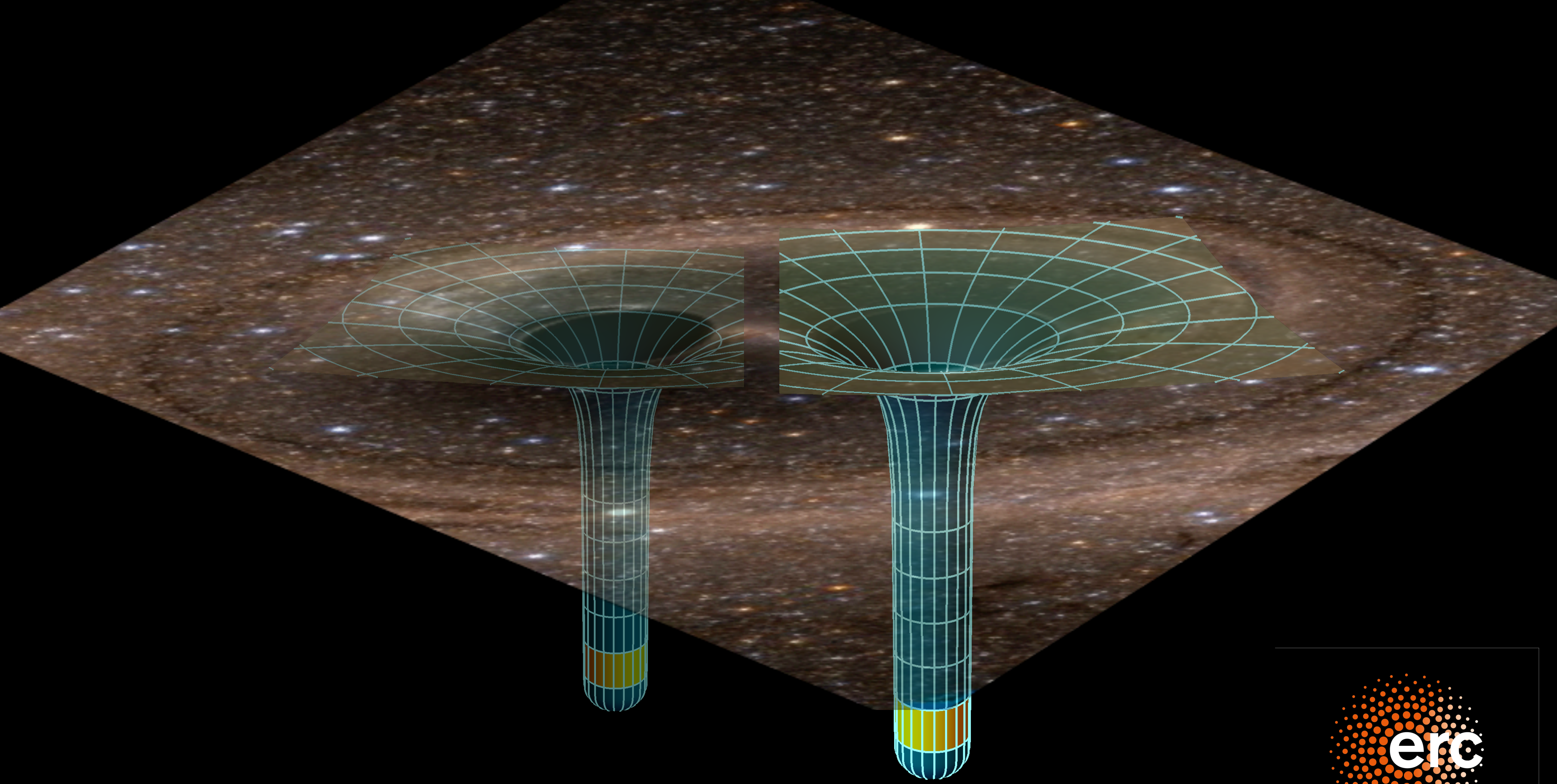
The Quantum from Geometry:

The States of the of Microstate Geometries



"*Geometry from the Quantum*"

Nick Warner, KITP Santa Barbara, *January 13-17, 2020.*

European Research Council

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Outline

The present state

- ★ Why microstate geometries are an essential part of black-hole physics

Illustrate these ideas:

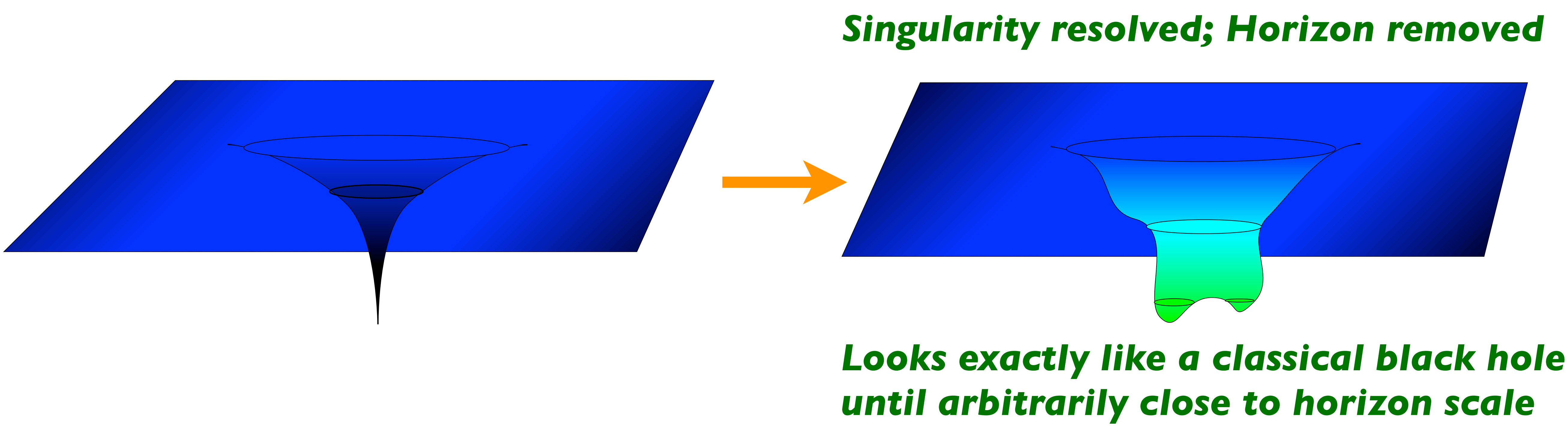
- ★ The structure of microstate geometries; *superstrata*
- ★ The holographic dictionary for *superstrata*
- ★ Probing superstata

The (hopefully near) future state

- ★ Infall and energy exchange; viscosity
- ★ The gravity dual of twisted-sector states
- ★ Non-extremal microstate geometries *and gauged supergravity*

Microstate Geometries

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



No horizons ⇔ No information problem

Fundamental mechanism: *Replace singular sources by topology and topological fluxes from geometric transitions*

Now have huge "zoos" of examples ….

