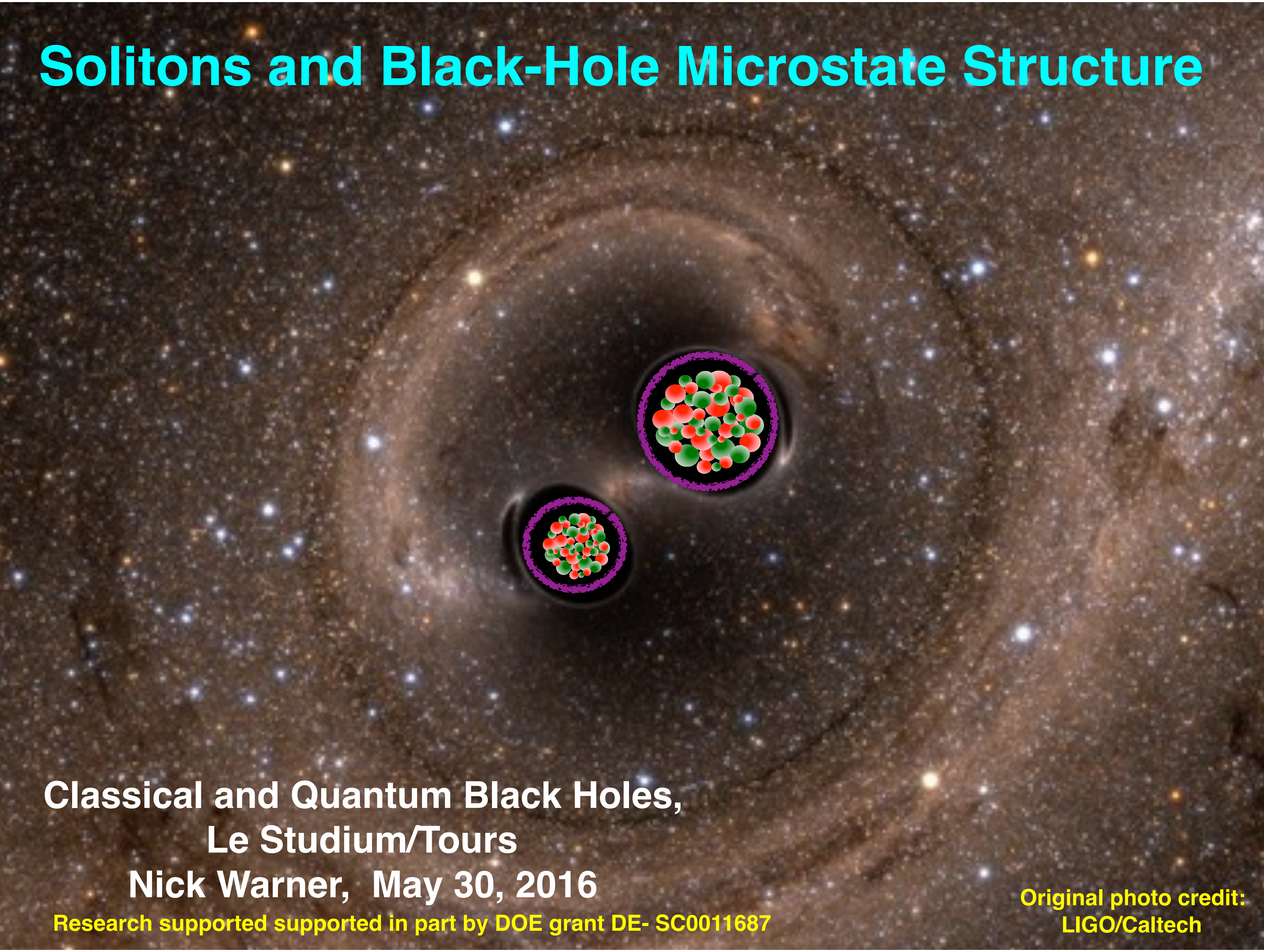
Solitons and Black-Hole Microstate Structure
Classical and Quantum Black Holes,
Le Studium/Tours
Nick Warner, May 30, 2016
Research supported supported in part by DOE grant DE- SC0011687
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LIGO/Caltech

Outline

- Motivation and Challenges
- Microstate Geometries:

  The only mechanism to avoid horizons
- Microstate Geometries as Holographic Phases
  - ★ *New scales for Black Hole Physics*
- Building BPS Microstate Geometries
  - ★ *Scaling Microstate geometries*
- Holography and Fluctuating Microstate Geometries
- Microstate Geometries as Backgrounds for New Physics
  - ★ *W-branes*
  - ★ *Tunneling*

Motivation for Microstate Geometries I

General Relativity + Quantum mechanics ⇒

Non-unitary evolution arising from Hawking evaporation of black holes

An old conceit: Black hole evaporation time- scales are incredibly long:

Fix with small corrections to GR?

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

New urgency

Mathur (2009): *Using strong subadditivity of quantum information*

⇒ **There must be *O(1)* corrections to the Hawking states at the horizon**

Microstate geometries/Fuzzballs

Find new structures and mechanisms *in string theory* that can address this issue by *avoiding the formation of horizons*

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

The Challenges for Horizon-Scale Structure

Old Story I: Black-Hole Uniqueness (1960-1980's)

In General Relativity coupled to electromagnetism in 3+1 dimensions:
Black holes are almost completely featureless

$\Rightarrow$ Microstate structure is invisible from outside the black hole

Once a black hole forms, matter (including a naive *firewall*) is swept away from horizon region in the light-crossing time of black hole …

Old Story II: Solitons in GR

GR non-linearities:

Could there be interesting ***solitons*** = Smooth, classical lumps

What could these represent in Nature?

Macroscopic/large scale, smooth, end-states for stars:

⋆ *Time independent* ⋆ *Massless fields*

In General Relativity coupled to massless fields:

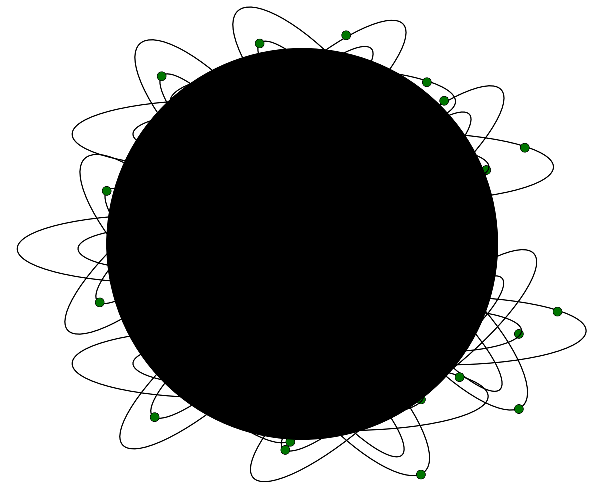
Time-independent solutions with time-independent matter necessarily have horizons $\Rightarrow$ *They must have singularities*

"No solitons without horizons"

Old Story III: The Fate of Weak-Coupling Resolutions

Set $G_{Newton} = 0$ and understand the microstate structure of material that will form a black hole at finite G_{Newton} …

e.g. String theory:* *Strominger and Vafa: hep-th/9601029



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

★ Matter/microstate structures ***shrink***

★ Horizon areas *grow*: $R_S = \dfrac{2\,G_{Newton}\,M}{c^2}$

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 Many Faces of the Same Underlying Problem

