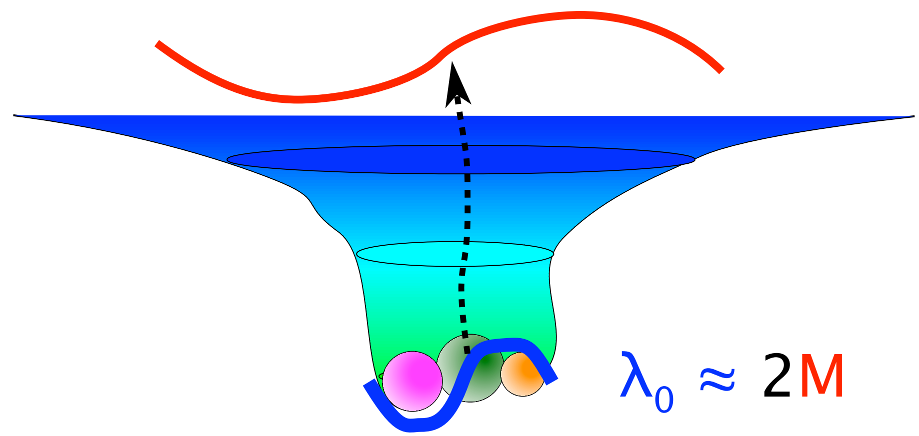
Correct holographic description of flows to confining N=1 gauge theories:

- ★ IR geometry: Branes undergo phase transition to "bubbled geometry"
- ★ Confining phase of field theory ⇔ Fluxed IR geometry:
  Fluxes dual to gaugino condensates = order parameter of confining phase
- ★ Transition scale, $\lambda_T \sim \lambda_{SQCD}$
- ★ Singular IR Geometry: wrong IR phase of the N=1 gauge theory

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

The Energy Gap

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



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

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

BPS: Semi-classical quantization of the moduli of the geometry:

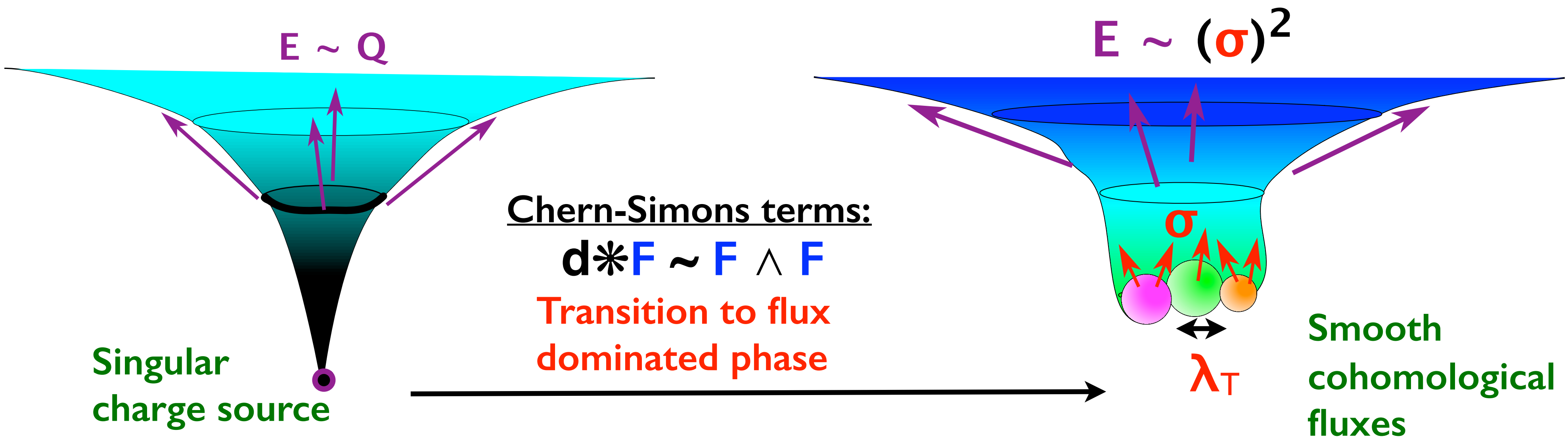
- ★ The throat depth, or z_{max} , is ***not*** a free parameter
- ★ E_{gap} is determined by the flux structure of the geometry
- ★ E_{gap} Longest possible scaling throat: $E_{gap} \sim (C_{cft})^{-1}$

Bena, Wang and Warner, arXiv:hep-th/0608217
de Boer, El-Showk, Messamah, Van den Bleeken, arXiv:0807.4556

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

⇒ Scaling microstate geometries are representatives of states in the "*typical sector*" that provides the dominant contribution to the entropy ...

Geometric Phases and Order Parameters



Many (classical) choices of bubbled geometry …

Cohomology of geometry ⟷ phase/sector of dual CFT

- ★ Magnitude of fluxes , **σ** = Order parameter of new phases
- ★ Size of the bubbles, λ_T = *Transition Scale*

Supergravity equations ⇒ λ_T ~ Magnitude of fluxes , **σ**

Balance: *Gravity* ⟷ *Flux expansion force*

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

Open issue: **What sets λ_T? Is large λ_T be entropically favored?**

BPS Microstate Geometries

Essential points so far….