… almost all are BPS

Why you *must* care about *Microstate Geometries* I

They embody the only *gravitational mechanism* that can support structure at the horizon scale

Gibbons and Warner, arXiv:1305.0957

Whatever quantum system you use to model a black hole:

- ★ It must look and behave like the astrophysical black hole described by GR close to the horizon scale … *it better have some gravity*
- ★ It must have microstructure accessible from near the horizon scale

This strongly suggest that such a quantum system

- has a *semi-classical limit* that supports horizon-scale microstructure against gravitational collapse $\Rightarrow$ *This limit* must be a *microstate geometry*
- there should be a limit in which some of the quantum states are described as stringy fluctuations in a *microstate geometry*
- … and coherent combinations of such quantum states should be describable as supergravity fluctuations about a *microstate geometry*

Microstate geometries provide a gravitational laboratory for studying horizon-scale microstructure

Why you *must* care about *Microstate Geometries* II

Holographic RG flows, phase transitions and geometric transitions

The problem: Start from a UV CFT, perturb the Lagrangian, determine the correct IR physics

The challenges: What is the *new IR phase*; *Multiple phases*? What are the *order parameters* and their *vevs* and *how do they evolve* into the IR? Are there *new scales generated in the IR*? Is there a *mass gap*, and how do you *compute it*?

Last 20 years: Large range of examples …. and some very important and general lessons for the gravity side of this duality.

★ IR geometry: Branes often undergo phase transition to create non-trivial cohomological cycles

- *Magnetic fluxes* on those cycles dual to *order parameters*
- *Scale of the cycle* is the emergent *scale of new phase*
- Scale of cycle + redshift between UV and IR geometry → Mass gap

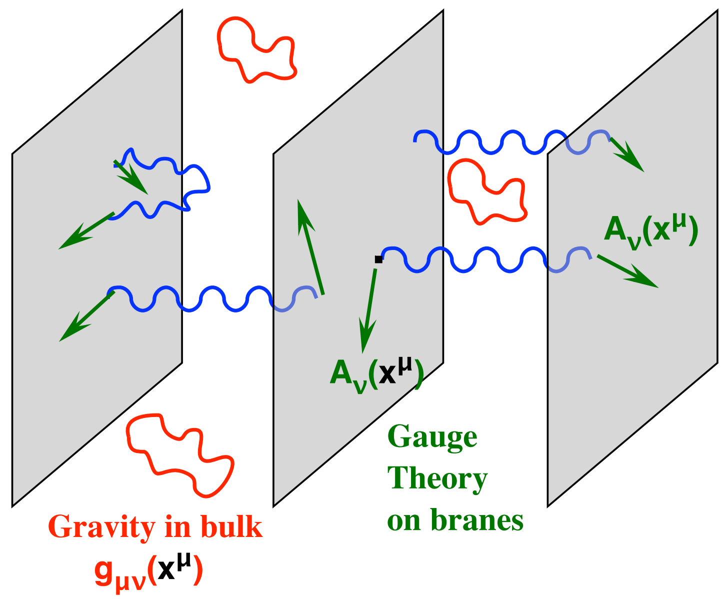
★ You *should impose too much symmetry*: you may be forbidding the transition to the new phase

★ You must *activate all appropriate IR degrees of freedom*: or you may be forbidding the order parameters of the new phase

★ Singular IR Geometry: usually the *missing essential physics*/*wrong IR phase*

The holographic dual of a flow to a confining gauge theory

N = 2 *or* N = 4 *Yang Mills*

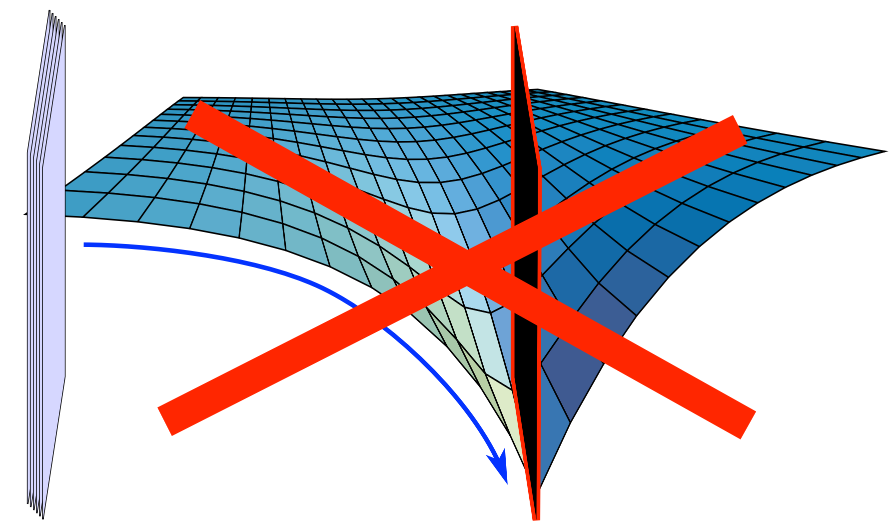


Turn on masses and flow to N=1 *SQCD*

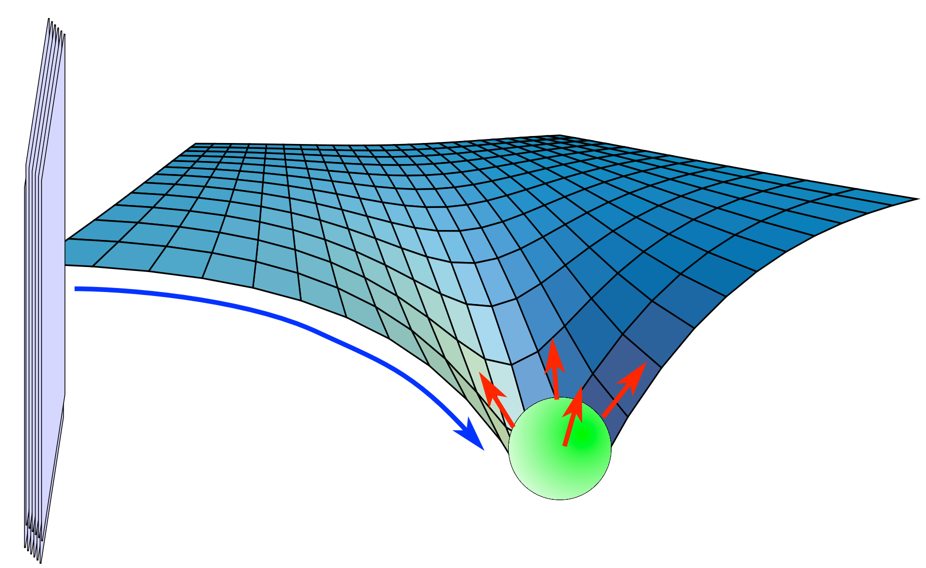
Interesting failures: Singular flows.