Black holes

Uniqueness theorems ⇔ All matter swept from horizon region

Massive Matter: Consequences of Tolman-Oppenmeir-Volkov equation

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

- ⋆ *Speed of sound > Speed of light*
- ⋆ *Buchdahl's Theorem: Central pressure/density infinite unless $R_{matter} > 9/4\, M$*

Weak/vanishing coupling resolutions

Will not survive at strong coupling:

Configurations of massive fields shrink as G_{Newton} (or g_s) increases

Massless fields

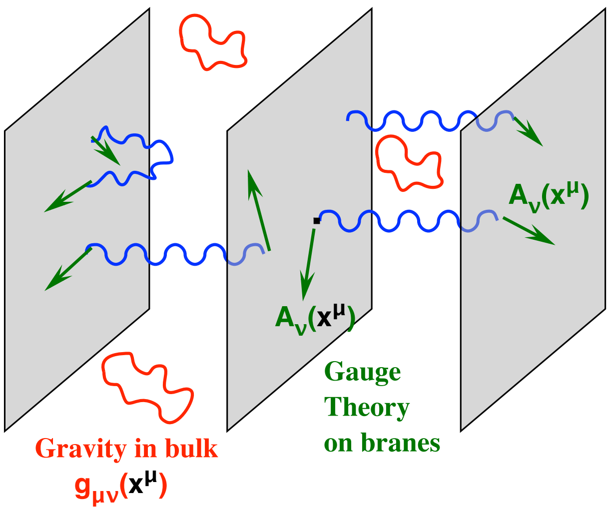
Appears hopeless: Massless fields travel at the speed of light

... only a "dark star" or black hole can hold such things into a star.

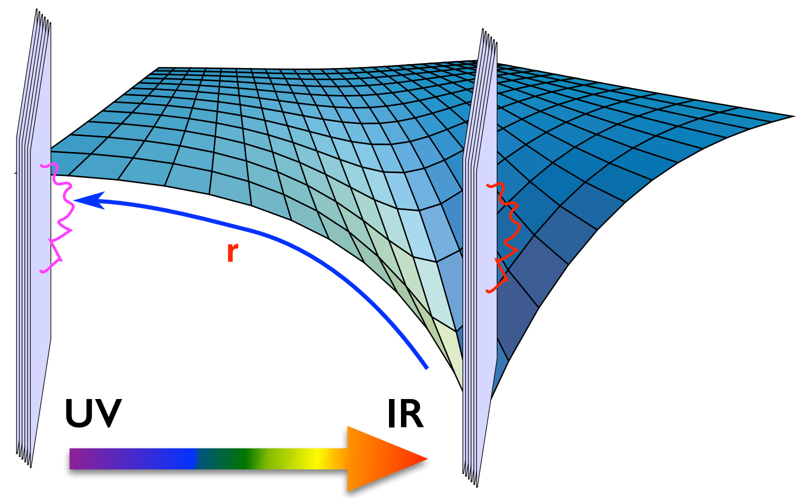
"No solitons without horizons"

Old Story IV: The Holographic Meta-Argument (~2000)

N=4 Yang-Mills on *D3 branes* is dual to String Theory in *$AdS_5 \times S^5$*



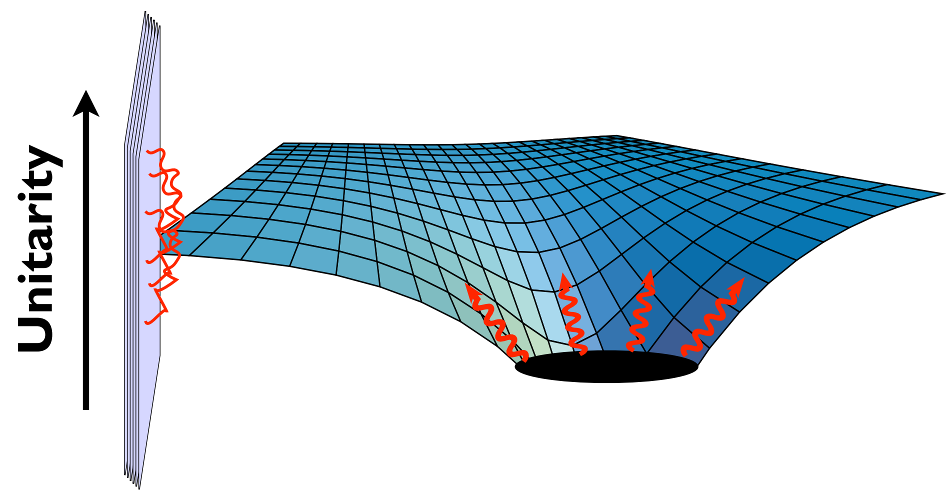
Gravitational back-reaction



N=4 Yang-Mills is a unitary quantum field theory

⇒ Quantum gravity must be unitary within String Theory

In particular, string theory, via holography, must provide a unitary description of black-hole evaporation in asymptotically AdS spaces ..



Motivation for Microstate Geometries II

How does all this work in practice at strong coupling?

- What are the ***strong coupling phases of matter*** underlying stringy black-hole physics?
- How do you describe these phases holographically?
- What are the states underlying stringy black-hole physics?
- How do you see the microstates holographically?
- How does this relate to microstate descriptions at vanishing string coupling, for example, Strominger/Vafa?

What are the holographic duals of the Strominger-Vafa microstates?

- How do you count the microstates at strong coupling?

The study of Microstate Geometries is a systematic program that addresses these issues… at non-vanishing string coupling

The Microstate Geometry Program:

Find mechanisms and structures that resolve singularities and prevent the formation of horizons in Supergravity

Finite G_{Newton} (or g_s): Stringy resolution at/grow with horizon scale
$\Rightarrow$ *Very long-range effects* $\Rightarrow$ *Massless* limit of string theory: ***Supergravity***

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

How to evade: "No solitons without horizons theorems?"

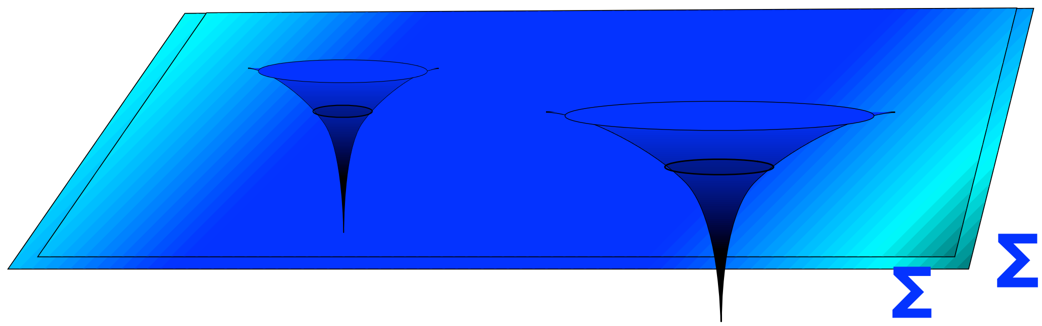
Solitons and Topology

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

$$T_{00} \equiv K^\mu K^\nu T_{\mu\nu}$$



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

$$\Rightarrow \int_\Sigma T_{00}\, d\Sigma \sim \int_\Sigma d\,[F \wedge B] \qquad \text{where} \qquad i_K(*F - F\wedge A) = dB$$