(i) Large scale, macrostate issues

Black-hole field theory and its phases ⇔ **Topology of resolution**

Order parameters and scales ⇔ **Scales of fluxes and cycles**

Next: Examine microstate structure in more detail

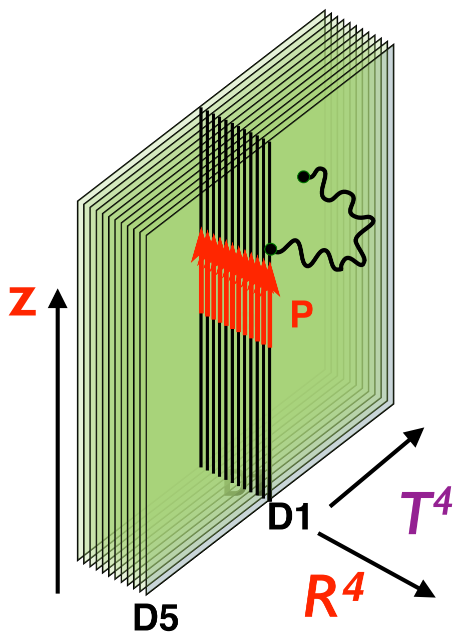
(ii) Microstate structure encoded semi-classically via AdS/CFT

Semi-classical microstates ⇔ **Coherent geometric fluctuations around each phase**

BPS Microstate Geometries

Microstate Structure: Encoding the microstates of black holes

The D1-D5-P System   IIB Supergravity on $T^4 \times S^1(z) \times R^{4,1}$



The CFT: Open strings between D1's and D5's

⇒ (1+1)-dimensional *SCFT* on common direction, **z**, of the D1 and D5 branes

Fields: $X^{\dot{A}A}_{(r)}(z,\bar{z})$ $\psi^{\alpha\dot{A}}_{(r)}(z)$ $\widetilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})$

Chan-Paton labels: r = 1 ,…, N = $N_1 N_5$

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

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

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

An orbifold SCFT with (4,4) supersymmetry and ***$c = 6N = 6 N_1 N_5$***

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

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

Note that only the fermions carry "polarizations" in the space-time directions ⇔ only fermions carry R-charge

Two charges: ¼ BPS Ground States in the D1-D5 System

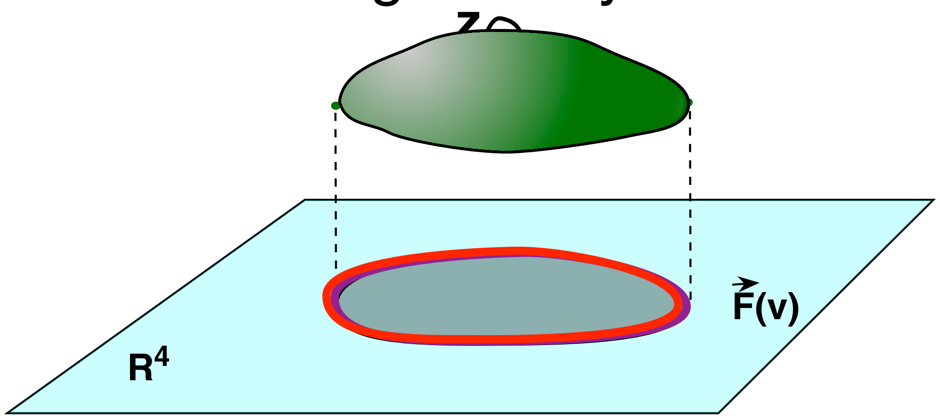
= RR vacua/Chiral primaries of D1-D5 SCFT

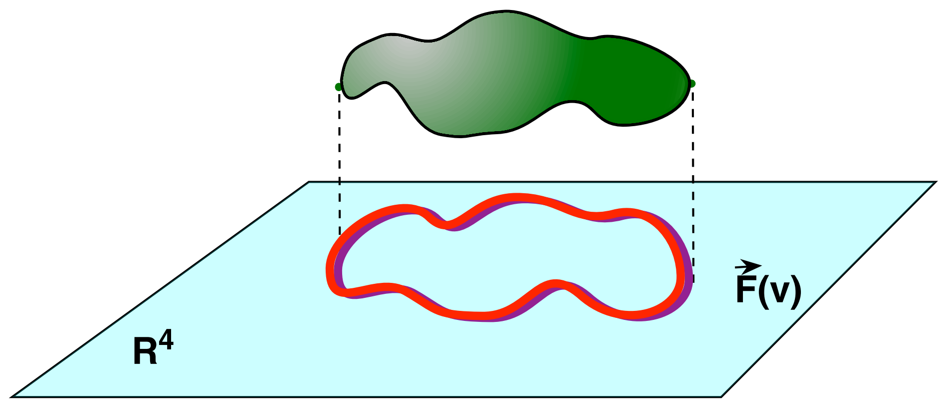
Balasubramanian, de Boer, Keski-Vakkuri, Ross, hep-th/0011217; Maldacena, Maoz, hep-th/0012025; Lunin, Mathur, hep-th/0202072; Lunin, Maldacena, Maoz hep-th/0212210

Angular momenta: $0 \leq j_L = j_R \leq N_1 N_5$

Singular D1-D5 **Rotating supertube**

Back-reacted geometry





Fiber pinches off at supertube

Topological S^3 bubble.