- **Gauged supergravity (GPPZ)**
- **Klebanov-Tseytlin**

Limited/Wrong IR Physics



Polchinski-Strassler flow
Klebanov-Strassler flow



The first attempts failed because they were missing critical degrees of freedom essential to the underlying physics … and too much symmetry

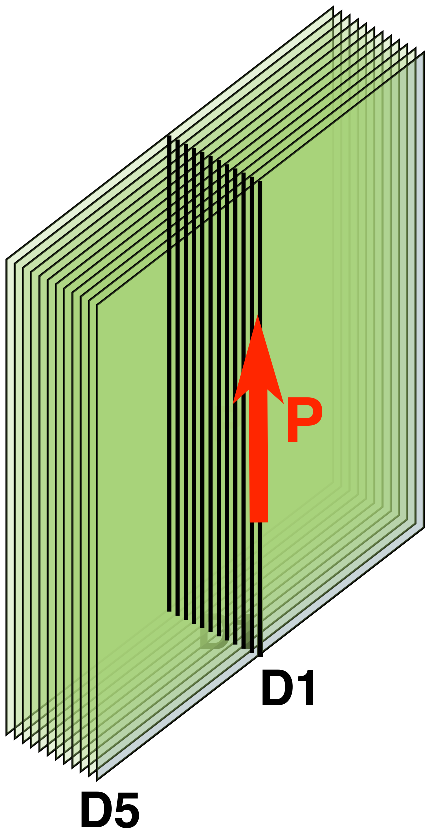
Correct holographic description

- *Magnetic fluxes dual to gaugino condensates*
- *Scale of the cycle dual to SQCD scale*
- Scale of cycle + redshift → Mass gap

***Microstate geometries*:**

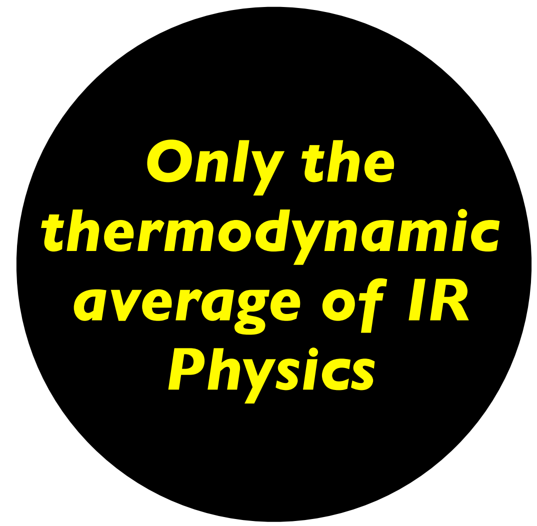
This collection of ideas applied to black holes …

Black-hole physics



Finite string coupling, g_s

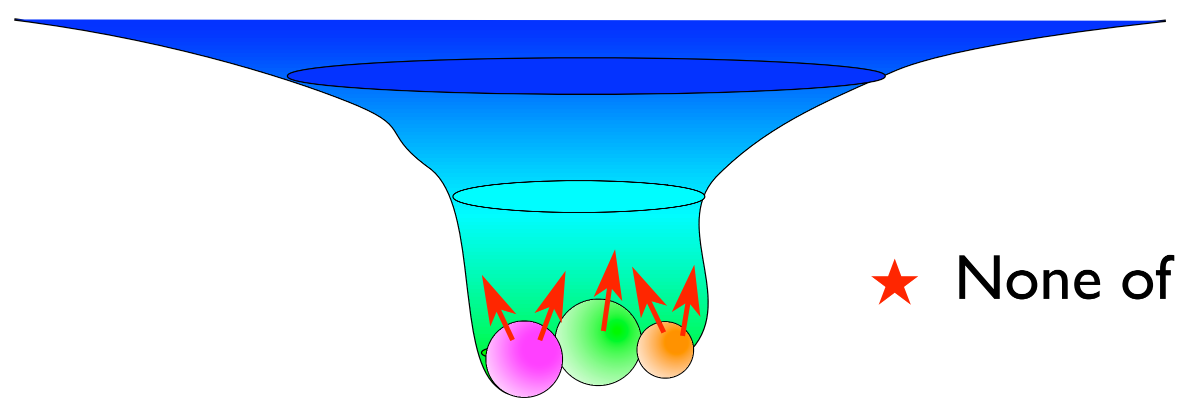
Spherically symmetric solution to gravity



Physics obscured by imposing too much symmetry

- ★ No scale, no mass gap
- ★ An information problem
- ★ Degrees of freedom *completely inaccessible*

