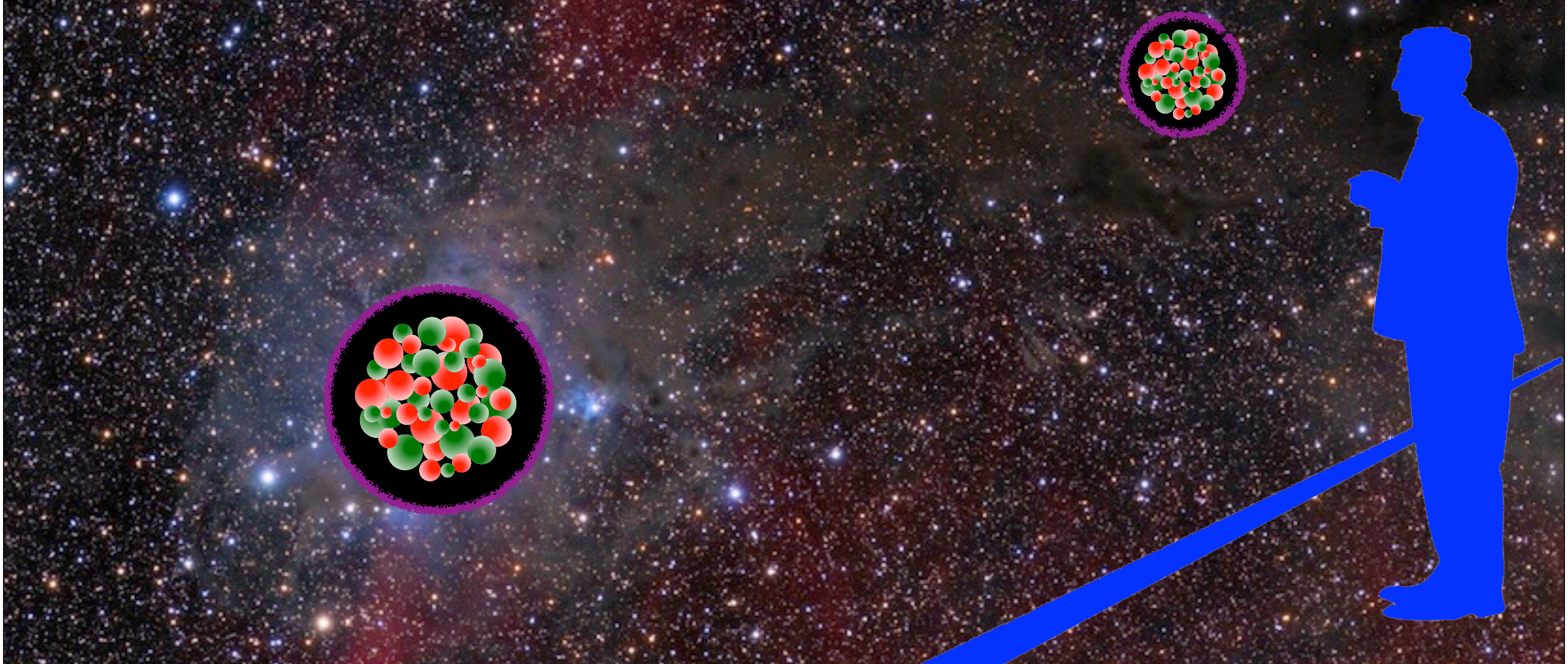
Resolving the Structure of Black Holes

Nick Warner, July 2, 2013



18th Claude Itzyson Meeting:
Frontiers of String Theory

Recent work with:

I. Bena, Gary Gibbons, Ben Niehoff, M. Shigemori, O. Vasilakis

Based on Collaborations with:

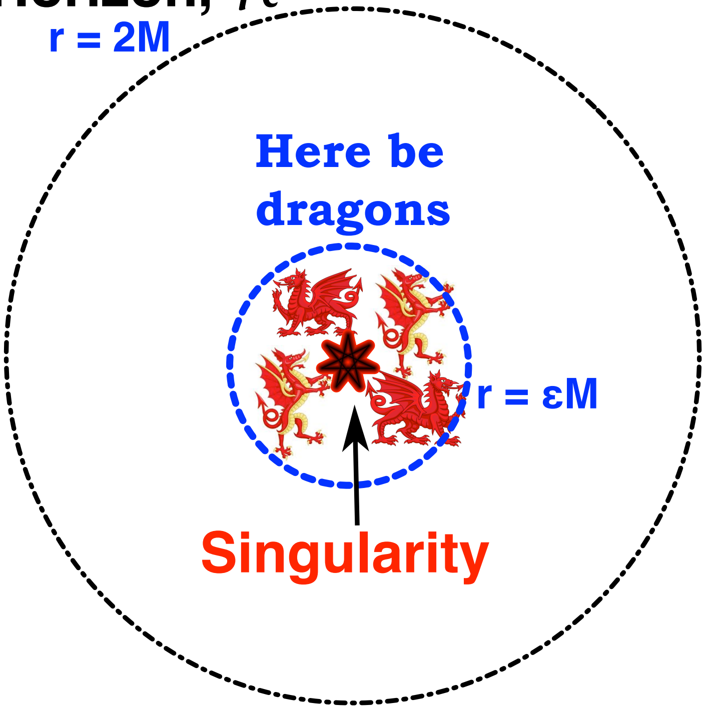
N. Bobev, G. Dall'Agata, J. de Boer, S. Giusto, A. Puhm, C. Ruef, C.-W. Wang

Outline

- General background + prejudicial commentary
- Smarr Formula: "No Solitons without Horizons"
- Topological stabilization: "No Solitons without *Topology*"
- Fluctuations of microstate geometries
- Current status of microstate geometries
- Conclusions

Ancient Wisdom for the Schwarzschild Black Hole

Horizon, $\mathcal{H}$



Tidal forces at $r = \varepsilon\, M$

$$R^{\mu\nu\rho\sigma}\, R_{\mu\nu\rho\sigma} \sim \frac{1}{\varepsilon^6\, M^4}$$

M large $\Rightarrow$ Tidal forces small

$\Rightarrow$ Equivalence principle works well in local frames

$\Rightarrow$ $\boxed{\text{(i) Effective field theory valid in regions: } r > \varepsilon\, M}$

Static solution: Time, **t**, measured at infinity with Fourier modes $e^{i\omega t}$

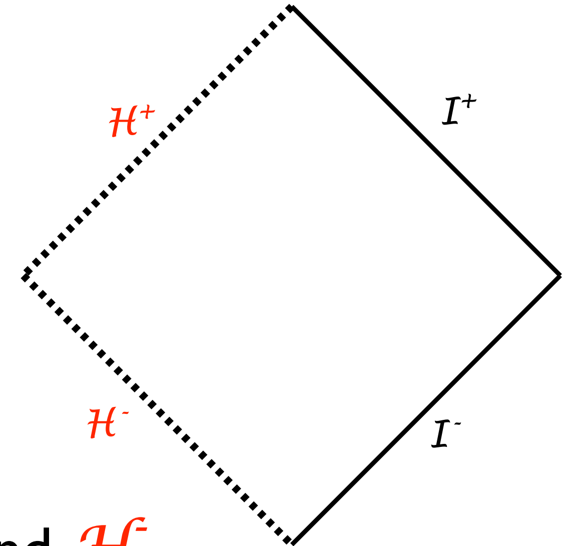
Use this time to do quantum mechanics: Defines Boulware vacuum $|\mathbf{B}\rangle$

Semi-classical Einstein equations: $R_{\mu\nu} - \frac{1}{2}\, R\, g_{\mu\nu} = \frac{8\,\pi G}{c^2} \langle B|\, (T_{\mu\nu})_{Ren}\, |B\rangle$

$\langle B|\, (T_{\mu\nu})_{Ren}\, |B\rangle$ vanishes at infinity ... a vacuum ...

but diverges at horizon

Hawking: Infalling classical observers see nothing unusual at the horizon and the correct quantum state must reflect this....