In general: **T_{00} = total derivative in Σ** ⇒ **M ≡ 0**

⇒ *If asymptotic to $R^{D-1,1}$, then space-time must be globally flat,* ***$R^{D-1,1}$***

<u>***The Error***</u>: *This argument neglects topology*

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

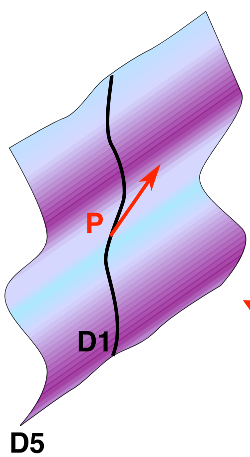
Correct calculation $\Rightarrow$

Gibbons and NPW

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

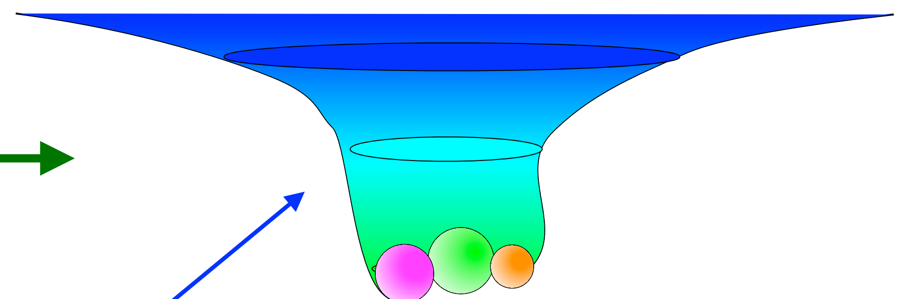
Correct conclusion: ***No solitons without topology***

Potentially singular brane sources



Geometric Transition

Microstate geometries supported by cohomological fluxes



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

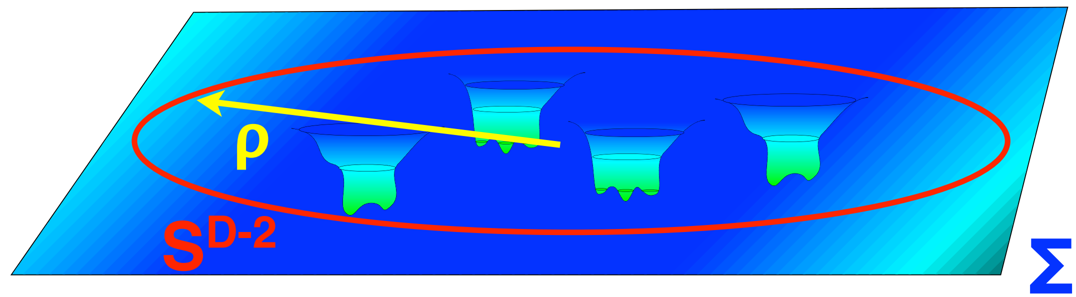
A phase transition driven by the Chern-Simons interaction

Subtleties in boundary conditions: *Yet more solitons …*

$$K^\mu \frac{\partial}{\partial x^\mu} = \frac{\partial}{\partial t} \;\longrightarrow\; T_{00} \equiv K^\mu K^\nu T_{\mu\nu} \;\longrightarrow\; M = \int_\Sigma T_{00}\, d\Sigma$$

This is just the *Komar* mass:

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



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

Subtlety: *If space-time is asymptotically* Minkowskian *then Komar mass and ADM mass are the same* and M ≡ 0 ⇒ *Entire space-time be globally flat,* $\mathbf{R}^{D-1,1}$

If space-time is asymptotic to $R^{d-1,1} \times (S^1)^n$ *then Komar mass* ≠ *ADM mass*

$M_{Komar} \equiv 0 \not\Rightarrow$ *space-time is globally* $R^{d-1,1} \times (S^1)^n$

Example: Euclidean Schwarzschild bolt + time

$$ds^2_{4,1} = -dt^2 + \left(1-\tfrac{2m}{r}\right)d\tau^2 + \left(1-\tfrac{2m}{r}\right)^{-1}dr^2 + r^2\, d\Omega_2^2$$

Asymptotic to, but not globally, $R^{3,1} \times S^1$ $M_{Komar} = 0$ but $M_{ADM} = m$

More solitons: Classify solitons asymptotic to $R^{d-1,1} \times (S^1)^n$ or $AdS^{d-1,1} \times S^n$?

Conclusions

1) ***Solitons CAN be supported by cohomological magnetic fluxes***

2) ***This is the only way to support solitons/microstate geometries***
for asymptotically Minkowskian geometries

Correct mantra: "No solitons without topology"

Is this also true for space-times asymptotic to $\mathbb{R}^{d-1,1} \times (S^1)^n$?

Geometric transitions to Microstate Geometries provide the

only possible

Supergravity mechanism that can support horizon-scale structure!

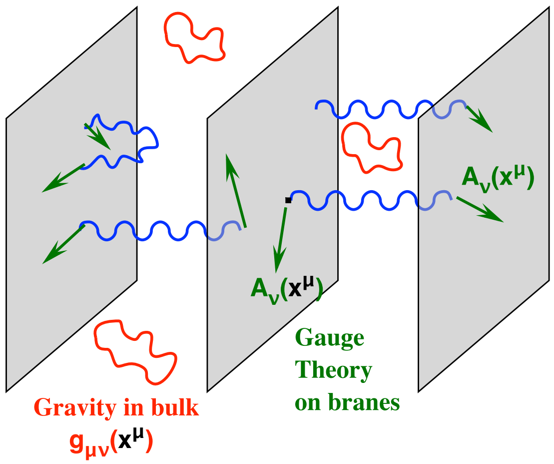
What is the holographic interpretation of this result?

Some General Principles of Holographic Field Theory

- Radial behavior in gravity ↔ RG flows in the holographic field theory
- Normalizable fluxes in gravity ↔ States in the holographic field theory
- Core of the gravity solution ↔ Deep Infra-red Limit of Field Theory
  - Asymptotically AdS backgrounds ↔ Conformal Fixed Points
  - Scales of gravitational core structures ↔ IR scales of field theory
  - Fluxes in the gravitational core structures ↔ Order parameters of the infra-red physics
- Families of phase transitions represented by *brane sources, as seen from infinity/UV,* replaced by *smooth cohomological fluxes in the IR*
  - Many important examples
    Gopakumar-Vafa; Dijkgraaf-Vafa; Lin-Lunin-Maldacena; Klebanov-Strassler
- Physically meaningful IR limits for holography:
  - Smooth supergravity solutions
  - Singular sources that can be identified in terms of branes
  - Stringy excitations around supergravity/brane backgrounds

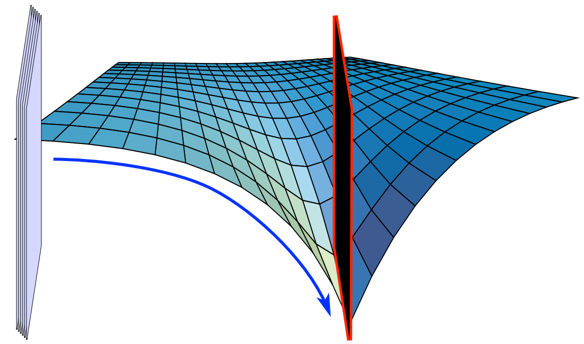
The holographic dual of a flow to a confining gauge theory