Near-brane limit $AdS_3 \times S^3$

holographic dual of (1+1) SCFT

Shape modes of supertube

= Shape modes of S^3 bubble

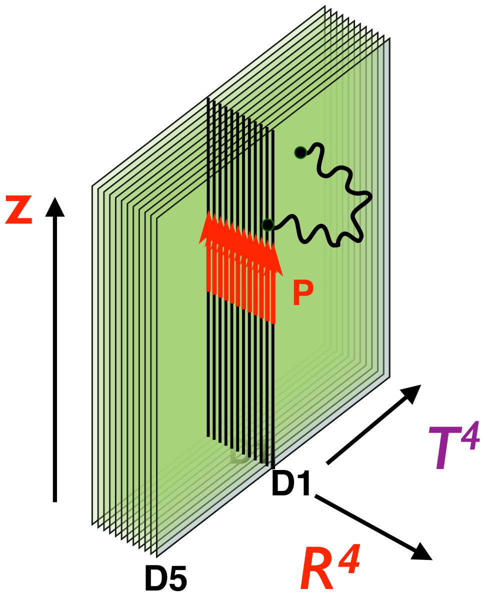
Functions of one variable, F(v)

⇒ One quantum number, j, for modes

The original microstate geometry of Mathur's fuzzball program

Detailed Holographic Dictionary: Lunin and Mathur; Kanitscheider, Skenderis and Taylor

Three charges: ⅛ BPS States in the D1-D5-P System



In the SCFT on common D1-D5 direction:

Fields: $\partial X^{\dot{A}A}_{(r)}(z)$, $\psi^{\alpha\dot{A}}_{(r)}(z)$; ~~$\bar{\partial} X^{\dot{A}A}_{(r)}(\bar{z})$, $\widetilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})$~~

Right-movers: RR vacua/Chiral primaries

Left-movers: Any momentum excitation, $L_0 = N_P$

Count states: Count partitions of N_P in a CFT with

$c = 6\, N_1 N_5$ ⇒ *Black-hole entropy*

$$S = 2\pi \sqrt{\frac{c}{6} L_0} = 2\pi \sqrt{N_1\, N_5\, N_P}$$

Strominger and Vafa: hep-th/9601029

Visible in space-time R^4: Transform under SO(4) R-symmetry $\psi^{\alpha\dot{A}}_{(r)}(z)$

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

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

generate $\frac{(SU(2)_{(1),L})^N}{S_N}$ *= CFT Degrees of freedom directly "visible" in R^4*

"Space-time CFT:" $c = N_1 N_5$ ⇒ $S \sim \sqrt{N_1\, N_5\, N_P}$

Construct holographic duals in space-time …

Superstrata and bubble shapes

Supertube ↔ Ground states of CFT, quantum number $0 \leq j \leq N_1 N_5$

⇔ Holographic dual: Functions of one variable, Modes on S^3 bubble.

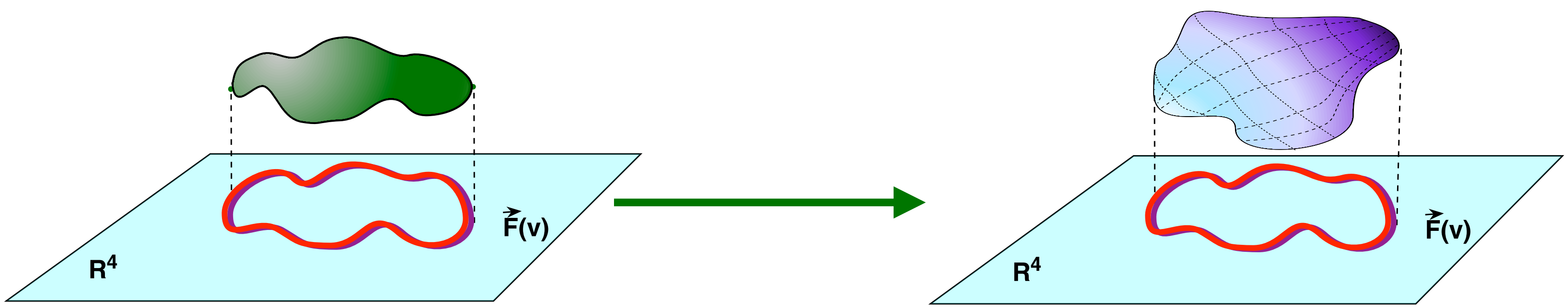
Superstrata are microstate geometries arising from a double supertube transition: Functions of ***two variables*** ⇒ carry *much more entropy*

Bena, de Boer, Shigemori and Warner, 1107.2650

Holographic dual geometry

Take bubbled D1-D5 geometry and add shape modes ***along z fiber***

Bena, Giusto, Mathur, Russo, Shigemori, Warner …



⅛ BPS states: Described by two quantum numbers (**j**,**m**)

j ↔ Right-moving ground state; *shapes in base* $\boldsymbol{R^4}$

m ↔ Left-moving momentum excitations; *shapes along **z** fiber*

Fully back-reacted superstratum constructed!
Holographic dictionary extended to large family of superstrata

Bena, Giusto, Russo, Shigemori and Warner, 1503.01463

Status of BPS Microstate Geometries

- Rigid bubbles (Multiple U(1) symmetries): Define black-hole field theories and IR phases

- Fluctuations of bubbles encode coherent microstate structure

  Arguments to suggest that semi-classical structure can see enough black-hole microstates to obtain correct entropy $S \sim \sqrt{N_1 \, N_5 \, N_P}$

- Detailed progress in constructing holographic duals of "Strominger-Vafa" states

  - Fluctuations and redshifts in *quantized scaling geometries*

    ⇒ $E_{gap} \sim (N_1 N_5)^{-1}$ = Same result as D1-D5 CFT

    ⇒ Microstate geometries accessing typical black-hole microstates

  - Some families of BPS fluctuations as functions of two variables, ***superstrata***, explicitly constructed. Holographic dictionary extended to new families of superstrata fluctuations