Microstate geometry

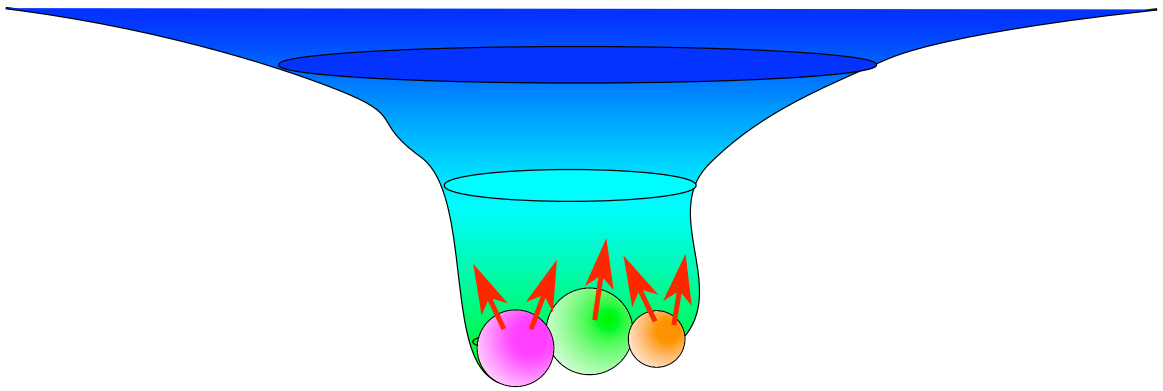


- ★ None of the above

The Microstate Geometry Program so far …

Two basic mechanisms underlying microstate geometries

Pure topology:
Charges from cohomological fluxes

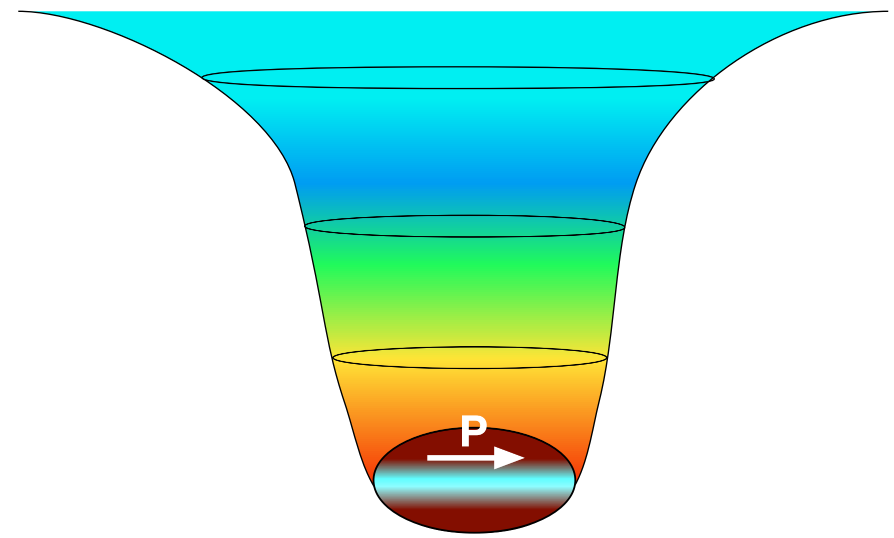


$$d * F^{(p)} \sim \sum_k G^{(k)} \wedge G^{(D-p-k)}$$

Charges from Chern-Simons interaction

Holographic Dictionary **= *Open problem!***

Superstrata:
Momentum waves on topological "bubbles"



Third charge adjusted via momentum waves on bubbled geometry

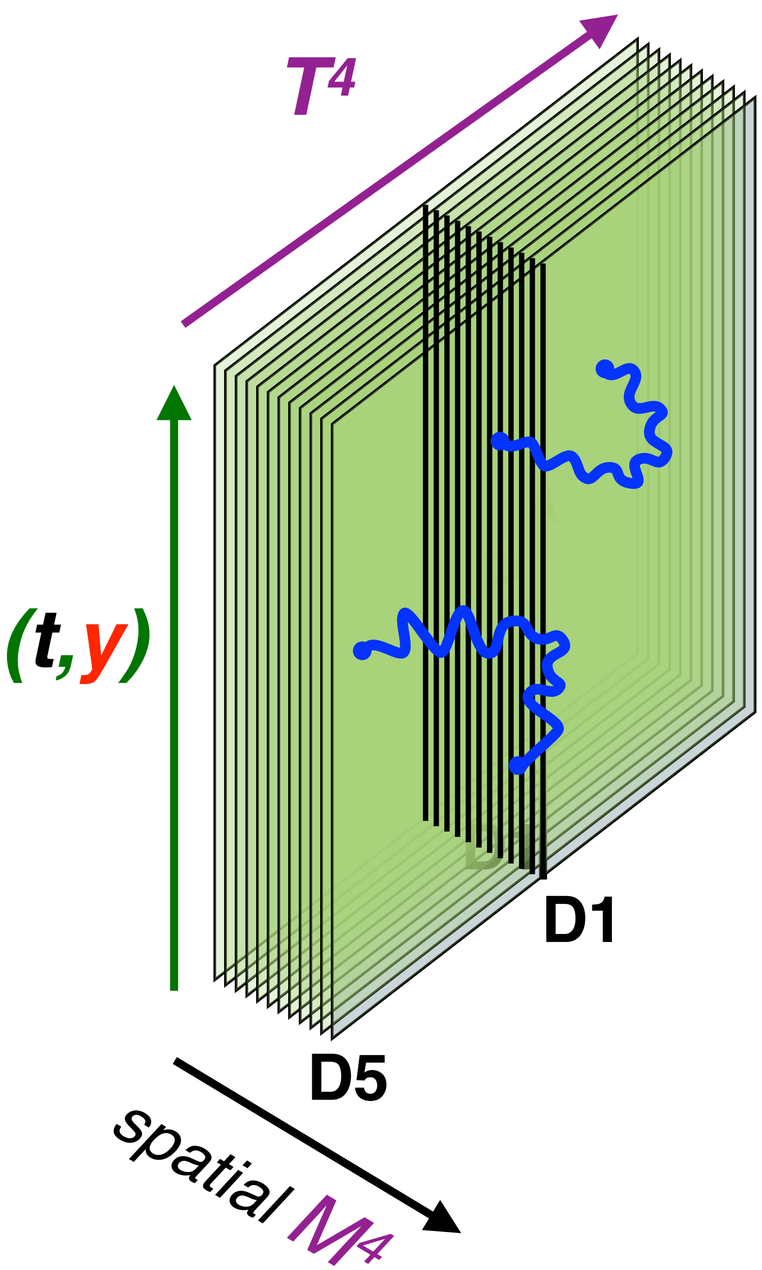
Well-developed holographic dictionary

⇒ Central focus for last few years

+ *Hybrids = Momentum waves on multi-bubble geometries* **= *Open problem!***

Superstrata

The Field Theory: The D1-D5 system wrapped on $T^4 \times S^1(y)$

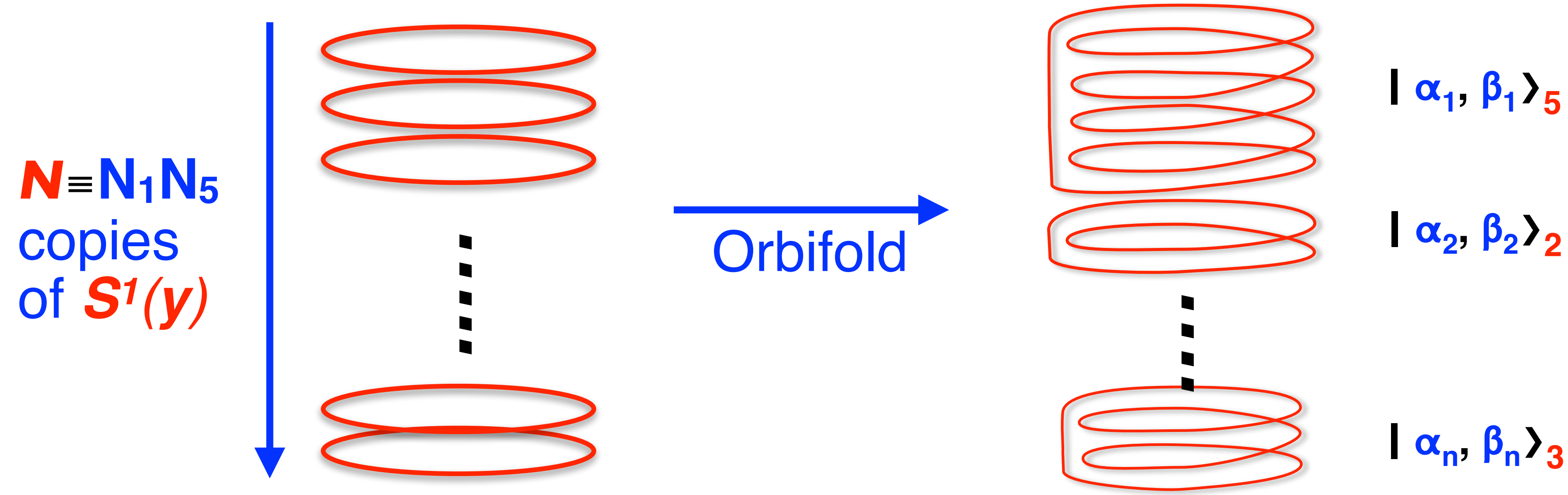


Open D1-D5 superstrings moving in T^4

with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$

$\Rightarrow$ Supersymmetric CFT with $c = 6\, N_1 N_5$

Ramond-Ramond Ground States



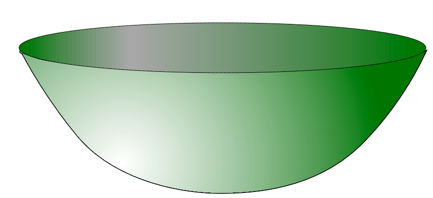
Ground-state spins on strand of length k: $|\, \alpha_i, \beta_i \rangle_k$