(ii) State of black hole after collapse:
Infalling vacuum at the future horizon.

$\Rightarrow$ Hawking radiation at infinity

$|H\rangle$ = Hartle-Hawking vacuum:
Use infalling/outgoing times to define vacua at $\mathcal{H}^+$ and $\mathcal{H}^-$
$\Rightarrow$ *Black hole in thermal equilibrium with heat bath*

$|U\rangle$ = Unruh vacuum:
Use Schwarzschild time to define vacuum at $\mathcal{I}^-$ and outgoing time to define vacua at $\mathcal{H}^-$ $\Rightarrow$ *Black hole evaporating*

(ii) Absolutely no drama at the future horizon: Choose vacua $|H\rangle$ or $|U\rangle$

$\langle H|\,(T_{\mu\nu})_{Ren}\,|H\rangle$ and $\langle U|\,(T_{\mu\nu})_{Ren}\,|U\rangle$ *regular at future horizon*

These vevs correctly reflect the Hawking radiation density or flow ....

Information loss:

Hawking:

Black holes have no hair

$\Rightarrow$ Hawking radiation is universal and purely thermal

$\Rightarrow$ Black hole formation and evaporation evolves pure quantum states into density matrices $\Rightarrow$ *Loss of information*

Mathur (**0909.1038**):

Beautiful development and strengthening of the Hawking "theorem" ...
Much Sharper: *Proved that small corrections to the Hawking Radiation states* ***cannot*** *restore information*

- Information cannot be recovered by small stringy or quantum gravity (e.g. $(Riem)^2$) corrections to radiation
- The horizon state must have large ($\mathcal{O}(1)$) corrections for information recovery

(iii) Black hole formation and evaporation from pure quantum state to pure quantum state
$\Rightarrow$ *There must be significant new physics at the horizon scale.*

Fuzzballs provide a mechanism that achieves this in string theory ...

More recent discussion based on Mathur's proof:

Almheiri, Marolf, Joseph Polchinski and Sully 1207.3123

The following are incompatible

(i) Effective field theory valid in regions: $r > 2M$.

(ii) No drama at the future horizon.

(iii) Hawking radiation is in a pure state

AMPS further argue that, at least when a black hole is old (after the Page time), *one must abandon (ii)* and that the state at the horizon, as seen by an infalling observer, must involve large excitations at all energy levels ....
A FIREWALL that burns up the infalling observer.

Essentially: Infinite blue-shift from a horizon + Mathur's argument that there are large corrections at the horizon scale $\Rightarrow$ *FIREWALL*

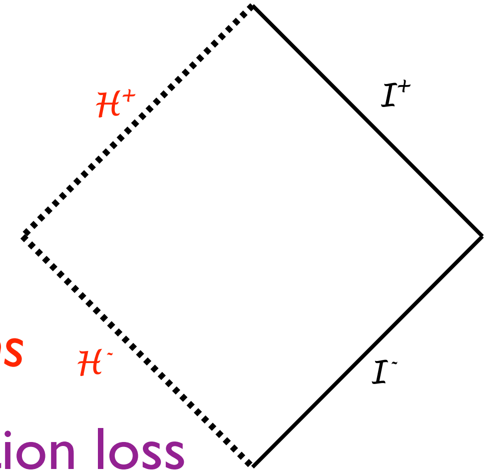
Fuzzballs have no horizon and so avoid such intense conflagrations

A step backwards: what is wrong with the Boulware vacuum?

$|B\rangle$ = Boulware vacuum:

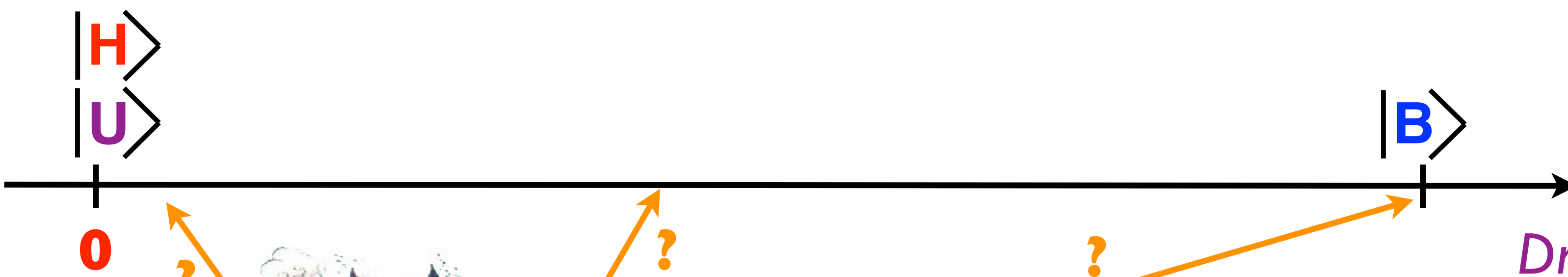
Use time at infinity to define vacuum at $\mathcal{I}^+$ and $\mathcal{I}^-$

$\Rightarrow$ ***No Hawking radiation***



$\langle B|\,(T_{\mu\nu})_{Ren}\,|B\rangle$ vanishes at infinity but *diverges at horizons*