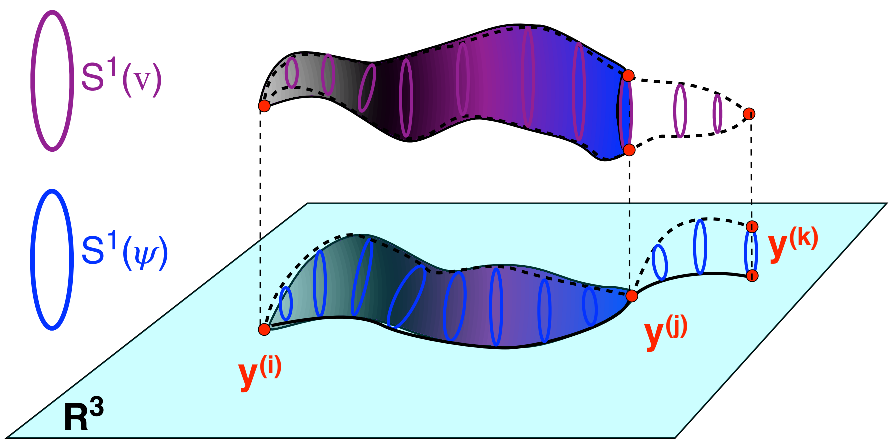
- Open problems for superstrata
  - We need to construct truly generic families of superstrata
  - We need to construct superstrata in scaling geometries
  - Holographic duals of twisted sector states

Giusto, Russo arXiv:1507.00945; Chakrabarty, Turton, Virmani, arXiv:1508.01231; Bena, Martinec, Turton, Warner to appear.;

New ideas:
W-Branes and Supergravity Hypermultiplets

W-branes

Niehoff and Martinec: arXiv:1509.00044



W-branes = branes wrapped around non-trivial cycles.

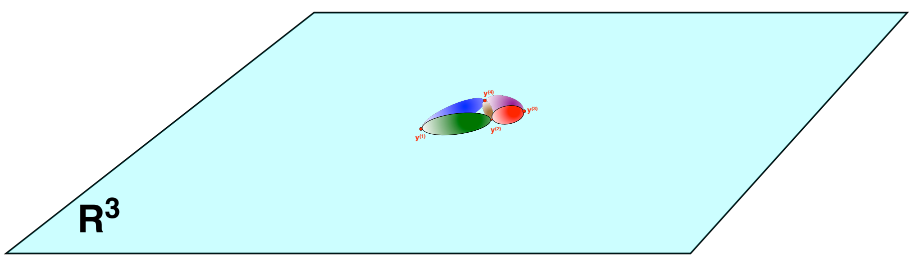
D-p brane wrap p-cycles can yield new BPS states of the system

These solitonic branes look like particles in remaining dimensions

Heterotic-type II Duality: Such brane-wrapping is how "W-bosons" of heterotic string are realized in the type II string … ***very interesting massless limits***

Base geometry

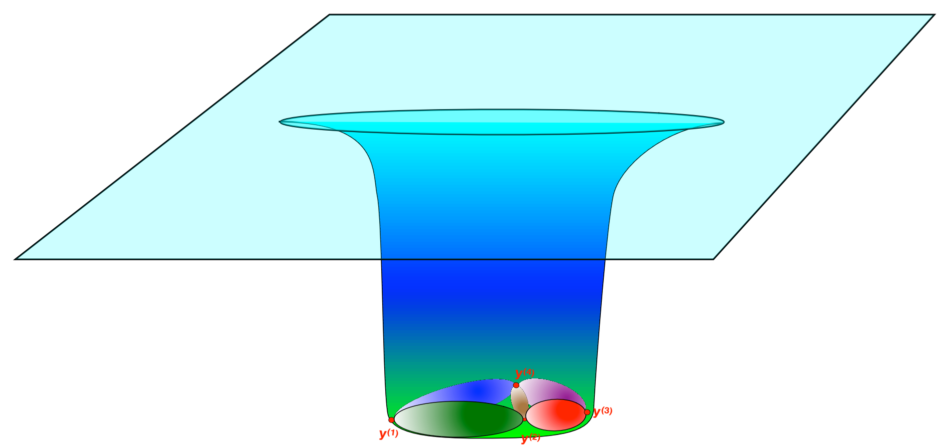
Cycles shrink to zero size



Which geometry governs the masses of these W-brane states?