N* = 2** or ***4 Yang-Mills *SCFT* on *D3 branes*



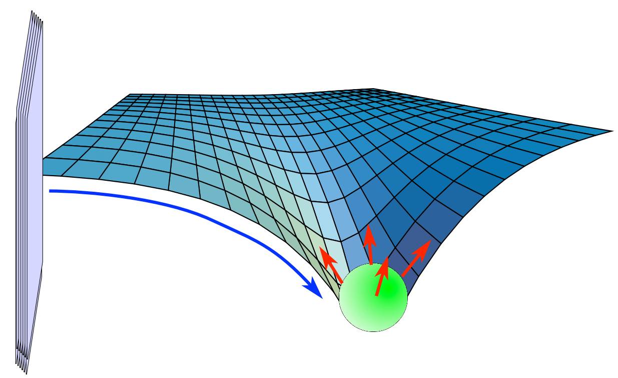
mass perturbation

Klebanov-Tseytlin: Singular flow



***N* = 1** Confining Gauge Theory

Klebanov-Strassler: Smooth limit

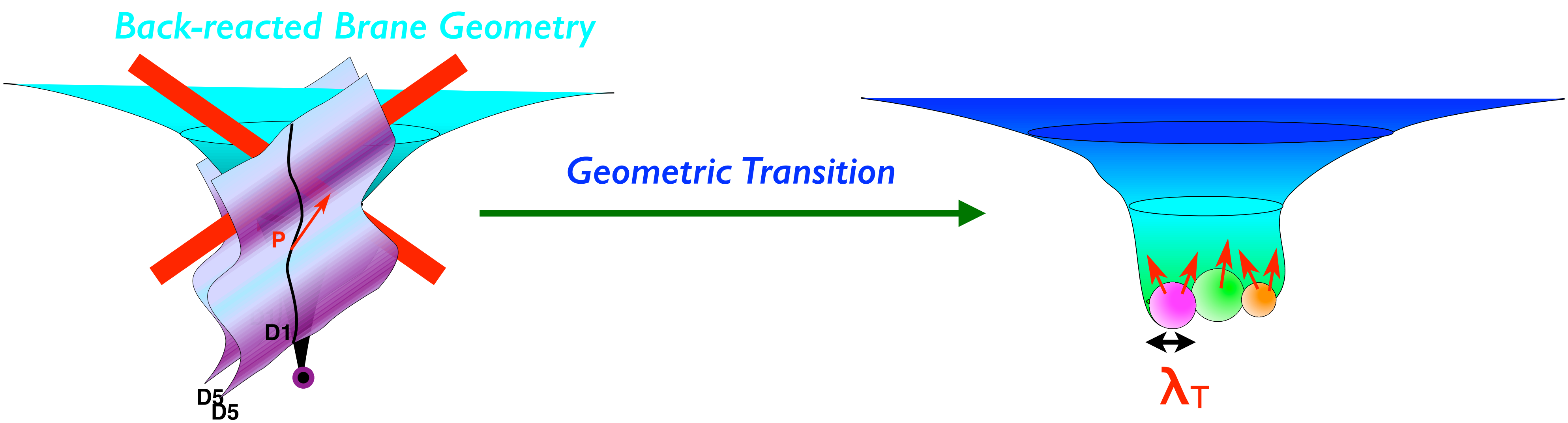


Correct holographic description

- ★ IR geometry: Branes undergo phase transition to "bubbled geometry"
- ★ Singular IR Geometry: wrong physics/ wrong IR phase of the gauge theory
- ★ Confining phase of field theory ⇔ Fluxed IR geometry:
  Fluxes dual to gaugino condensates = order parameter of confining phase
- ★ Scale of the bubble ~ λ_{SQCD}

Apply exactly the same holographic principles to black holes …

Microstate Geometries represent new phases of black-hole physics:



Wrong IR Phase **Correct IR Phase**

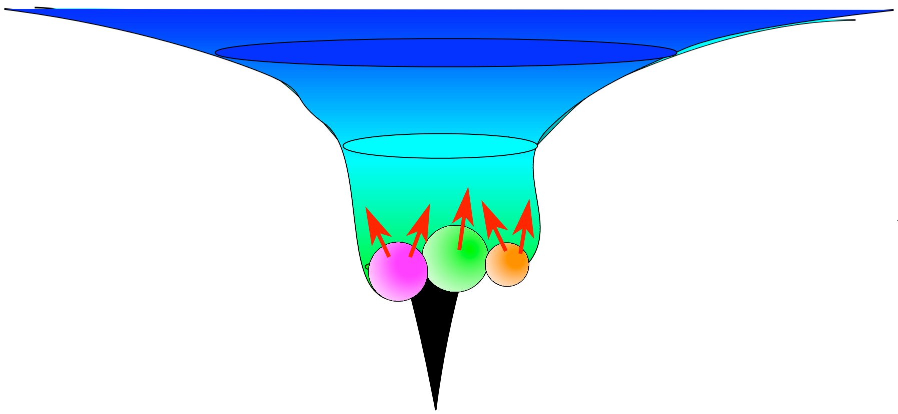
Features of the new phase

★ Size, λ_T, of a typical cycle ↔ Scale of phase transition

★ Fluxes through cycles ↔ Order parameters of new phase

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

Traditional black-hole physics misses all the rich complexity of truly stringy black holes … with new emergent phases of matter



★ Size of black hole: $$R = \frac{2\,G\,M}{c^2}$$

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

Stringy Black Holes

New physics, new phases, new order parameters and two new scales (at least)

★ Scale of a typical cycle, λ_T

★ "Depth" of the "throat," z_{max}

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

No solitons without topology ↔ Only these phases of stringy matter can give structure at the horizon scale

<u>Two distinct and independent ideas from *microstate geometries*</u>

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 describe a phases of the black-hole physics*

2) Microstates: Fluctuations/Configurations in these phases

- Supergravity 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)**

- *Holography: Understand the Microstates that are being captured*

Note: Discussion so far is general … not just BPS/supersymmetric

BPS Microstate Geometries

Phase structure and the supergravity mechanism

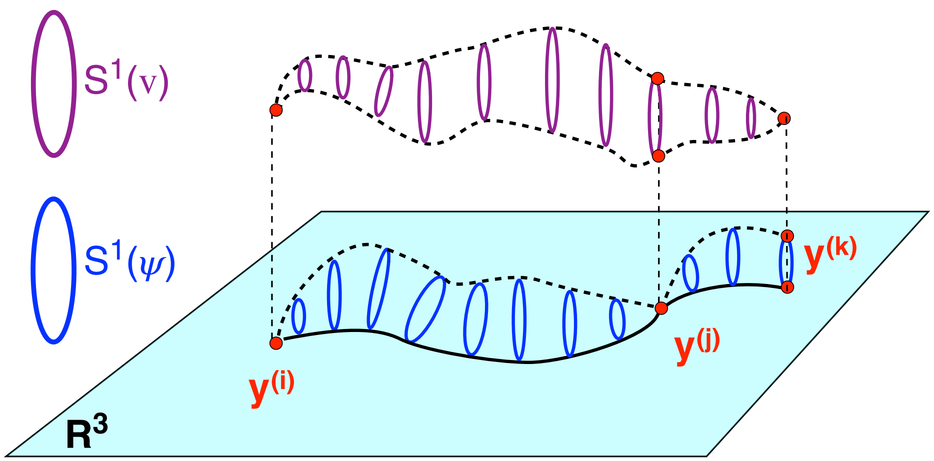
Building *BPS* Microstate Geometries

IIB Supergravity on T^4: Supergravity in six-dimensions + BPS $\Rightarrow$ Six dimensional metric ansatz:

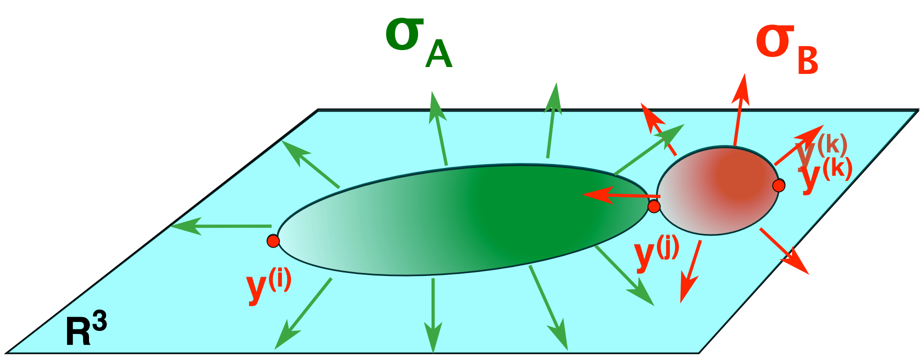
Gutowski, Martelli and Reall

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

u = null time; (v, ψ) define a double *S¹* fibration over a flat *R³* base with coordinates, y.



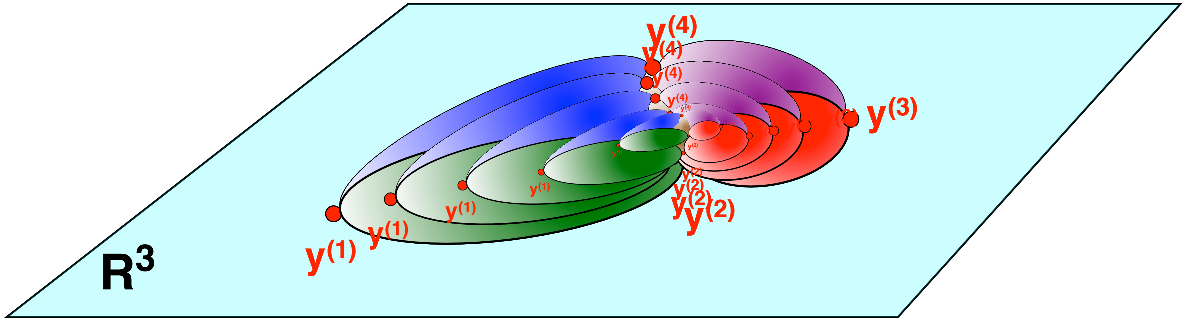
The non-trivial homology cycles are defined through the pinching off of the *S¹* × *S¹* fibration at special points in the *R³* base.



Cycles support non-trivial cohomological fluxes …

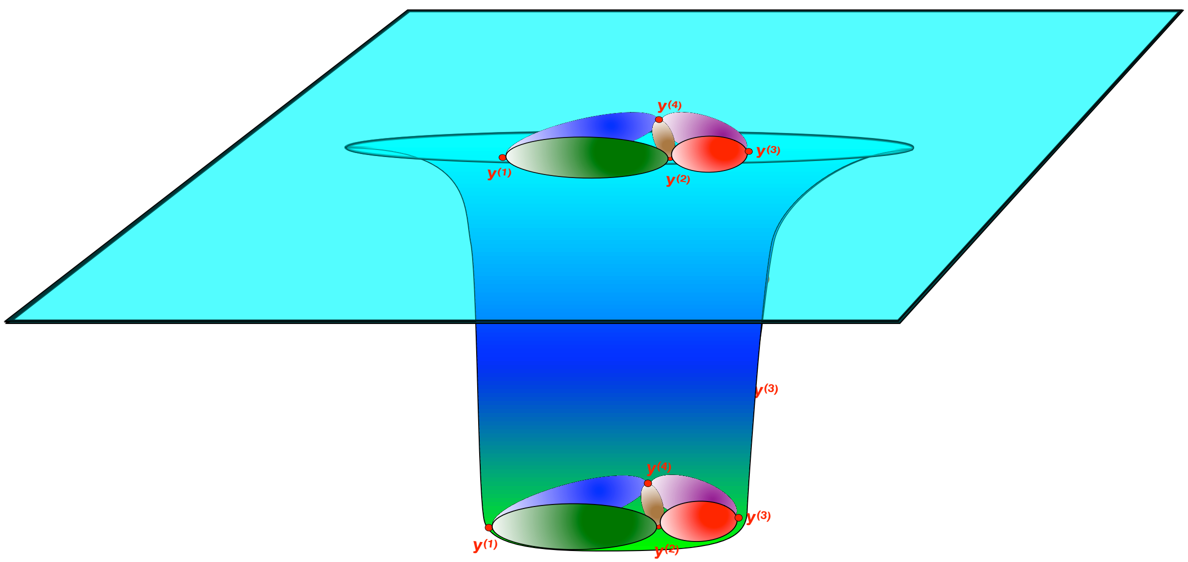
The scale of everything is set by the "warp factors:" *V*, *P* and *Z₃*

Scaling solutions



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

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

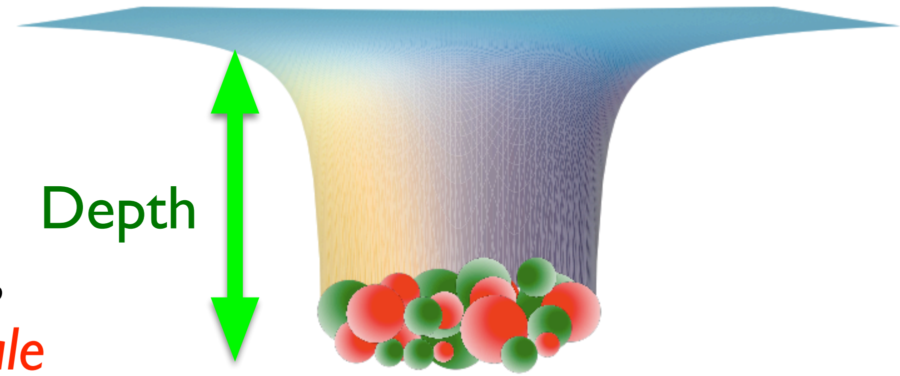
End result: Looks almost exactly like a BPS black hole to as close to the horizon as one likes … but then it caps off in a smooth microstate geometry.