The ultimate firewall: Immolation at the horizon; no information loss



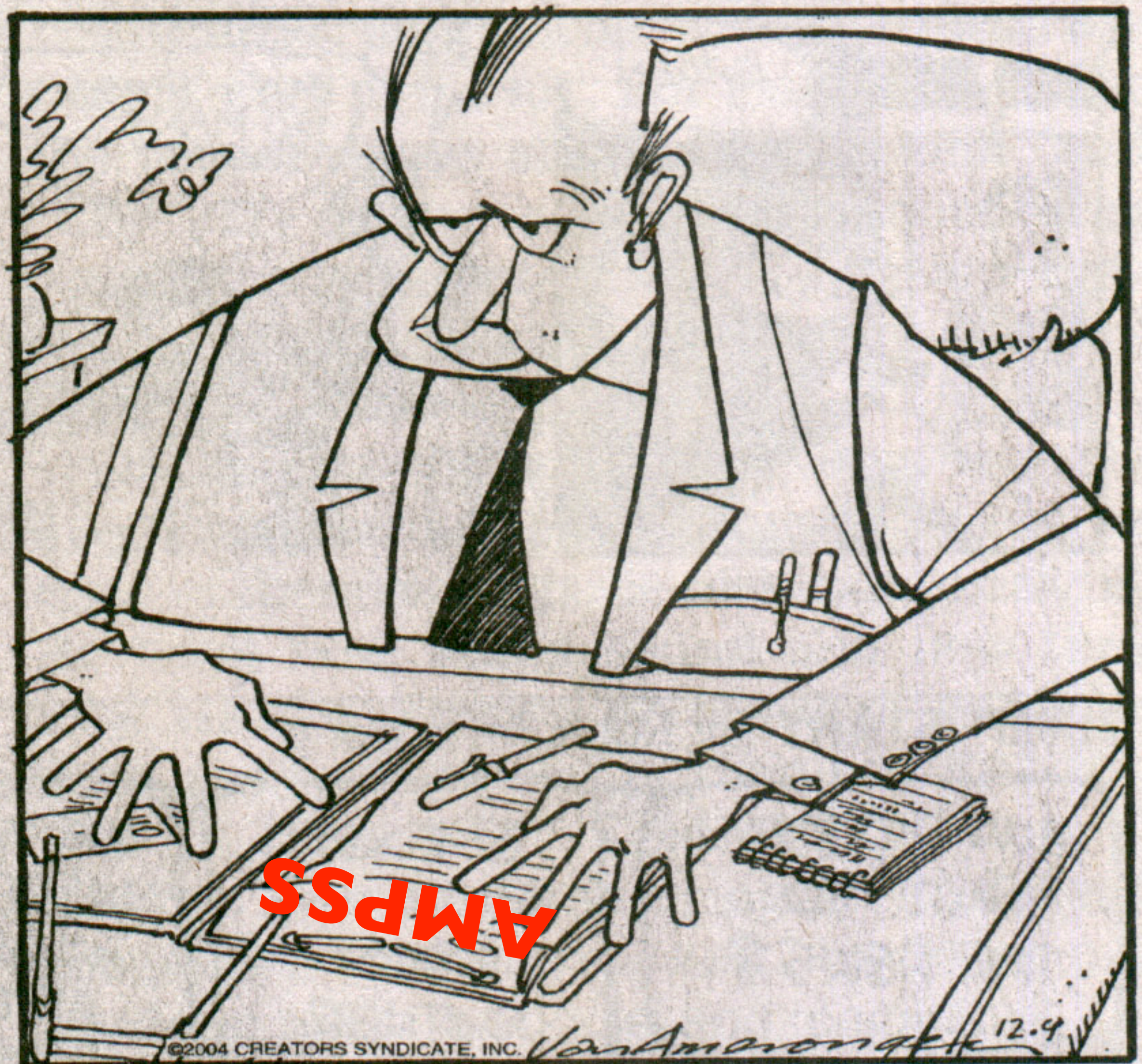
Drama at future horizon

Where is the firewall on this line?

If you think there is a firewall, why not simply choose the Boulware vacuum get rid of all the annoying Hawking radiation?

What happens with the back-reaction of the firewall?

BALLARD STREET By Jerry Van Amerongen



After studying the material, Nick awaits the arrival of meaning.

The Firewall State?

AMPS want the coarse-grained firewall state to be Hartle-Hawking ... so there is still Hawking radiation ... but to recover information an "old" black hole must have a large number of excitations that

- Localize on the horizon
- Have all energies up to the Planck scale

⇒ Infalling observer burns up on this "energetic curtain" or firewall.

Firewalls thus require a vast amount of very hot ***hair at the horizon***

This is utterly untenable in four-dimensional General Relativity + ordinary matter. These excitations would fall in or be expelled ...

Black holes have NO HAIR!

The *No-Hair theorems* *washed the Hawking Radiation clean* of information and so must *prevent any horizon state that can restore the information loss*.

In four-dimensional GR there is no mechanism to support a firewall state!

Gravity is a Classical Phenomenon:
Perhaps such a strongly quantum system as a black hole will require a classical observation in order to behave classically?

… but don't bet your life on it…

Fuzzballs: Use String Theory!

- More space-time dimensions, much richer spectrum of interacting long-range (massless) fields ... what are the new possibilities for stellar end-states?
  - ★ For given boundary conditions are there alternatives to black holes?
  - ★ Are black holes artifacts of symmetry?

Four dimensions: No! Singularity theorems ...

- Correct state counting in BPS and near-BPS black holes $g_s \to 0$ limit
  - ★ What do these states look like at finite g_s?

- Open string - Closed string duality → Holographic Field Theory
  - ⇒ Black holes (in AdS/with AdS throats) can be described by a dual CFT for which evolution is unitary
  - ⇒ Every state in the CFT has a closed string (gravity) dual

Microstate Geometries:

= Fuzzballs that can be described within the supergravity approximation

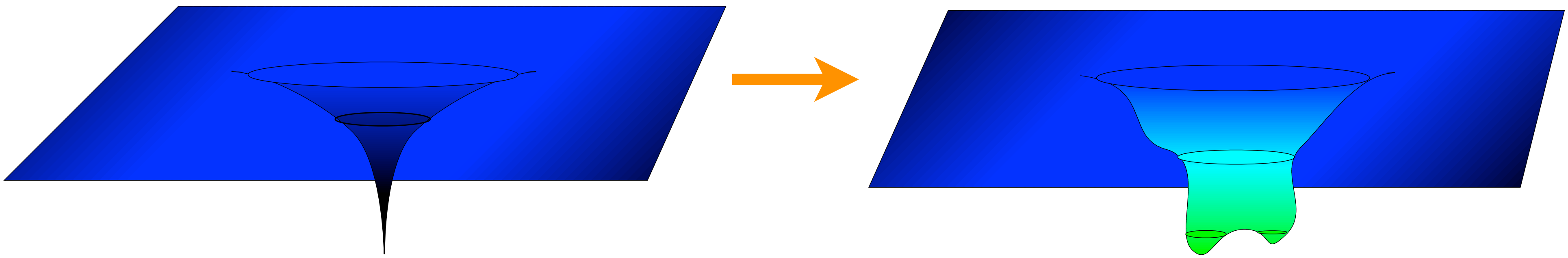
- ★ Horizonless, smooth solutions with same large-distance appearance as a black hole.
- ★ Gravity dual to (relatively coherent) CFT states
- ★ Mechanism to support fuzzballs (and maybe even firewalls) against gravitational collapse

Microstate Geometries:

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



Simplifying assumption:

- Time independent metric (stationary) *and time independent matter*

Smooth, stable, end-states of stars in massless bosonic sector of string theory?

This is supposed to be impossible because of many no-go theorems:

"No Solitons without horizons"

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

Time Independent Solutions in Five Dimensional Supergravity

Not necessarily BPS

N=2 Supergravity coupled to two vector multiplets

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

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

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

Assume:

(i) The metric is stationary:

$$ds_5^2 = -Z^{-2} (dt + k)^2 + Z\, ds_4^2$$

Non-space-like Killing vector $K = \dfrac{\partial}{\partial t}$,

(ii) The fields are time independent:

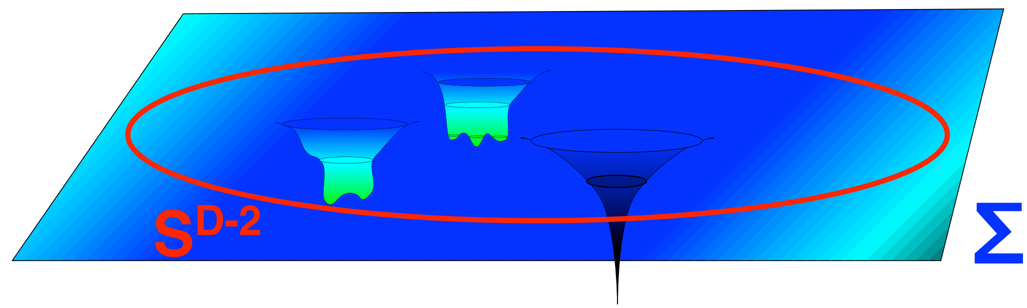
$$\mathcal{L}_K F^I = 0\,, \qquad \mathcal{L}_K X^I = 0$$

The Komar Mass Formula

In a D-dimensional space-time with a Killing vector, K, that is time-like at infinity one has

$$M \;=\; -\,\frac{1}{16\pi G_D}\,\frac{(D-2)}{(D-3)}\int_{S^{D-2}} *dK \qquad\qquad K \;=\; \frac{\partial}{\partial t}$$

where S^{D-2} is (topologically) a sphere near spatial infinity in some hypersurface, Σ.