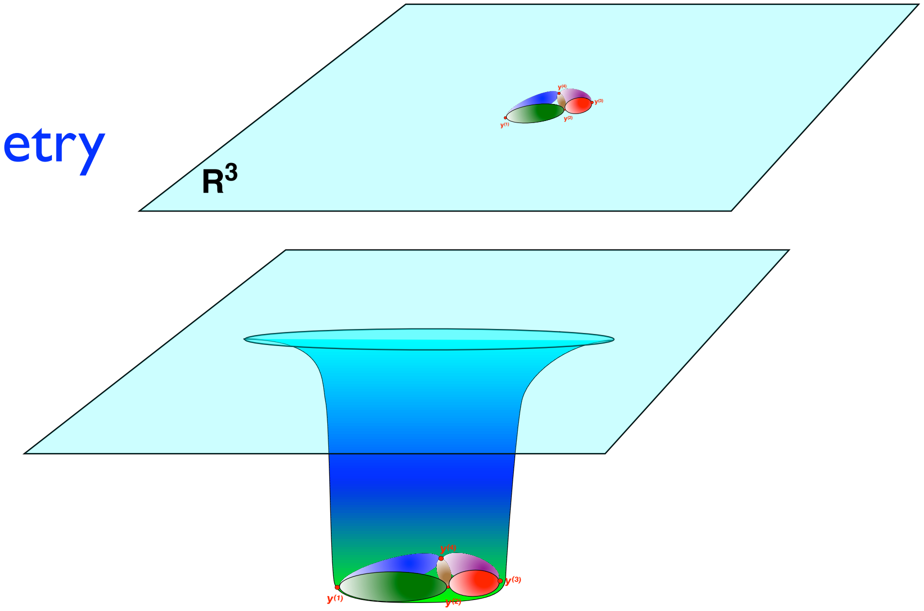
Complete space-time geometry

Cycles retain finite size but descend AdS throat



Massless W-branes

DBI action:
Mass of W-brane states ~ Scale in base geometry



~ Scale in full geometry
× (Red Shift from scaling BPS throat)

⇒ *Deep scaling geometries* have new classes of low mass/massless states

How many such states?

Naive count: One per cycle. A brane can wrap each non-trivial cycle

Actual count: Vastly larger number.

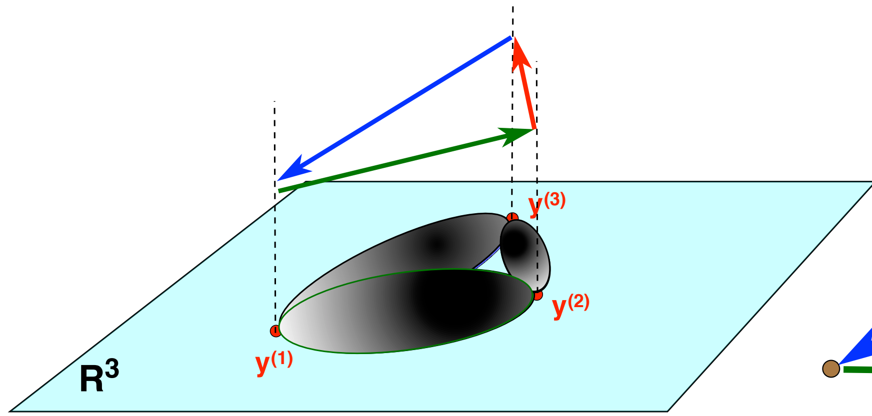
Crucial insight: Solitonic W-branes look like particles on the T^4 but this T^4 is threaded by magnetic fluxes and so each W-brane wrapping cycles in the space-time actually occupies *distinct Landau levels* on the T^4.

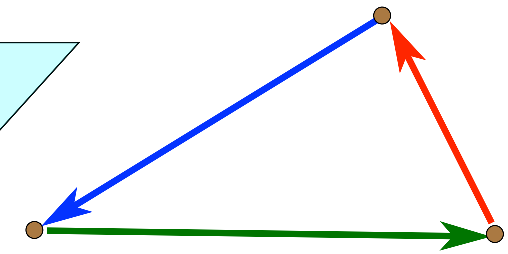
Niehoff and Martinec: arXiv:1509.00044

Three-node quiver

Naive count:

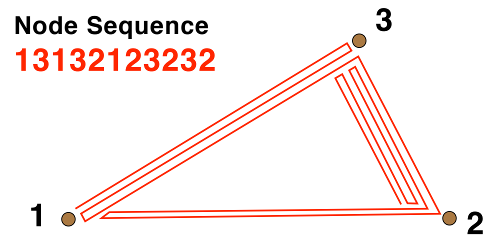
Three distinct W-branes

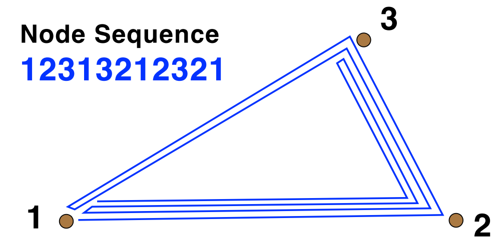




Actual count: Brane wrappings are distinguished by Landau levels

W-branes ⇔
Walks on the three node quiver





Every distinct node sequence = Independent W-brane

Number of such W-branes ⇔ Number of 3-derangements

3-derangements count Higgs Branch states in quiver quantum mechanics

Bena, Berkooz, de Boer, El-Showk, Van den Bleeken: arXiv:1205.5023

Niehoff and Martinec: arXiv:1509.00044

Distinct W-branes ⇔ Higgs branch states of quiver quantum mechanics

This gives a semi-classical, solitonic description of the Higgs branch states

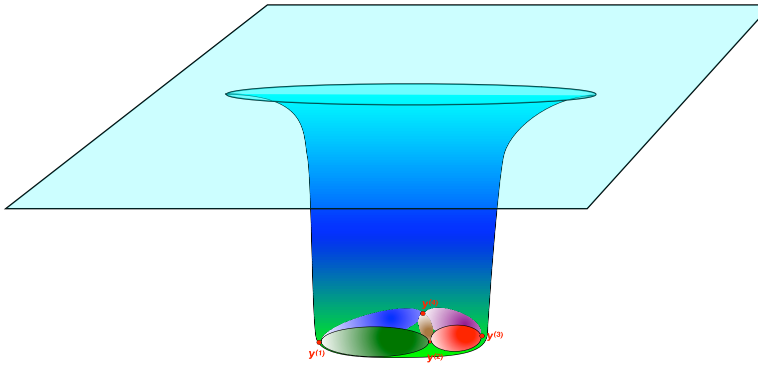
The numbers of such states have the right growth with total charge to get the correct parametric entropy growth of the black hole …