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

- ★ Six-Dimensional Microsite Geometries ↔ D1-D5 CFT

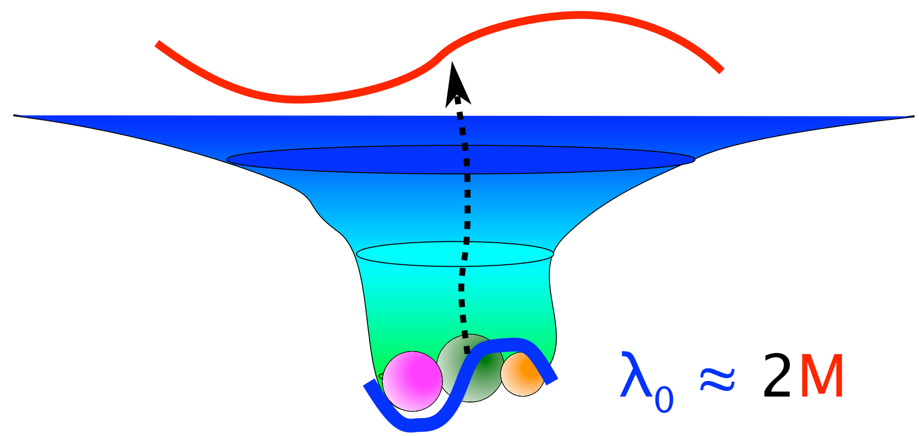
  Goal: construct precise map:

  Bubbled geometry ⟷ *Phase of CFT*

  Geometric fluctuations ⟷ *Coherent combinations of microstates*

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:

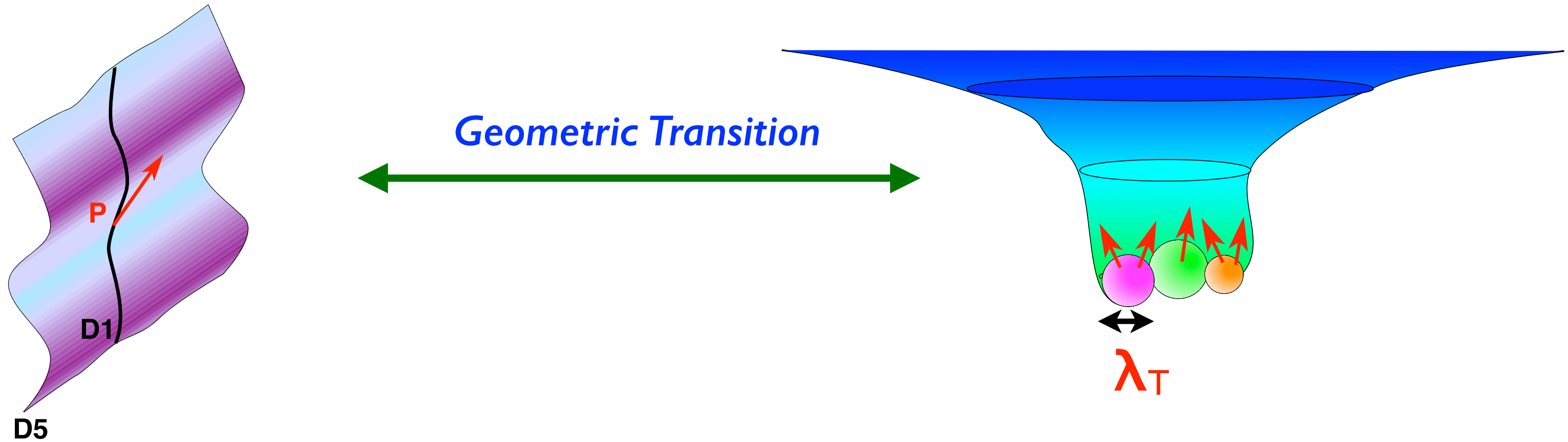
- ★ The throat depth, or z_{max} , is ***not*** a free parameter
- ★ E_{gap} is determined by the flux structure of the geometry
- ★ E_{gap} Longest possible scaling throat: $E_{gap} \sim (C_{cft})^{-1}$

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 ***phases***/representatives of states in the "*typical sector*" that provides the dominant contribution to the entropy ...

Complete realization of geometric transition to new phases



Supergravity balance: *Gravitational attraction in bubbles* $\longleftrightarrow$ *Flux expansion force*

$\Rightarrow$ *Transition Scale,* λ_T ~ Magnitude of fluxes

Field theory: *Scale of new phase* ~ vevs of order parameters

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

Field theory: *Phase structure and order-parameter vevs are freely choosable*

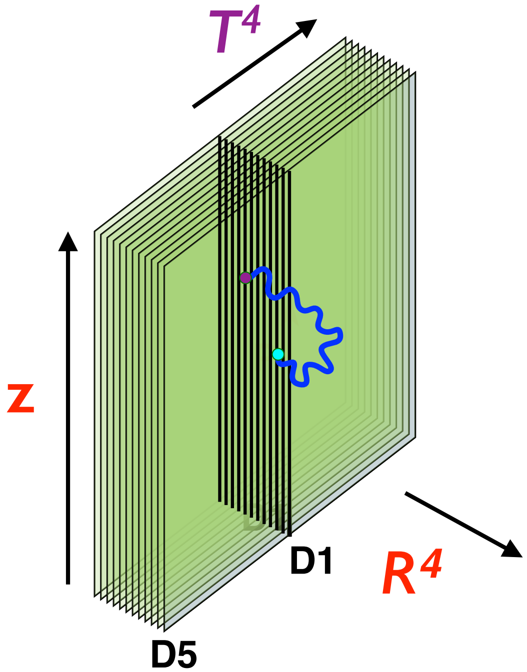
Open issues:

- **Are the phases selected by dynamics/phase space volume?**
- **What sets λ_T? Is large λ_T be entropically favored?**

BPS Microstate Geometries

Semi-Classical Microstate structure

The D1-D5 System: ¼ BPS = 8 supersymmetries



IIB Superstring on $T^4 \times S^1(z) \times R^{4,1}$

- ★ N_5 D5 branes wrap a $T^4 \times S^1(z)$
- ★ N_1 D1 branes wrap $S^1(z)$
- ★ (1+1)-dimensional CFT on $S^1(z)$ from open strings stretched between D1's and D5's

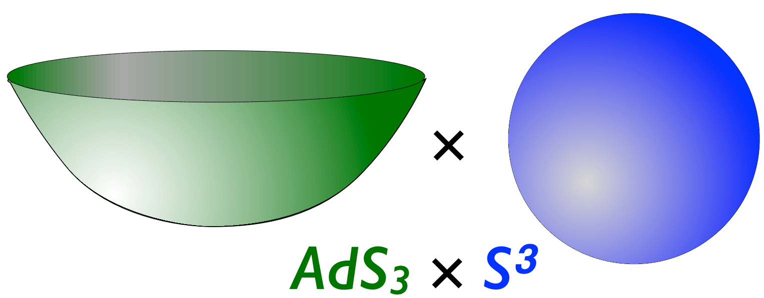
$$X^{\dot{A}A}_{(r)}(z,\bar{z}) \qquad \psi^{\alpha\dot{A}}_{(r)}(z) \qquad \widetilde{\psi}^{\dot{\alpha}\dot{A}}_{(r)}(\bar{z})$$

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

- ★(4,4) supersymmetry and $c = 6N = 6\, N_1 N_5$

Holographic Dual: IIB Supergravity on $T^4 \times S^1(z) \times R^{4,1}$

⇒ Supergravity in six-dimensions



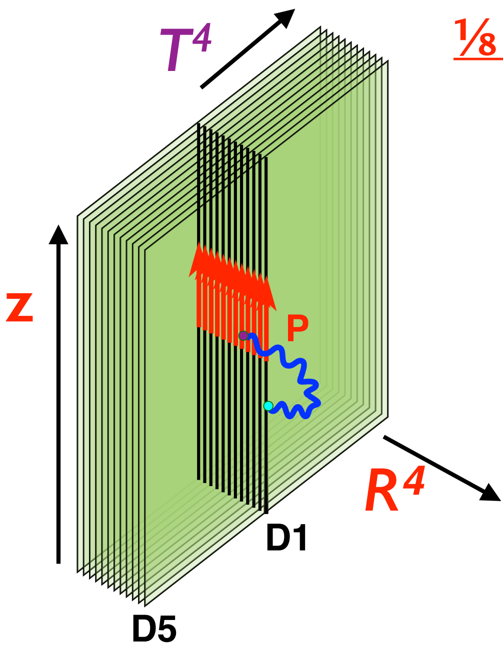
Geometric transition:

- ★ D1/D5 replaced by RR 3-form flux
- ★ Conformal vacuum: global $AdS_3 \times S^3$

Rich ¼ BPS ground state structure: The ~$N_1 N_5$ RR ground states

¼ **BPS Holographic Dictionary**: Lunin and Mathur; Kanitscheider, Skenderis and Taylor

The D1-D5-P System: ⅛ BPS = 4 supersymmetries



⅛ BPS States: Add Left-moving momentum

Right-movers: RR vacua (4 susies)

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

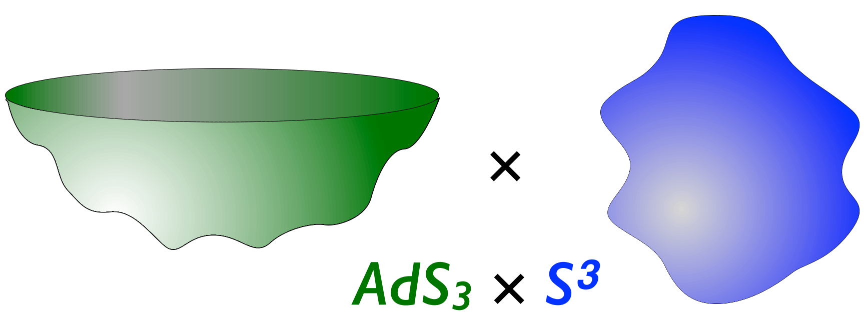
Count states: Count partitions of N_P in a CFT with $c = 6\, N_1 N_5$

$\Rightarrow$ *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

Holographic Dual of the Strominger-Vafa (Index) States?



⅛ BPS Shape modes on $AdS_3 \times S^3$

Goals:

- Construct fully-back-reacted fluctuating microstate geometries
- Holographic dictionary for these ⅛ BPS states
- Determine the stringy microstate structure visible within supergravity?

Status of BPS Microstate Geometries

BPS Microstate geometries define strongly interacting phases of the D1-D5 CFT

- Microstate geometries accessing *correct phase* and *typical black-hole microstates* with correct $E_{gap} \sim (C_{cft})^{-1}$

Where we are computationally with classical microstate geometries:

- Single Bubble/Two-centered geometries: Difficult but manageable
- Holographic dictionary for these ⅛ BPS states is now quite well-developed
- Constructing the holographic duals of the complete *supergraviton gas* on single bubble is within reach

Semi-classical geometries cannot see all string states, however:

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

- Broader goal: Identify semi-classical moduli spaces whose quantization can describe all the microstates of the black hole

Where we need to go next

- *Strominger-Vafa:* Most of the black-hole entropy comes from the highly-twisted sectors of the underlying CFT

- Deep, scaling geometries access these highly-twisted sectors ($E_{gap} \sim (N_1 N_5)^{-1}$)

  ★ *Necessarily involve multi-center, multi-bubble solutions*

- Most general fluctuating geometries (*superstrata*) only constructed for shallow, single-bubble/two-centered geometries

  ✦ Understand the links and *holographic dictionary* between deep, scaling geometries and twisted sectors of CFT

  ✦ Construct generic, multi-centered families of *superstrata* in scaling geometries ($E_{gap} \sim (N_1 N_5)^{-1}$)

  ⟷ ***Holographic duals of twisted sector states***

New ideas:

- W-Branes and Supergravity Hypermultiplets
- Quantum Tunneling and Microstate Geometries

Old Story V: Heterotic-Type II duality

Abelian Maxwell fields arise directly in compactification of perturbative type II strings/supergravity: $$F_{(p)} = \sum_J F^J_{(2),space-time} \wedge \omega^J_{(p-2),internal}$$

Where can one get the *non-Abelian* Maxwell fields, "*W-bosons*," of $E_8 \times E_8$?

Hull and Townsend: Brane-wrapping of homology cycles.

The harmonic forms, **ω**, are dual to (p-2)-cycles in the compactification manifold and wrapped branes carry vector-multiplets in supergravity …

- Mass of vector multiplets ~ Volumes of dual (p-2)-cycles
- Interactions of vector multiplets ~ Intersection form of cycles

When the size of cycles in the compactification manifold shrink to the string scale then the vector bosons become massless → *massless W-bosons*

For K_3 there is a point in the moduli space where 16 2-cycles shrink to zero size and where the intersection form of these cycles is given by the Dynkin diagram of $E_8 \times E_8$ → *non-Abelian Maxwell fields, "W-bosons," of* $E_8 \times E_8$

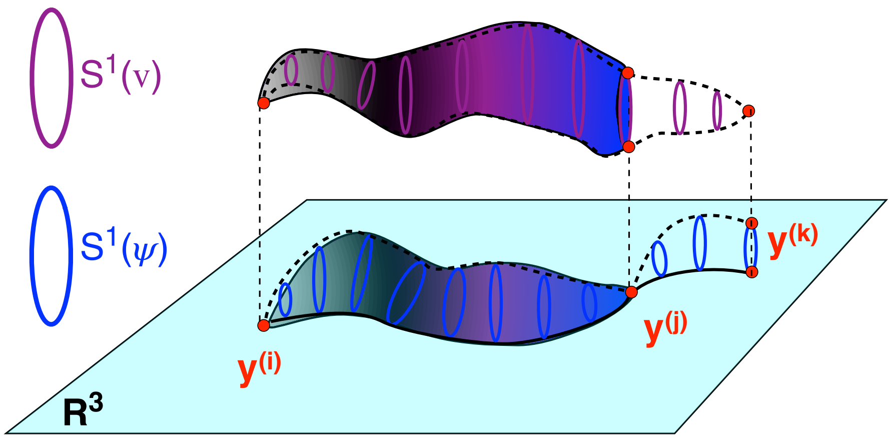
NB: Number of BPS brane wrappings > size of homology basis

W-branes in Scaling Microstate Geometries

Martinec and Niehoff: arXiv:1509.00044

Topological Structure Microstate Geometry ↔ New Field Theory Phases

New low-mass excitations in these phases ….



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

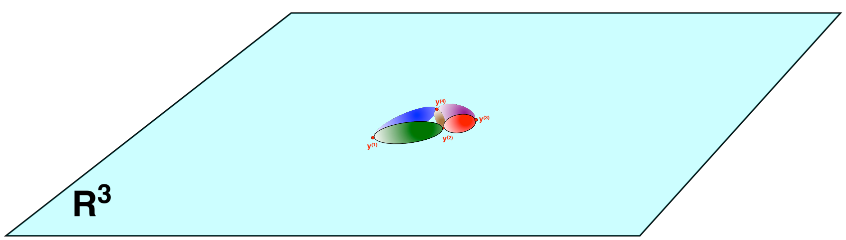
D-p brane wrap p-cycles can yield new BPS states of the system

These solitonic branes look like particles in remaining dimensions.