$$g_{00} \;=\; -1 \;+\; \frac{16\pi G_D}{(D-2)\,A_{D-2}}\,\frac{M}{\rho^{D-3}} \;+\;\dots \qquad\qquad *dK \;\approx\; -\,(\partial_\rho g_{00})\,*\,(dt\wedge d\rho)$$

More significantly

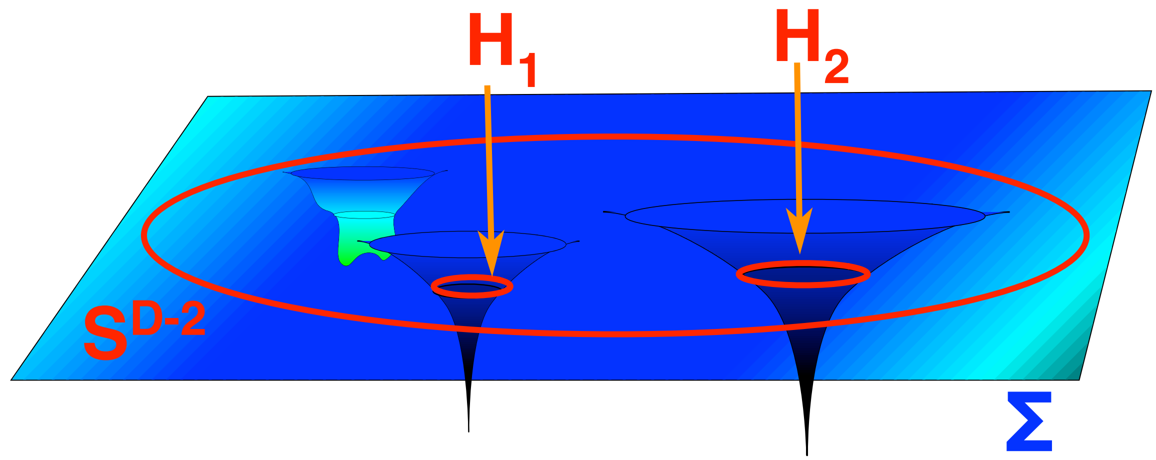
$$d*dK \;=\; -\,2\,*\,(K^\mu R_{\mu\nu}dx^\nu) \qquad\qquad R_{\mu\nu} \;=\; 8\pi G_D\left(T_{\mu\nu}-\frac{1}{(D-2)}\,T\,g_{\mu\nu}\right)$$

If Σ is smooth with *no interior boundaries*:

$$M \;=\; \frac{1}{8\pi G_D}\,\frac{(D-2)}{(D-3)}\int_\Sigma K^\mu R_{\mu\nu}\,d\Sigma^\nu \;\xrightarrow[\textbf{linearized}]{}\;\approx\;\int_\Sigma T_{00}\,d\Sigma^0$$

Smarr Formula I

More generally, Σ will have *interior boundaries* that can be located at horizons, H_J.



Excise horizon interiors: $\Sigma \to \widetilde{\Sigma}$

$$\frac{8\pi G_D\,(D-3)}{(D-2)}\,M \;=\; \int_{\widetilde{\Sigma}} \cancelto{0}{R_{\mu\nu}K^\mu}\, d\Sigma^\nu \;+\; \tfrac{1}{2}\sum_{H_J}\int_{H_J} *dK$$

Null generators of Kerr-like horizons: $\xi \;=\; K \;+\; \vec{\Omega}_H \cdot \vec{L}_H$

Surface gravity of horizon, κ $\quad \xi^a \nabla_a\, \xi^b \;=\; \kappa\, \xi^b \quad \Rightarrow \quad \frac{1}{2}\int_H *d\xi \;=\; \kappa\,\mathcal{A}$

$$\Rightarrow \quad \frac{1}{2}\sum_{H_J}\int_{H_J} *dK \;=\; \sum_{H_I}\left[\kappa_{H_I}\,\mathcal{A}_{H_I} \;+\; 8\pi G_D\,\vec{\Omega}_{H_I}\cdot\vec{J}_{H_I}\right]$$

Vacuum outside horizons:

$$\frac{8\pi G_D\,(D-3)}{(D-2)}\,M \;=\; \sum_{H_I}\left[\kappa_{H_I}\,\mathcal{A}_{\mathcal{H}_\mathcal{I}} \;+\; 8\pi G_D\,\vec{\Omega}_{H_I}\cdot\vec{J}_{H_I}\right]$$

Smarr Formula II: No Solitons Without Horizons

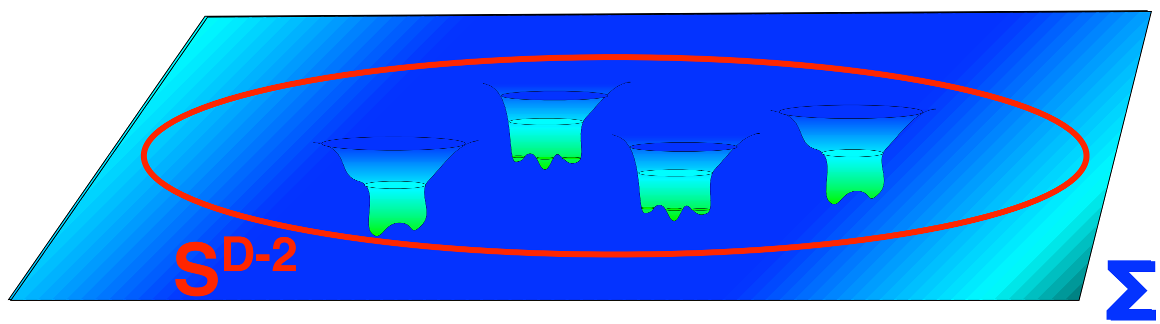
$$\frac{8\pi G_D\,(D-3)}{(D-2)}\,M \;=\; \int_{\widetilde{\Sigma}} R_{\mu\nu} K^{\mu}\, d\Sigma^{\nu} \;+\; \frac{1}{2}\sum_{H_J}\int_{H_J} *dK$$

Goal: Show that $\displaystyle\int_{\Sigma} R_{\mu\nu} K^{\mu}\, d\Sigma^{\nu}$ = Boundary term

(with no contribution at infinity)

✦ *Not* true for *massive* field ... but (almost) true for *massless* fields

If Σ is a smooth space-like hypersurface populated only by smooth solitons (no horizons) the one must have:



M ≡ 0

Positive mass theorems with asymptotically flatness:

⇒ *Space-time can only be globally flat,* $\mathbf{R}^{4,1}$

⇒ "No Solitons Without Horizons" ....

Simplifying $R_{\mu\nu}K^{\mu}$ in Five Dimensional Supergravity

Einstein Equations:

$$R_{\mu\nu} \;=\; Q_{IJ}\left[F^I{}_{\mu\rho}\,F^J{}_{\nu}{}^{\rho} - \tfrac{1}{6}\,g_{\mu\nu}\,F^I{}_{\rho\sigma}F^{J\,\rho\sigma} + \partial_\mu X^I\,\partial_\nu X^J\right]$$

Time independence: $\mathcal{L}_K F^I \;=\; 0 \qquad \mathcal{L}_K X^I \;=\; 0$

$$\mathcal{L}_K X^I \;=\; 0 \;\;\Leftrightarrow\;\; K^\mu \partial_\mu X^I \;=\; 0 \;\;\Rightarrow$$

Scalars drop out of $R_{\mu\nu}K^{\mu}$

Cartan formula for forms: $\mathcal{L}_K \alpha \;=\; d(i_K(\alpha)) \;+\; i_K(d\alpha)$

$$\Rightarrow\;\; d(i_K(F^I)) \;=\; 0 \;\;\Rightarrow\;\; K^\rho F^I_{\rho\mu} \;=\; \partial_\mu \lambda^I$$

for some functions, λ^I . *Assuming that the base is simply connected*.