Mode excitations on sphere

These are ¼ BPS States with (4,4) supersymmetry

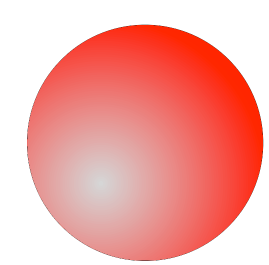
Gravity dual: $AdS_3 \times S^3$

Maximally spinning ground state: $\left(|+\tfrac{1}{2}, +\tfrac{1}{2}\rangle_1\right)^N$



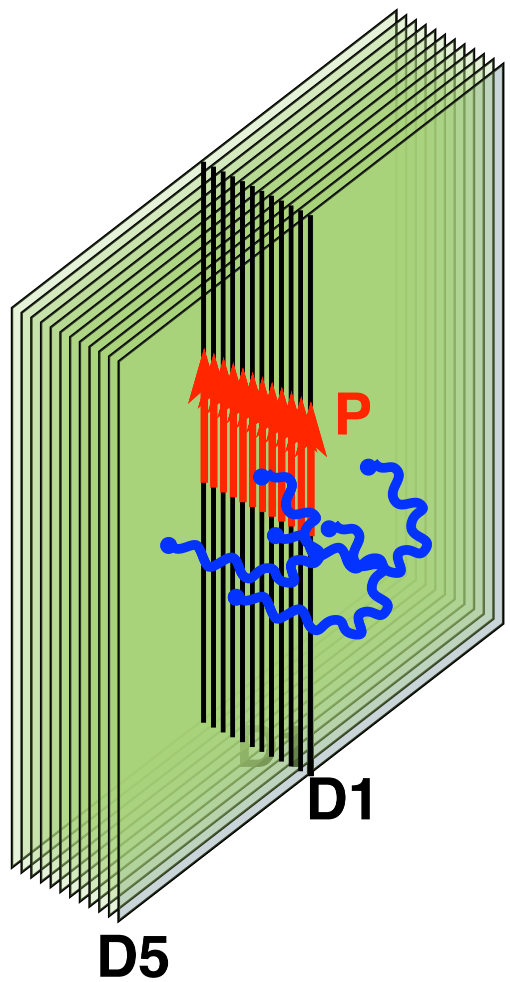
(t, y, r)

×



(θ, ψ, ϕ)

Momentum Excitations:



Add purely left-moving momentum:

$Q_P \sim N_P = L_{0,\text{left}} \neq 0$

Right moving sector: Ramond ground state

$\Rightarrow$ ⅛ BPS states

At vanishing string coupling, ***$g_s \to 0$***, *Cardy formula*:

$$S \equiv \log\big(\Omega(Q_P)\big) = 2\pi\sqrt{\frac{c}{6}\,L_0}$$

$$= 2\pi\sqrt{N_1\,N_5\,N_P} = 2\pi\sqrt{Q_1\,Q_5\,Q_P}$$

Finite string coupling, ***g_s***

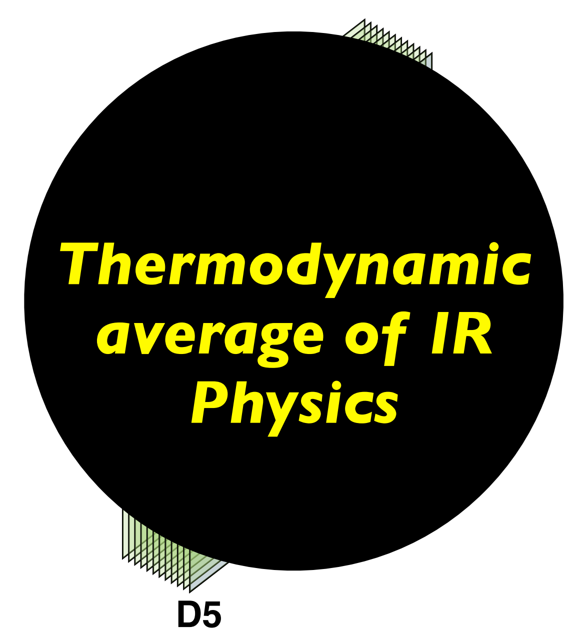
★ *Spherical symmetry*: Matter/microstate structure disappears inside black-hole horizon

$$S = \frac{1}{4}\,A = 2\pi\sqrt{Q_1\,Q_5\,Q_P}$$

Perfect match! Declare victory ….

Strominger, Vafa 1996

Horizon Area, A



Too much symmetry

Superstrata and the holography of the D1-D5 CFT

We now know the holographic dual of a very specific coherent subsets of the BPS states counted by Strominger and Vafa: ***"Supergraviton gas"***

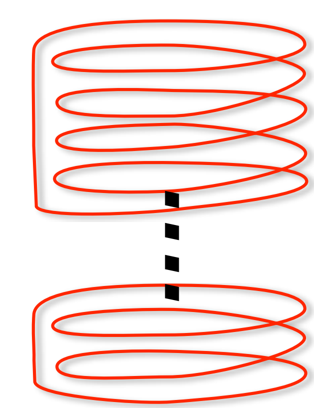
Left-moving states: (Right moving sector: *Ramond ground state;* ⅛ BPS)

$$\big(|+\tfrac{1}{2}\,,+\tfrac{1}{2}\rangle_1\big)^{N_0}\otimes\Bigg[\bigotimes_{k_i,m_i,n_i}\bigg(\frac{1}{m_i!\,n_i!}\,(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\bigg)^{N_{k_i,m_i,n_i}}\Bigg]$$