W-branes in Supergravity

Large numbers of W-branes wrapping cycles in space-time geometry

$\Rightarrow$ *Supergravity back-reaction*

The story before W-branes



Geometry and fluxes of the geometric transition

IIB on T^4: Six-dimensional supergravity
+ tensor multiplets

W-branes source hypermultiplet scalars

To find the corresponding BPS solutions one must generalize all the work of the last decade classifying the BPS solutions to supergravity + vector/tensor multiplets so as to include hypermultiplets …

Raeymaekers, Van den Bleeken, arXiv:1407.5330, 1510.00583.pdf

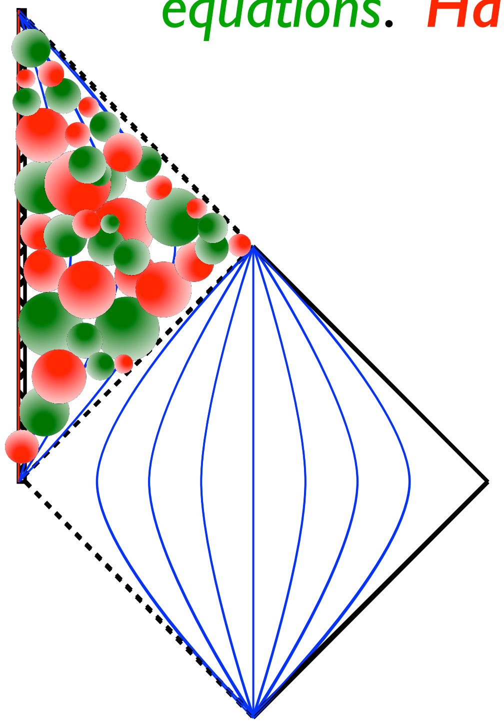
Analsysis just begun … far from simple!

Going Beyond BPS

Non-BPS extremal; Near BPS and Far from BPS

Extremal, Non-BPS Microstate Geometries

Problem: Now have to cope with full, *second order, non-linear Einstein equations*. ***Hard!*** *Particularly for solutions involving more than one variable*



Large body of work on "almost-BPS" solutions in which one makes solutions out of supersymmetric elements that "disagree" about the supersymmetry.

Goldstein and Katmadas, arXiv:0812.4183

Bena, Giusto, Ruef and Warner,
arXiv:0908.2121, arXiv:0909.2559 , arXiv:0910.1860

Bena, Dall'Agata, Giusto, Ruef and Warner, arXiv:0902.4526

Bossard, Ruef arXiv:1106.5806

Bossard, Katmadas 1405.4325, 1412.5217

This simple trick generates a substantial fraction of the known extremal, non-BPS solutions and a very large number of new, far more general solutions ......

Results suggest that the BPS story should extend at least to almost BPS solutions … but technically far more difficult

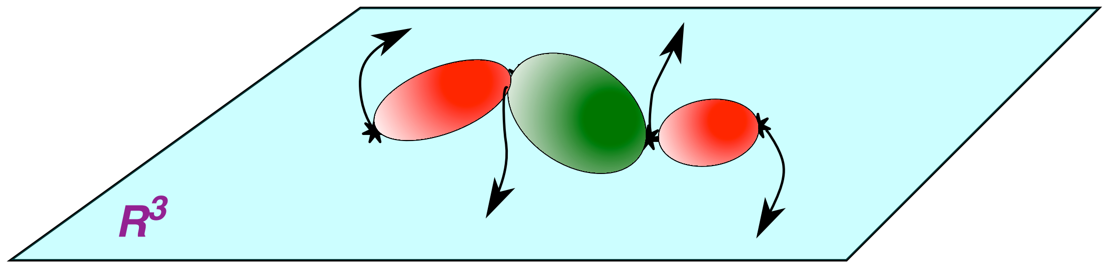
Near-BPS Microstate Geometries

Bubbled geometries are "topologically robust" and stable to perturbation …

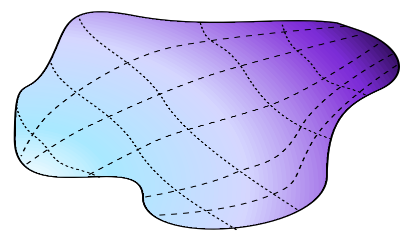
Motion on Moduli Spaces

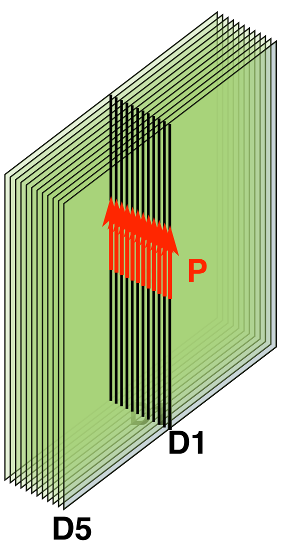
Size of bubbles ~ fixed by (quantized) fluxes

Intersection points can move on moduli space



Non-BPS shape fluctuations





D1-D5-P:

Allow excitations of ***all fields***

$$\partial X^{\dot{A}A}_{(r)}(z)\,,\ \psi^{\alpha\dot{A}}_{(r)}(z)\ ;\quad \bar{\partial} X^{\dot{A}A}_{(r)}(\bar{z})\,,\ \widetilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})$$

Left-movers only: ⅛ BPS

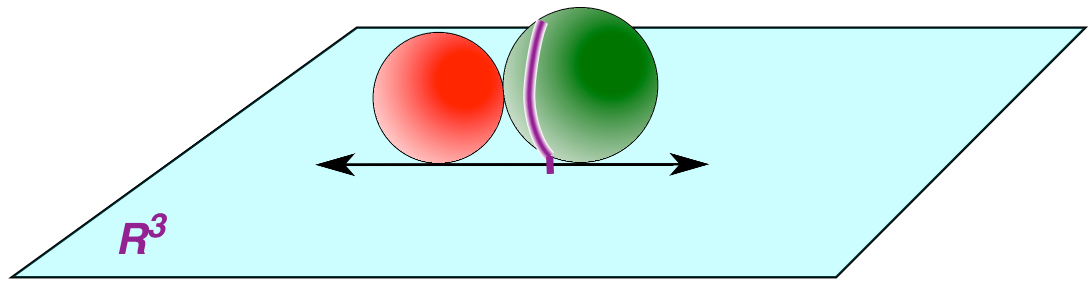
Perturbative addition of right-movers: Non-extremal

Near-BPS Microstate Geometries: Add (probe) anti-Branes

Find stable and metastable locations for *probe anti-supertubes* in BPS bubbled background

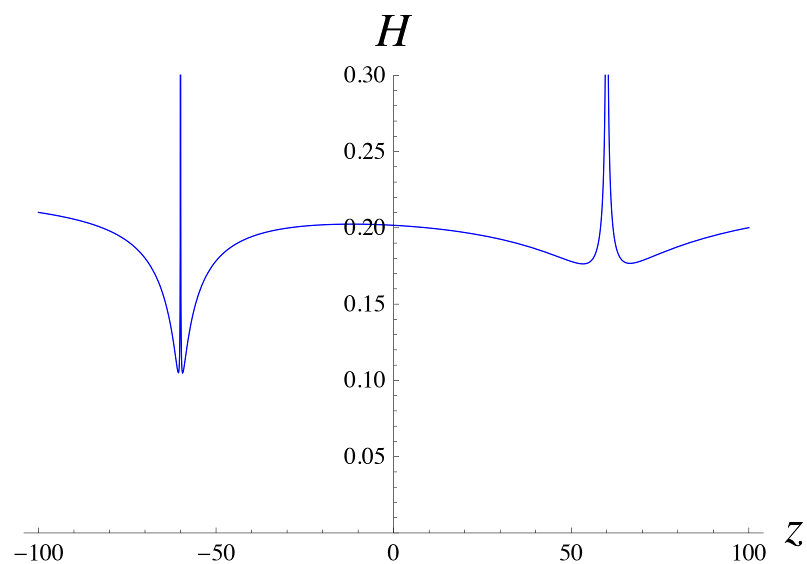
Construct non-extremal bubbled black holes using metastable branes

Bena, Puhm and Vercnocke, 1109.5180, 1208.3468



In six-dimensions the *anti-supertube* becomes and S3 bubble threaded by anti-brane flux.

de Lange, Mayerson, Vercnocke, 1504.07987



From Bena, Puhm and Vercnocke, 1109.5180

✦ First example of classes of non-extremal configurations supported by flux and anti-flux bubbles

Apparently stable states actually unstable to other decay directions.

Bena and Pasini, arXiv:1511.01895

✦ Decay generates Hawking radiation?

Far from Extremality

0) The "JMaRT" Solution

Jejjala, Madden, Ross, Titchener, 0504181

A microstate geometry for a non-extremal "overspinning" black hole.

Two-centered/single bubble solution

Has an "ergo-region instability"

Cardoso, Dias, Hovdebo, Myers, 0512277
Cardoso, Dias, Myers, 0707.3406

⇒ Apparently very rapid decay but consistent with Hawking radiation from very special state within dual CFT

Chowdhury and Mathur, 0711.4817

Very far from being a typical state within black-hole microstate structure

1) Generalizing the "JMaRT" Solution

Multi-centered/multi-bubble solutions non-extremal microstate geometries

Bossard, Katmadas, 1412.5217; Bena, Bossard, Katmadas, Turton, arXiv:1511.03669

Probably lead to microstates for overspinning black holes …

Far from typical black-hole microstate geometries

Huge Open Problem: *Construct examples of non-BPS microstate geometries that correspond to the typical sector of the black-hole and have generic Hawking radiation.*

2) Inverse scattering methods

Generic charged black-object geometries in D-dimensions with $U(1)^{D-2}$ symmetry: *Effective two-dimensional problem*. Inverse scattering methods *etc.* have led to many black-Saturn solutions

Generalize this to non-supersymmetric microstate geometries?

Virmani, arXiv:1409.6471

3) Numerical Methods

Simplest, interesting bubbled geometries have multiple centers and are co-dimension 2 …

- ✦ Numerical solutions for co-dimension 2 multi-black-holes
- ✦ Generalize to non-supersymmetric microstate geometries?
- ✦ Extend to non-supersymmetric microstate geometries in **AdS_5**?