Using this and the equations of motion

$$K^\mu\big(Q_{IJ}\,F^I{}_{\mu\rho}\,F^J{}_{\nu}{}^{\rho}\big) \;=\; -\nabla_\rho\big(Q_{IJ}\,\lambda^I\,F^{J\rho\nu}\big) \;+\; \tfrac{1}{16}\,C_{IJK}\,\epsilon^{\nu\alpha\beta\gamma\delta}\,\lambda^I\,F^J{}_{\alpha\beta}\,F^K{}_{\gamma\delta}$$

= Boundary term + Chern-Simons contribution

But we still need to deal with the F^2 term ....

Introduce the dual fields: $G_I = *_5\, Q_{IJ}\, F^J$ then one can write

$$R_{\mu\nu} \;=\; Q_{IJ}\left[\tfrac{2}{3}\, F^I{}_{\mu\rho}\, F^J{}_\nu{}^\rho + \partial_\mu X^I\, \partial_\nu X^J\right] \;+\; \tfrac{1}{6}\, Q^{IJ}\, G_{I\,\mu\rho\sigma}\, G_{J\,\nu}{}^{\rho\sigma}$$

Use the Cartan formula on G_I : $\quad 0 \;=\; \mathcal{L}_K G_I \;=\; d(i_K(G_I)) \;+\; i_K(dG_I)$

However $\quad d(G_I) \;=\; d*(Q_{IJ}\, F^J) \;\sim\; C_{IJK}\, F^J \wedge F^K$

but $\quad i_K F^J \;=\; d\lambda^J \quad\Rightarrow\quad i_K\big(C_{ILM}\, F^L \wedge F^M\big) \;\sim\; C_{ILM}\, d\big(\lambda^L F^M\big)$

Therefore $\quad d\Big(i_K(G_I) \;+\; \tfrac{1}{2}\, C_{IJK}\, \lambda^J\, F^K\Big) \;=\; 0$

$$\Rightarrow \quad K^\rho G_{I\,\rho\mu\nu} \;=\; \partial_\mu \Lambda_{I\,\nu} - \partial_\nu \Lambda_{I\,\mu} \;-\; \tfrac{1}{2}\, C_{IJK}\, \lambda^J F^K_{\mu\nu} \;+\; H_{I\,\mu\nu}$$

where Λ_I are global one-forms and H_I are *closed* but *not exact* two forms ...

$$K^\mu \partial_\mu X^I \;=\; 0$$

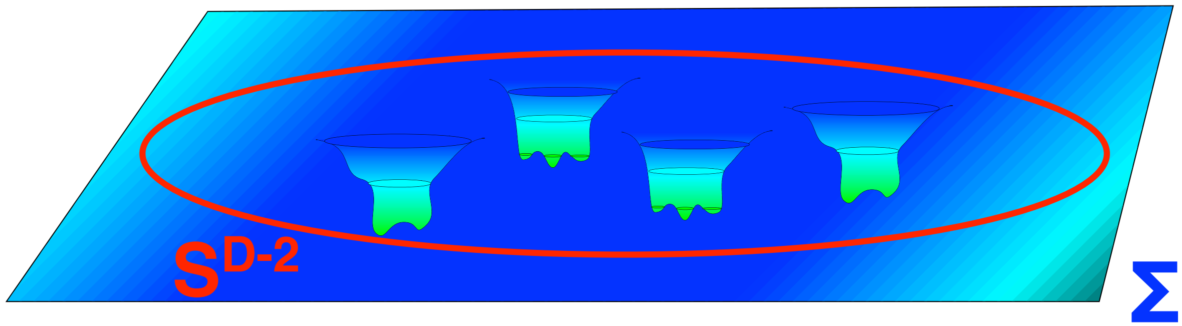
$$K^\mu\big(Q_{IJ}\, F^I{}_{\mu\rho}\, F^J{}_\nu{}^\rho\big) \;=\; -\nabla_\rho\big(Q_{IJ}\, \lambda^I\, F^{J\rho\nu}\big) \;+\; \tfrac{1}{16}\, C_{IJK}\, \epsilon^{\nu\alpha\beta\gamma\delta}\, \lambda^I\, F^J{}_{\alpha\beta}\, F^K{}_{\gamma\delta}$$

$$K^\mu\big(Q^{IJ}\, G_{I\,\mu\rho\sigma}\, G_J{}^{\nu\rho\sigma}\big) \;=\; -2\,\nabla_\rho\big(Q^{IJ}\, \Lambda_{I\,\sigma}\, G_J{}^{\rho\nu\sigma}\big) \;-\; \tfrac{1}{4}\, C_{IJK}\, \epsilon^{\nu\alpha\beta\gamma\delta}\, \lambda^I\, F^J{}_{\alpha\beta}\, F^K{}_{\gamma\delta} \;+\; \boxed{Q^{IJ}\, H_I^{\rho\sigma}\, G_{J\,\rho\sigma\nu}}$$

$$\Rightarrow \quad K^\mu R_{\mu\nu} \;=\; \underbrace{-\tfrac{1}{3}\, \nabla^\mu \big[2\, Q_{IJ}\, \lambda^I\, F^J{}_{\mu\nu} \;+\; Q^{IJ}\, \Lambda_I{}^\sigma\, G_{J\,\mu\nu\sigma}\big]}_{\text{boundary terms}} \;+\; \underbrace{\boxed{\tfrac{1}{6}\, Q^{IJ}\, H_I^{\rho\sigma}\, G_{J\,\rho\sigma\nu}}}_{\text{cohomology}}$$

The Generalized Smarr Formula

If Σ 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 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*

"No Solitons without topology!"

Not just BPS

BPS Results

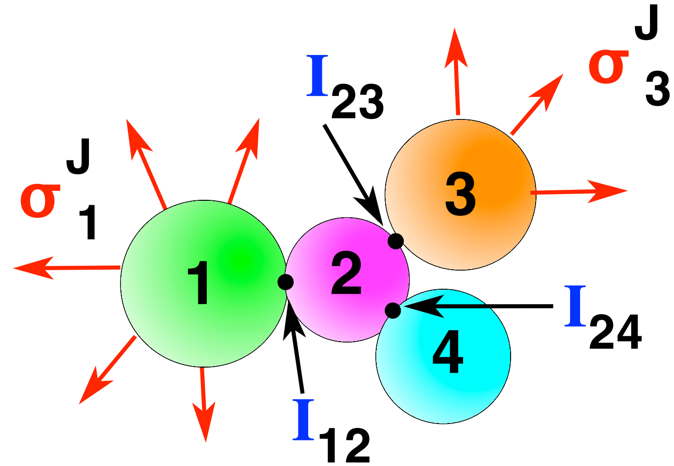
So far general stationary smooth solution. For BPS it simplifies further:

$$M = -\frac{1}{32\pi G_5} C_{IJK}\,\alpha^I \int_\Sigma F^J \wedge F^K = -\frac{1}{32\pi G_5} C_{IJK}\,\alpha^I\,\mathcal{I}^{AB}\,\sigma_A^J\,\sigma_B^K$$

where $\alpha^I \equiv Z\,(X^I)^{-1}\big|_\infty$ $\longleftrightarrow$ normalization of U(1) couplings

σ_A^J = Flux of F^J through A^{th} cycle in $H^2(\Sigma, R)$

$\mathcal{I}^{AB}$ = Inverse of the Intersection Form



Note: σ_A^J = Magnetic fluxes

Chern-Simons Interaction:

$$\nabla_\rho\left(Q_{IJ}F^{J\rho}{}_\mu\right) = \tfrac{1}{16}\,C_{IJK}\,\epsilon_{\mu\alpha\beta\gamma\delta}\,F^{J\,\alpha\beta}\,F^{K\,\gamma\delta}$$