$i = 1, \ldots, N \equiv N_1 N_5$

Momentum and R-charge excitations

$|\alpha_1, \beta_1\rangle_5$



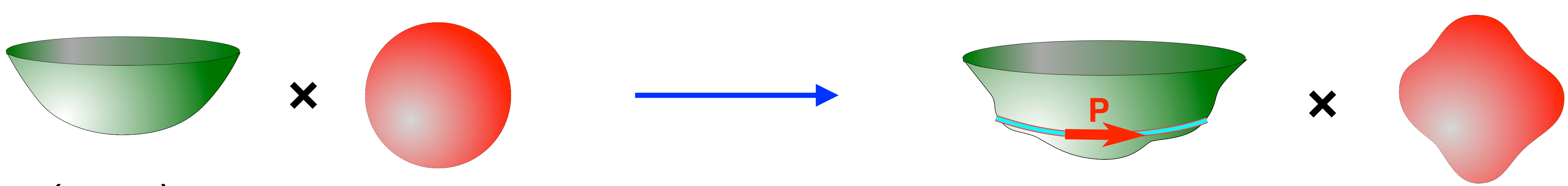
$|\alpha_n, \beta_n\rangle_3$

Geometric modes:

$$\chi_{k_j,m_j,n_j} \;\equiv\; R^{-1}\,(m_j+n_j)\,v \;+\; \tfrac{1}{2}\,(k_j-2m_j)\,\psi \;-\; \tfrac{1}{2}\,k_j\,\phi$$

Coherent states $\quad N_{k_i,m_i,n_i} \gg 1$

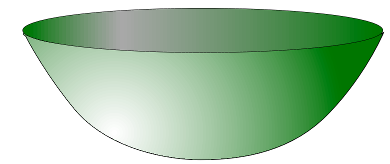
$AdS_3 \times S^3$ Harmonic deformation of $AdS_3 \times S^3$



(u,v,r) (θ,ψ,ϕ)

Superstrata: Holomorphic waves of microstructure

Coherent states of the supergraviton gas:



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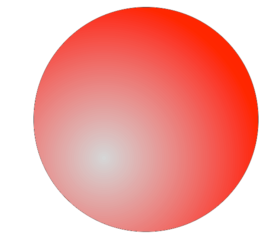


(u,v,r) (θ,ψ,ϕ)

Geometric modes:

$$\chi_{k_j,m_j,n_j} \equiv R^{-1}(m_j+n_j)\,v \;+\; \tfrac{1}{2}(k_j-2m_j)\,\psi \;-\; \tfrac{1}{2}\,k_j\,\phi$$

with arbitrary Fourier coefficients

⇒ Supergravity solutions based on arbitrary functions of ***three variables***

Generic ***BPS*** Superstrata ⇒ arbitrary *holomorphic* functions of three variables

$$\xi \equiv \frac{r}{\sqrt{r^2+a^2}}\, e^{i\frac{\sqrt{2}}{R_y}v}\,, \quad \chi \equiv \frac{a}{\sqrt{r^2+a^2}}\,\sin\theta\, e^{\frac{i}{2}(\psi+\phi)}\,, \quad \eta \equiv \frac{a}{\sqrt{r^2+a^2}}\,\cos\theta\, e^{i\left(\frac{\sqrt{2}v}{R_y}-\frac{1}{2}(\psi-\phi)\right)}$$

Hugely simplifies the construction …

P. Heidmann, N.P. Warner: 1903.07631

P. Heidmann, D.Mayerson, R. Walker, N.P. Warner: 1910.10714

Superstrata → largest classes of solutions ever built = States of the supegraviton gas

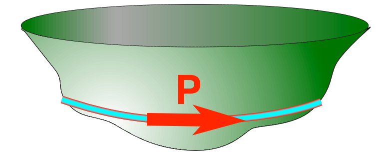
Counting superstrata:

$$S_{superstrata} \sim \sqrt{Q_1Q_5}\,(Q_P)^{1/4} \quad \ll \quad \sqrt{Q_1Q_5Q_P} \sim S_{black\ hole}$$

M. Shigemori, 1907.03878

What are superstrata missing? *The twisted sector states of the CFT …*

The structure of the (2+1)-geometry



Asymptotically flat $R^{4,1} \times S^1$ → BTZ ($\times S^3$) → Capped in IR by global AdS_3

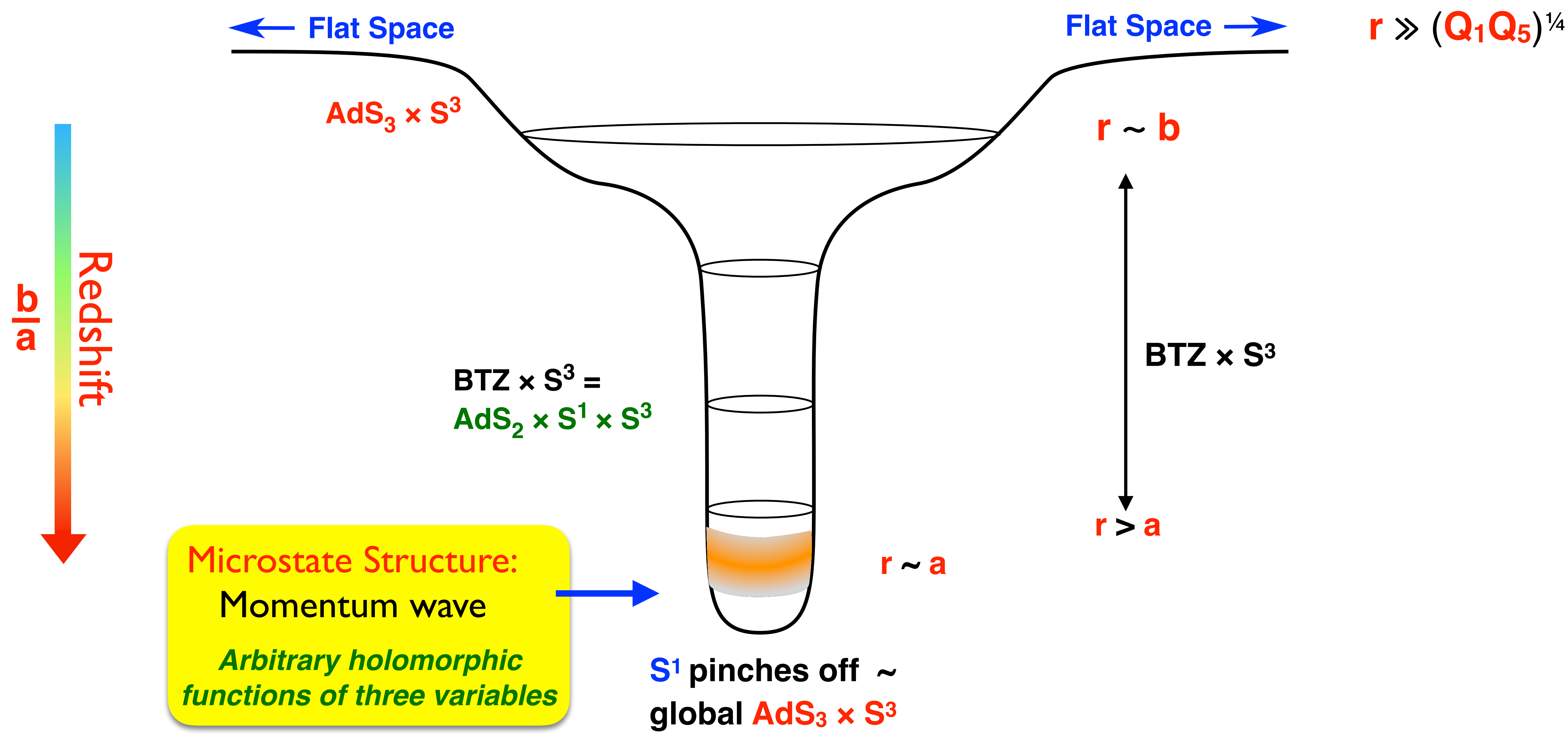
Looks just like a five-dimensional black hole