Speculative Ideas

The Invisible Quantum Elephant of Black-Hole Physics

Curvature at horizon: $R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}|_{horizon} = \frac{3}{16}\frac{G^2}{M^4}$ $\Rightarrow$ *Large black hole is classical at horizon scale*

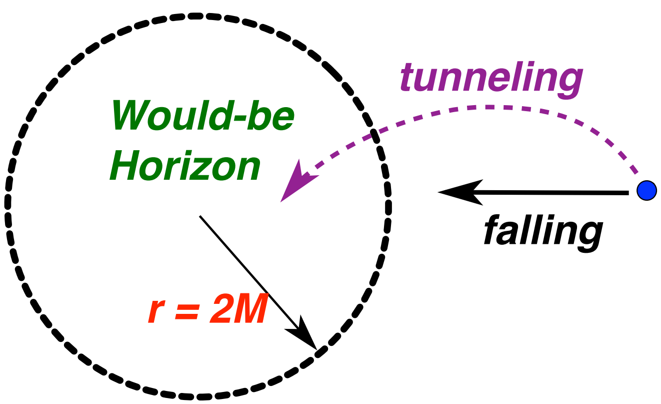
Fermi Golden Rule: $\mathcal{T}_{i\to f} = \frac{2\pi}{\hbar} <\psi_f|\mathcal{H}_{int}|\psi_i>|^2 \rho$ ← *density of states*

Number of states in the black hole in the middle of Milky Way: $e^{10^{90}}$

It is the extreme density of states that makes an apparently classical black hole behave as a quantum object

Consider a particle falling into a black hole ...

Mathur: 0805.3716; 0905.4483 Mathur and Turton: 1306.5488



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 $\sim e^{+16\pi M^2/m_P^2}$

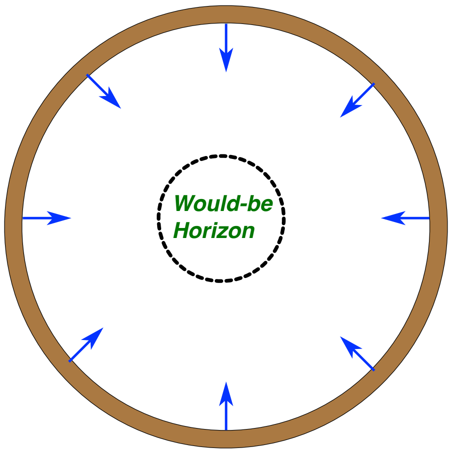
Probability of tunneling during infall time ~ *O(1)!*

Black hole formation is intrinsically a quantum tunneling transition!

Collapse to a Black Hole

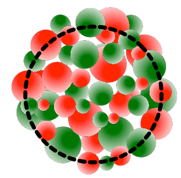
Mathur: 0805.3716; 0905.4483
Mathur and Turton: 1306.5488

A shell of spherically symmetric matter collapses ...



Tunneling!

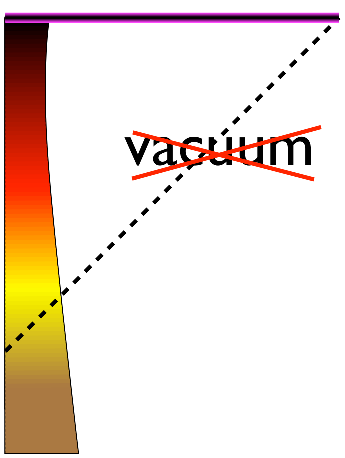
Microstate
Geometry



How can this happen?

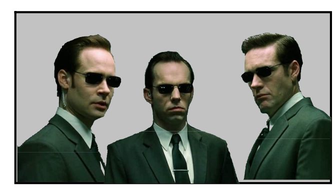
A quantum phase transition

Old Black Holes



Vast density of quantum states

Final Stage of Infall
= Tunneling



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?

Microstate Geometries are the semi-classical limit of these quantum effects: The gravitational expression of coherent sets of black-hole quantum states …

Supergravity 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

- Solving the information problem requires *O(1)* changes to the physics at the horizon scale
- Large scale resolutions must be based on microstate geometries with non-trivial topology and fluxes   Holography: Phase structure and fluctuations
- New scales in black-hole physics: Transition scale, λ_T, and maximum red-shift, z_{max}; related to E_{gap} of fluctuation spectrum
- BPS solutions: Vast families of explicit examples
  - ★ *Holographic E_{gap} matches SCFT E_{gap}*
  - ★ *Holographic dictionary for geometric fluctuations and CFT states is becoming well-developed*
  - ★ *Semi-classical description of entropy with* $S \sim \sqrt{N_1 N_5 N_P}$ *is within reach*
  - ★ *Holographic duals of "Strominger-Vafa" states under construction*
- New BPS configurations and geometries:

  W-branes, Higgs branches and hypermultiples
- Near BPS: Useful for Gedanken experiments, several new explicit examples..
- Far from BPS: Lots of really interesting conceptual and computational ideas!

Final questions

- ★ *BPS: To what degree does the superstratum access black-hole microstates?*
- ★ *BPS: Can we construct a superstratum in a deep, scaling geometry?*
- ★ *BPS: How are twisted sectors encoded in supergravity?*
  How are twisted sectors related to scaling solutions?
- ★ *BPS: Can we access W-branes from supergravity?*
  Can we classify BPS supergravity solutions with hypermultiplets?
- ★ *BPS: What determines the the phase of the black-hole field theory?*
- ★ *BPS: What determines the transition scale/typical bubble size,* λ_T *?*

- ★ *How do we extend all of these ideas to non-extremal objects?*

- ★ ***To what extent are black holes quantum objects at the horizon scale?***