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

$$\Rightarrow \quad M = Q_1 + Q_2 + Q_3$$

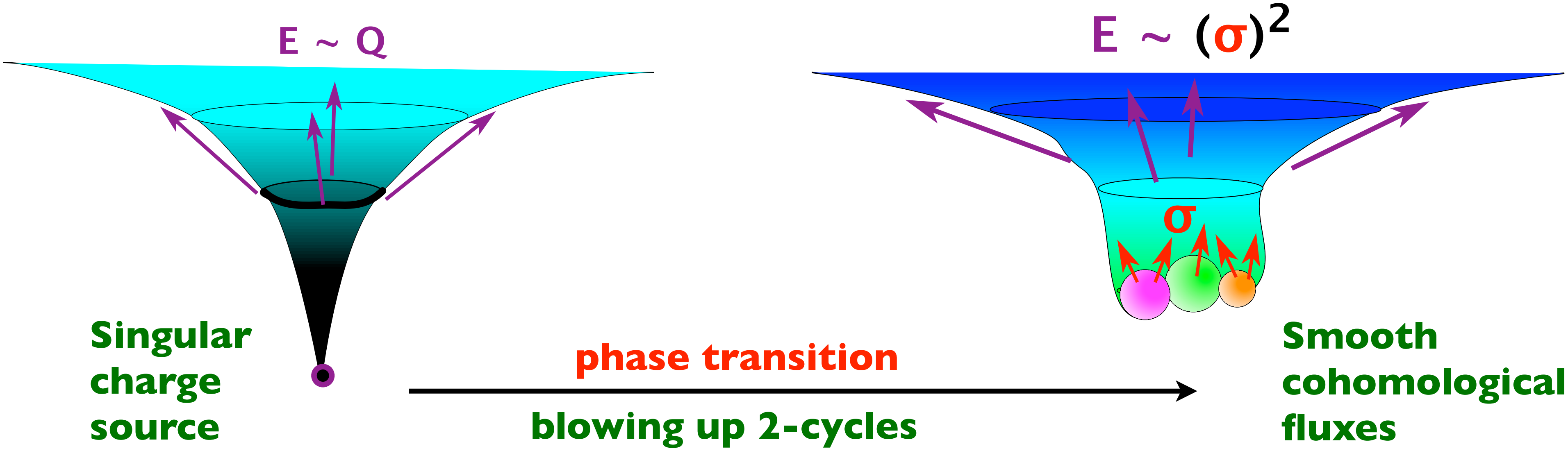
Formula is more general for non-BPS ....

Resolving Black Holes by Geometric Transitions

Chern-Simons Interaction is also the dynamical key to the geometric transition that resolves the singularity and removes the horizon of a black hole

$$\nabla_\rho \left(Q_{IJ} F^{J\rho}{}_{\mu} \right) \;=\; \tfrac{1}{16}\, C_{IJK}\, \epsilon_{\mu\alpha\beta\gamma\delta}\, F^{J\,\alpha\beta}\, F^{K\,\gamma\delta}$$

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



★ The Transition scale, λ_T = Scale of a typical cycle

~ Flux quanta on typical cycle × ℓ_P

Freely choosable parameter: Can have $\lambda_T \gg \ell_P$

Dynamically generated scale?

Geometric Transitions in Holographic Field Theory

Branes collapse cycle to singularity $\xrightarrow{\textbf{Geometric transition}}$ **Branes replaced by *smooth fluxes* threading a *new cycle***

Singular Geometry $\longrightarrow$ Smooth geometry

Wrong *IR* phase of field theory $\xrightarrow{\textbf{Phase transition}}$ Correct *IR* phase of field theory

★ Order parameter of new phase: Scale of new cycle

★ Holographic duals of N=1 gauge theories
Transitioned geometry → Confining phase; fluxes = gaugino condensate

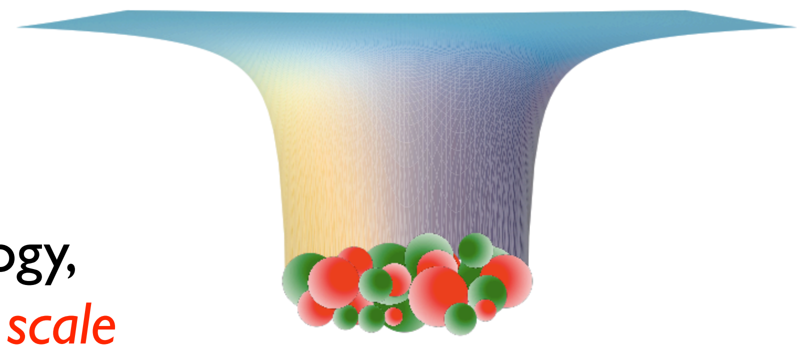
★ Scale of transitioned cycle typically set by parameters in UV field theory

Black holes: Number/size, λ_T, of blown up cycles ***not*** fixed by UV limit ...

Can we elevate these ideas from properties of static solutions to a dynamical principle?

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*

Typical bubble scale: λ_T , a *free parameter*: Number of bubbles $\sim (M/\lambda_T)^3$

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

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

Another free parameter? $\lambda_{\mathbf{gap}}$ = *redshifted wavelength, at infinity of lowest mode of bubbles at the bottom of the throat.* Field theory: $E_{gap} \sim (\lambda_{gap})^{-1}$

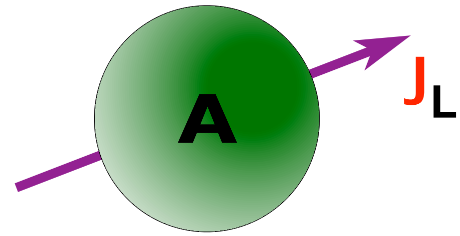
★ Semi-classical quantization of moduli:
The throat depth, or $\lambda_{\mathbf{gap}}$, is not a free parameter $E_{gap} \sim (C_{cft})^{-1}$

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

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

Comment on semi-classical quantum effects

- Each bubble has an intrinsic angular momentum



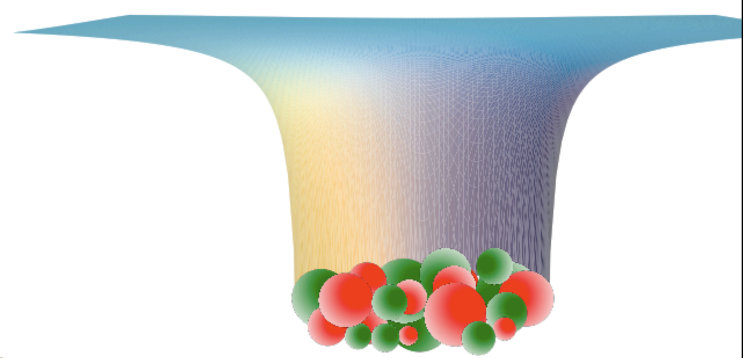
$$J_{L,\,A} \;\sim\; C_{IJK}\,\sigma^I_A\,\sigma^J_A\,\sigma^K_A \;\sim\; \sum_I Q_{I,\,A}\,\sigma^I_A$$

arising from intrinsic E x B interaction.