Important scales related to charges

b ↔ *momentum charge*, Q_P

a ↔ *angular momenta*, j_L, j_R

Low angular momentum: $b \gg a$



A Simple Class of D1-D5 States

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{n!}\,(L_{-1}-J^3_{-1})^n|00\rangle_1\right)^{N_n} \qquad \text{with} \qquad N_1\,N_5 \;=\; N_0 \;+\; N_n$$

(0,4) supersymmetry; **⅛** BPS states

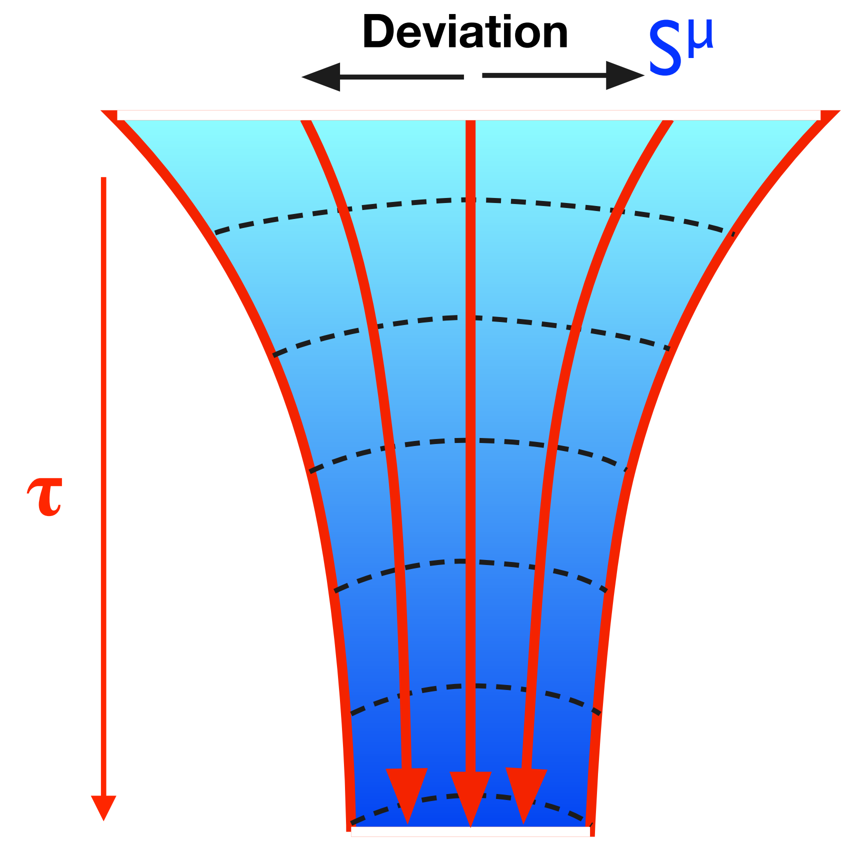
Supergravity Parameters: Fourier Coefficients **a, b**; Momentum mode, **n**

Compactification/Planck Scale: $\mathcal{K} \;\equiv\; \dfrac{\mathrm{Vol}(T^4)\,R_y^2}{\ell_{10}^8}$

Quantized Parameters:

$$j_L \;=\; \tilde{j}_R \;=\; \tfrac{1}{2}\,\mathcal{K}\,\mathbf{a^2} \qquad\qquad N_P \;=\; \tfrac{1}{2}\,\mathcal{K}\,n\,\mathbf{b^2}$$

Probing Microstate Geometries: Tides



Consider a family of *time-like* geodesics with velocity vectors, V^μ, and proper time, τ

A *deviation vector*, S^μ, is any *space-like* unit vector (at $\tau = 0$) and everywhere perpendicular to the geodesics:

$$S^\mu S_\mu \big|_{\tau=0} = 1 \,, \qquad V^\mu S_\mu = 0$$

The *relative acceleration* between geodesics in a family is then given by:

$$a^\mu \equiv \frac{d^2 S^\mu}{d\tau^2} = \mathcal{A}^\mu{}_\nu S^\nu$$

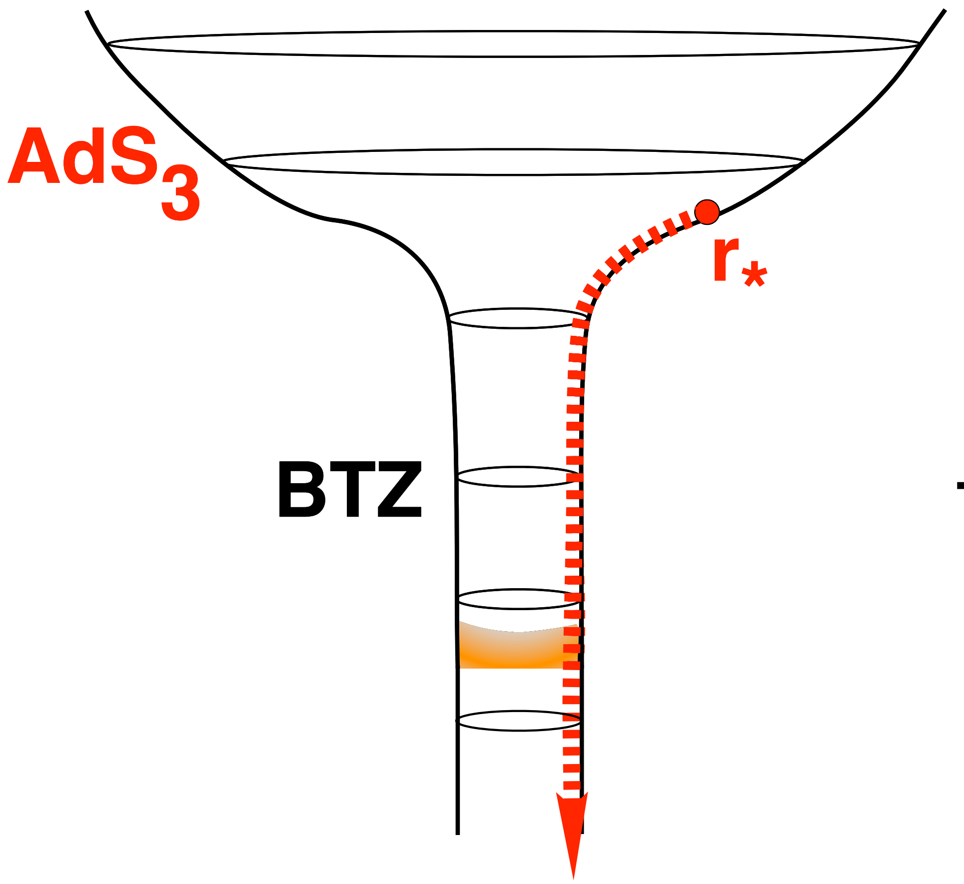
where $\mathcal{A}^\mu{}_\nu \equiv - R^\mu{}_{\rho\nu\sigma} V^\rho V^\sigma$ is the *tidal tensor*.