Duals of "Higgs Branch states"

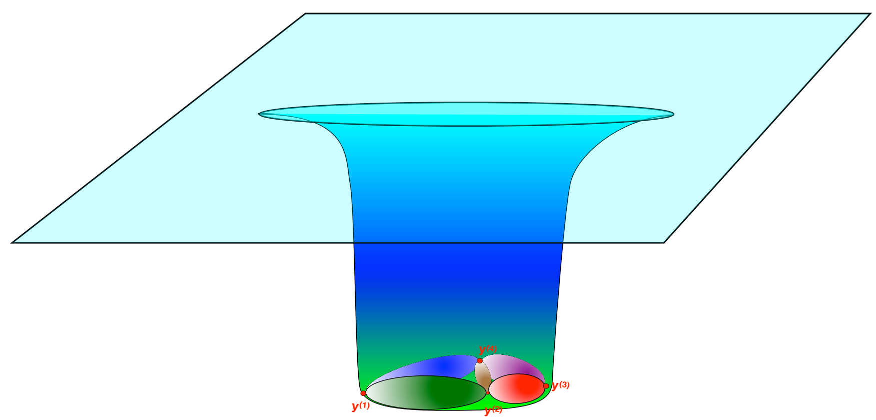
Base geometry

Cycles shrink to zero size



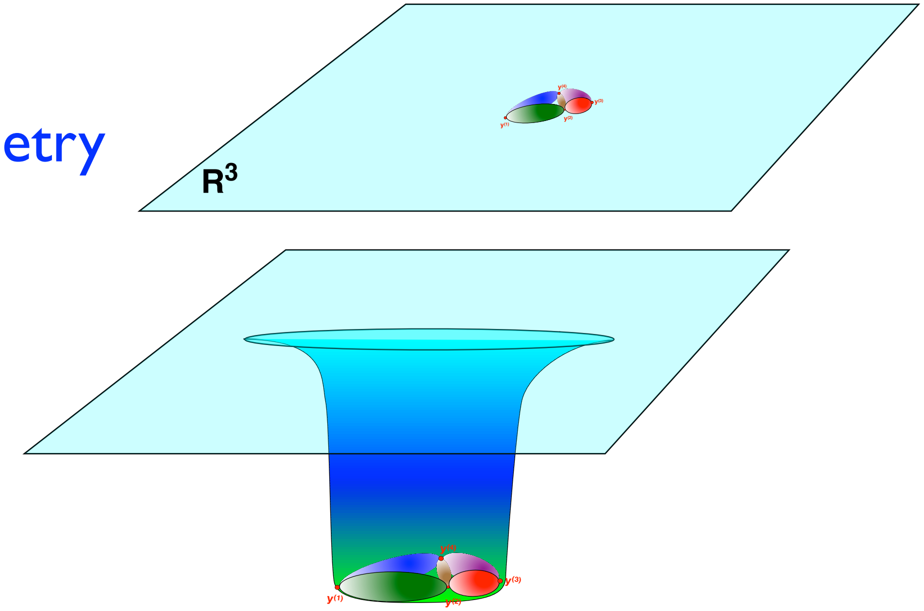
Complete space-time geometry

Cycles retain finite size but descend AdS throat



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

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.

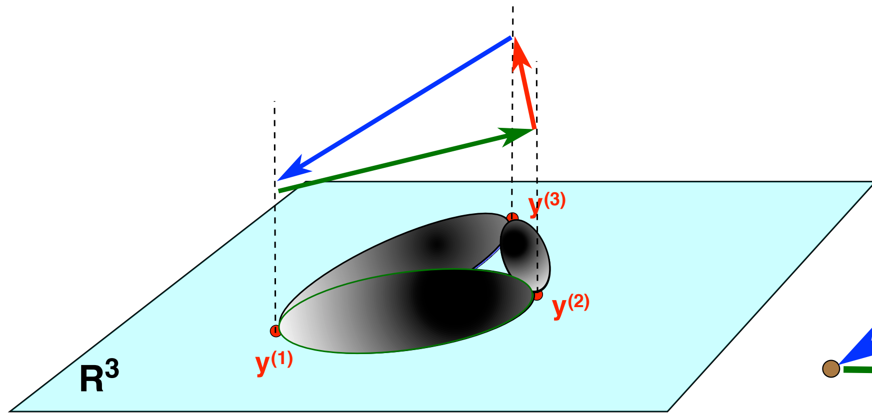
Crucial insight: Solitonic W-branes look like particles on the T^4 but this T^4 is threaded by magnetic fluxes and so each W-brane wrapping cycles in the space-time actually occupies *distinct Landau levels* on the T^4.

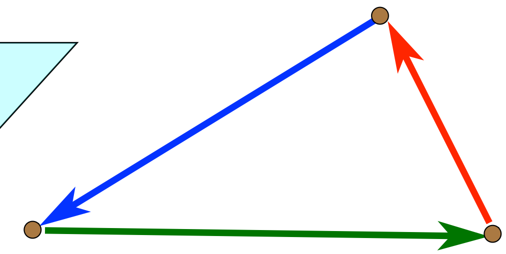
Martinez and Niehoff: arXiv:1509.00044

Three-node quiver

Naive count:

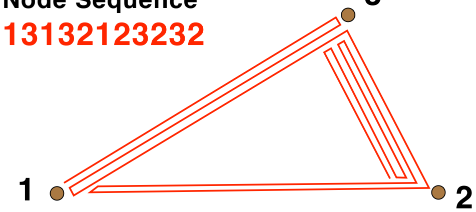
Three distinct W-branes

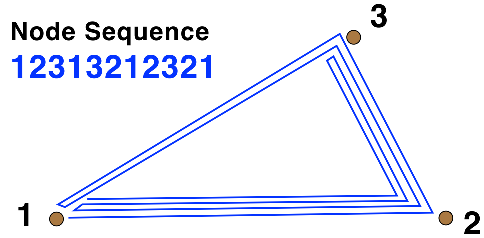




Actual count: Brane wrappings are distinguished by Landau levels

W-branes $\Leftrightarrow$
Walks on the three node quiver





Every distinct node sequence = Independent W-brane

Martinec and Niehoff: arXiv:1509.00044

Distinct W-branes $\Leftrightarrow$ Higgs branch states of quiver quantum mechanics Denef

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

Count strings of sausages:

Number of such W-branes $\Leftrightarrow$ 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

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

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

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 Mathur: 0805.3716; 0905.4483 Mathur and Turton: 1306.5488

Macroscopic tunneling probabilities ~ O(1)?

Iosif Bena, Daniel R. Mayerson, Andrea Puhm, Bert Vercnocke, arXiv:1512.05376

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 what good is all this classical supergravity analysis?

Obvious, boring answer:

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

Much more interesting "holographic" answer:

Supergravity identifies the long-range, large scale degrees of freedom that control physics at the horizon scale ...

- *Supergravity controls the phase structure of the new black-hole physics*
- *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 ..*

Supergravity is the emergent description of horizon-scale physics.

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
- Microstate geometries define, holographically, new phases of black-hole physics
- Solving the information paradox via holography in supergravity ***requires** the new black-hole phases described by microstate geometries*
- 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*
  - ★ *Remarkably good laboratory for developing all these ideas*
  - ★ *Holographic dictionary for geometric fluctuations and CFT states is becoming well-developed*
  - ★ *Holographic duals of "Strominger-Vafa" states under construction*
  - ★ *Semi-classical description of entropy with* $S \sim \sqrt{N_1 N_5 N_P}$ *is within reach*
- Lots of exciting new ideas: W-branes and Higgs branches; tunneling calculations; non-BPS; Investigations of infall …