Semi-classical quantization of solutions corresponds to quantizing these angular momenta

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

- The depth of the AdS throat is a *very sensitive* function of the orientations of these angular momenta and quantization can make vast, *macroscopic* changes in geometry



Bena, Wang and Warner, arXiv:0706.3786
de Boer, El-Showk, Messamah, Van den Bleeken, arXiv:0807.4556 arXiv:0906.0011

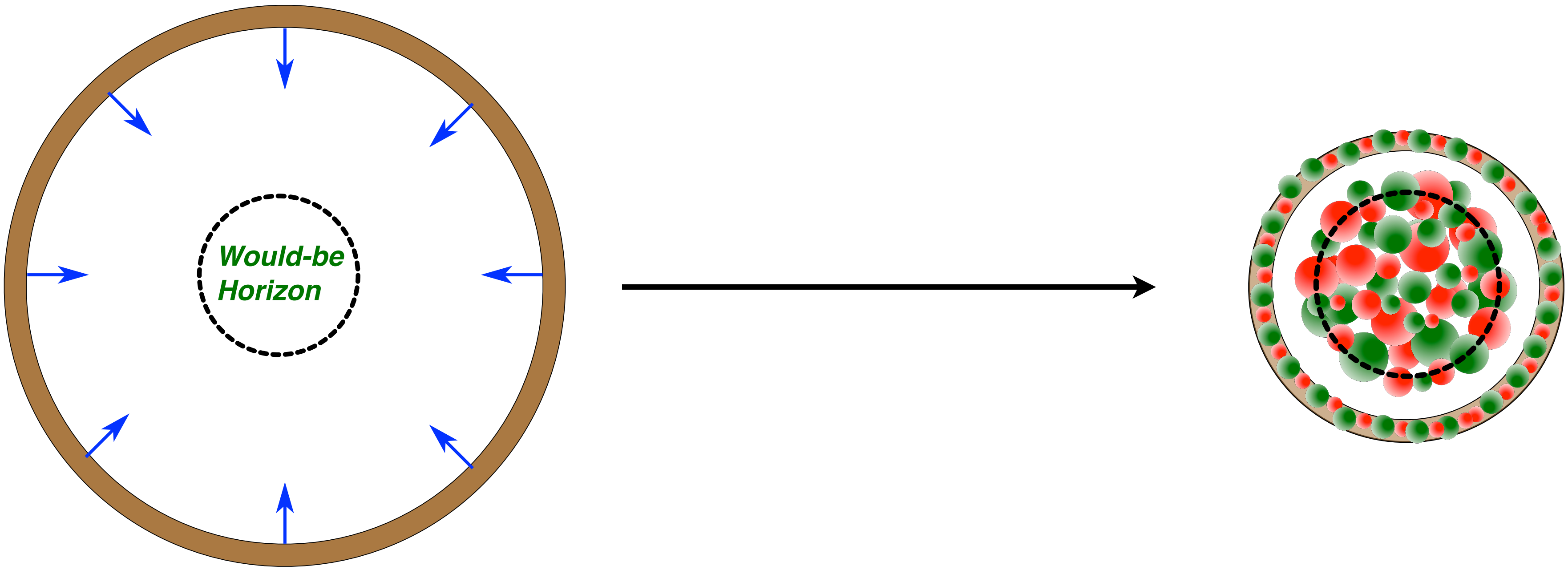
$\Rightarrow$ Quantum effects can wipe out vast regions of geometry in which curvature is small and supergravity is a good approximation, and this can happen in regular, horizonless geometries ...

Mechanism for driving infalling matter through geometric phase transition to bubbled geometries?

Collapse to a Black Hole

Mathur: 0805.3716; 0905.4483
Mathur and Turton: 1306.5488

A shell of spherically symmetric matter collapses ...



When matter densities approach those of a classical black hole then amplitudes for tunneling into a fuzzball state are no longer exponentially suppressed ..

Infalling matter tunnels onto the physical IR branch of the dual field theory.

Spherical symmetry is wiped out by the generic tunneling transition ...

The gravity dual of large-scale (λ_T) coherent families of such IR field theory states are microstate geometries.

BPS Fluctuating Bubbled Geometries

★ The geometric transition stabilizes a fuzzball against gravity and makes microstate geometries possible … this happens at scales ~ λ_T

★ 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, ℓ_P.

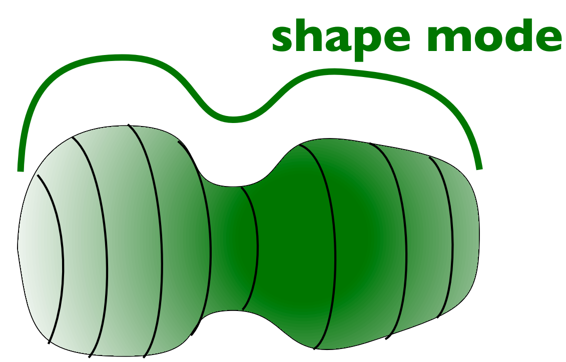
Most of the entropy probably lies in the shape fluctuations…

Extensive work in five-dimensions:

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

Expect entropy like that of a supertube

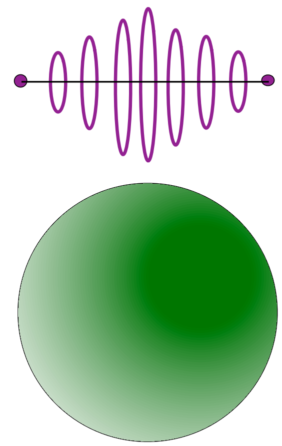
$$S \sim \sqrt{Q_1 Q_2} \sim Q$$



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 $\Rightarrow$ $\mathbf{S \sim Q^{5/4}}$

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

BPS Microstate Geometries in Six Dimensions



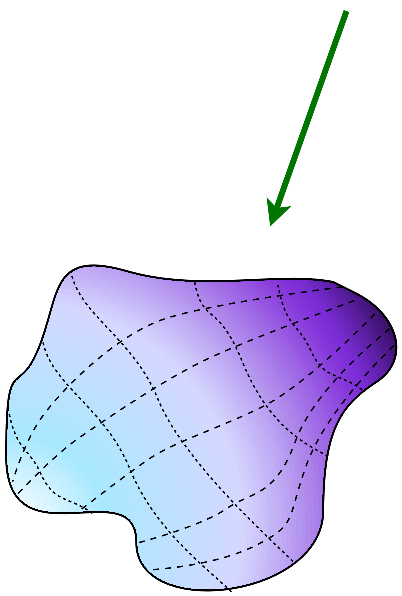
Extra circle is now fibered over every
five-dimensional 2-cycle $\Rightarrow$ 3-cycle.

Make the fluctuating cycles in five-dimensions also depend upon new U(1) fiber ... and still be a BPS state?

Conjectured object **Bena, de Boer, Shigemori and Warner, 1107.2650**

The superstratum:

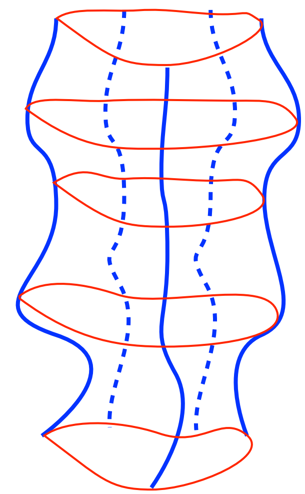
Completely ***new class*** of BPS soliton is six dimensions



- New solitonic *bound state* made of three electric charges + two independent dipole charges
- Completely smooth (microstate geometry)
- Defined by a topological 3-cycle fluctuates as *functions two variables*

Construction of examples? **$S \sim Q^{3/2}$???**

The Superstratum in Supergravity



✦ Incomplete implementation of the process:

Niehoff, Vasilakis and Warner   arXiv:1203.1348

Supersheets: New *three-charge*, *two-dipole* charge BPS solutions that depends upon functions of two variables.

Incomplete charge structure

⇒ Singular profiles ...

✦ Complete, restricted implementation:

Niehoff and Warner   arXiv:1303.5449   **Giusto, Martucci, Petrini and Rodolfo Russo, 1306.1745**

Restricted superstrata:

- Microstate geometries (smooth, horzonless)
- Functions of two independent variables

Restricted structure

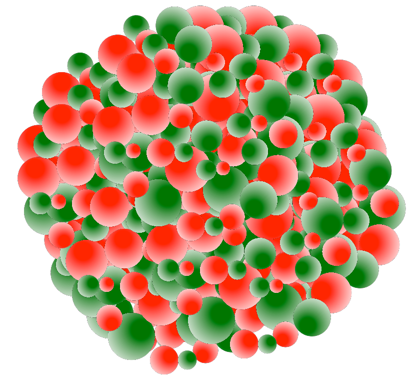
⇒ Made from large number of independent functions of one variable

$$F(\theta, \psi) = \sum_{j=1}^{N} f_j(a_i \theta + b_i \psi)$$

✦ Generic function of two variables ....?   **Bena, Niehoff, Shigemori and Warner**

✦ **S ~ $Q^{3/2}$?**

Final Comment on the Transition Scale

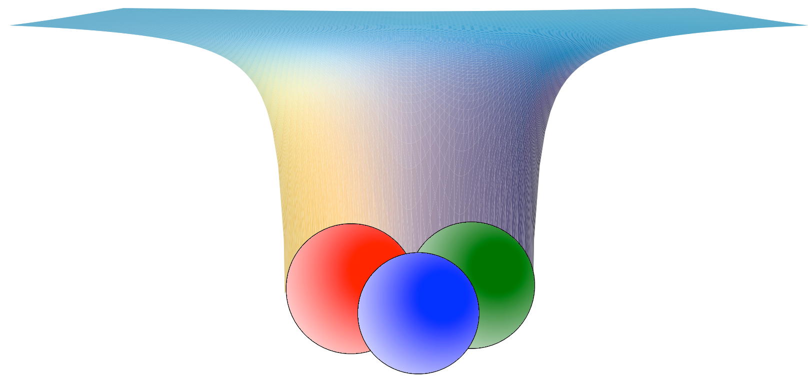


Natural to expect that there many small bubbles are entropically favoured so that $\lambda_T \sim \ell_P$.

Quite probably incorrect:

(i) Denef and Moore: **hep-th/0702146**

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



Quiver quantum mechanics for a scaling 3-node quiver

⇔ quantum fluctuations around scaling solution with 3 bubbles

⇒ Black-hole like entropy growth ...

(ii) N centers → k N centers increases the number of fluctuation modes by a factor of k but $E_{gap} \sim k^2$ or k^3

⇒ Entropy decreases...

Resolutions with large transition scales could be entropically favored!

Conclusions

- Part of fuzzball program: Classify and study ***smooth, horizonless*** solutions to supergravity

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

- Emerge from geometric transitions:

  Singular brane sources → Smooth cohomological fluxes

  Bubbles start at horizon

- ***Mechanism*** for supporting matter before a horizon forms

  Perhaps useful to "firewalls" and other "gravitationally unsupported" ideas

- Generalized "no go" theorem for semi-classical solitons in string theory:

  If the space-time is even remotely classical, then only ***topological fuzz*** *at the horizon scale can support a soliton: No Solitons without Topology*

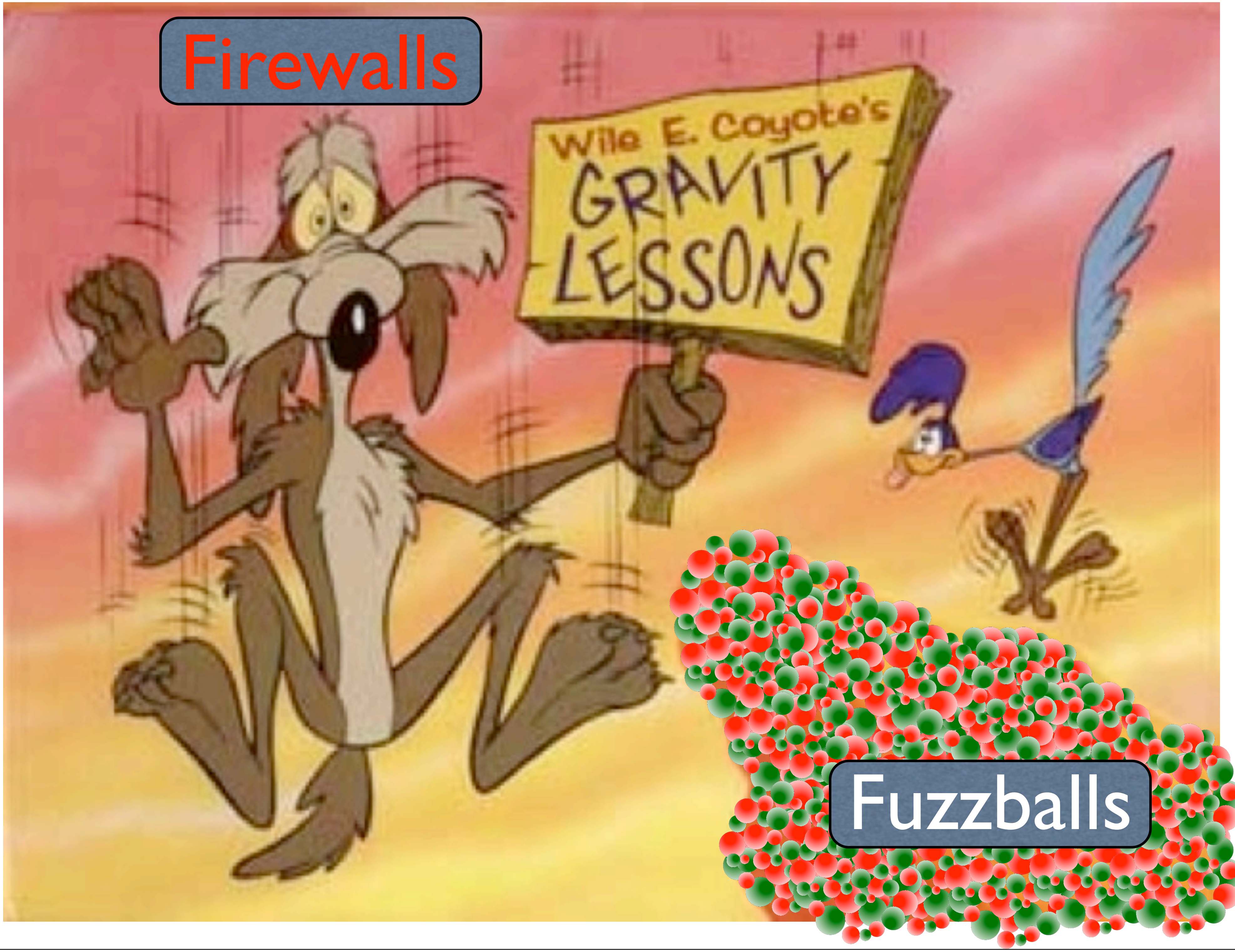
- Transition scale, λ_T = Scale of individual bubbles:

  Not fixed classically, large values entropically favored? $\lambda_T >> \ell_P$?

- Fluctuations of transitioned geometries: Scale E_{gap}. *Majority of entropy*?

- Multiple scales: The Horizon scale, M; The Transition scale, λ_T;

  The Energy Gap, $E_{gap} = (\lambda_{gap})^{-1}$; The Planck Length, ℓ_P.


Firewalls
Wile E. Coyote's
GRAVITY
LESSONS
Fuzzballs