The tidal tensor satisfies $\mathcal{A}^\mu{}_\nu V^\nu = 0$ and so only has space-like components

The norm of the tidal tensor is defined by: $|\mathcal{A}| \equiv \sqrt{\mathcal{A}^\mu{}_\nu \mathcal{A}^\nu{}_\mu}$

and sets the scale of the tidal force per unit length, per unit mass

Tidal Forces: BTZ



BTZ Metric: ***a = 0***

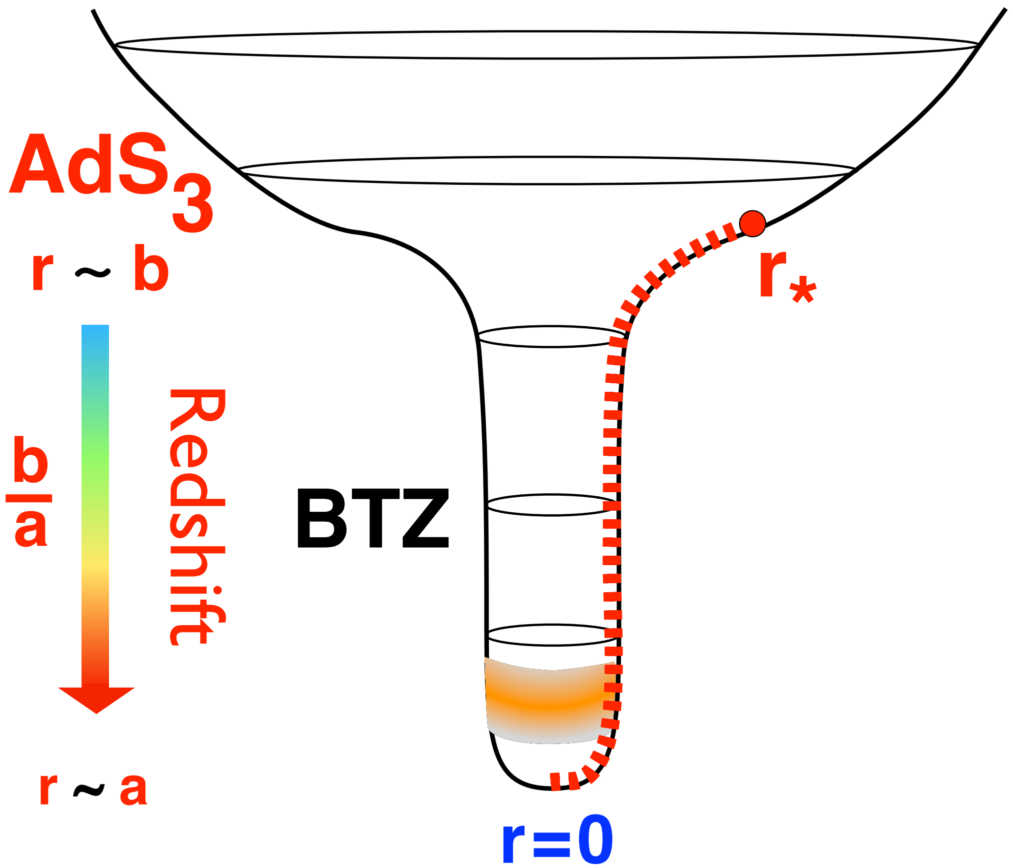
- No "drama at the horizon"
- Locally same curvature as *AdS3*

Tidal tensor magnitude along radial infall:

$$|\mathcal{A}| = \frac{2}{R_y\, b} = \frac{\sqrt{2}}{\sqrt{Q_1 Q_5}} = \frac{\sqrt{2}}{\sqrt{N_1 N_5}} \frac{\sqrt{\text{Vol}(T^4)}}{\ell_{10}^4}$$

Vanishes for large ***N*** $\equiv N_1 N_5$

Tidal Forces in Superstrata



Tidal tensor has BTZ term: $|\mathcal{A}| = \dfrac{2}{R_y\, b}$

Tidal tensor also has higher multipole moments:

$$|\mathcal{A}|_{\text{throat}} \sim \frac{a^2\, b^2\, E^2}{r^6}$$

E = energy of geodesic particle

Note that this vanishes for BTZ (a=0)

$$r_* \approx b\sqrt{n} \quad \Rightarrow \quad |E| \approx \sqrt{\frac{b\, n}{R_y}} \quad \Rightarrow \quad |\mathcal{A}|_{\text{throat}} \sim \frac{a^2\, b^3\, n}{R_y\, r^6}$$

At $r \sim \sqrt{a\, b}$ this gives $|\mathcal{A}|_{\text{throat}} \sim \dfrac{n}{a\, R_y} \sim \dfrac{n}{\sqrt{2\, j_L}} \dfrac{\sqrt{\text{Vol}(T^4)}}{\ell_{10}^4}$

At $r \sim \sqrt{a\, b}$ in the deepest possible throats: $|\mathcal{A}|_{\text{throat}} \sim \dfrac{\sqrt{\text{Vol}(T^4)}}{\ell_{10}^4}$

$\Rightarrow$ Tidal forces hit the Planck/Compactification scale at $r \sim \sqrt{a\, b}$

String probes

E. Martinec, N.P. Warner: 200X.XXXX

Penrose limit of ultra-relativistic *radially infalling* string:

Light-cone gauge: $x^- = \alpha' p^+ \tau$

Transverse oscillations

$$(\partial_\tau^2 - \partial_\sigma^2) z^i = (\alpha' p^+)^2 \mathcal{A}_{ij}(\alpha' p^+ \tau)\, z^j$$

***A*$_{ij}$** is a "time-dependent" mass term.

AdS or BTZ: ***A*$_{ij}$** $\equiv 0$

Superstratum at large r, ***A*$_{ij}$** has eigenvalues ~ $+\frac{a^2\, b^2}{r^6}$ and $-\frac{a^2\, b^2}{r^6}$

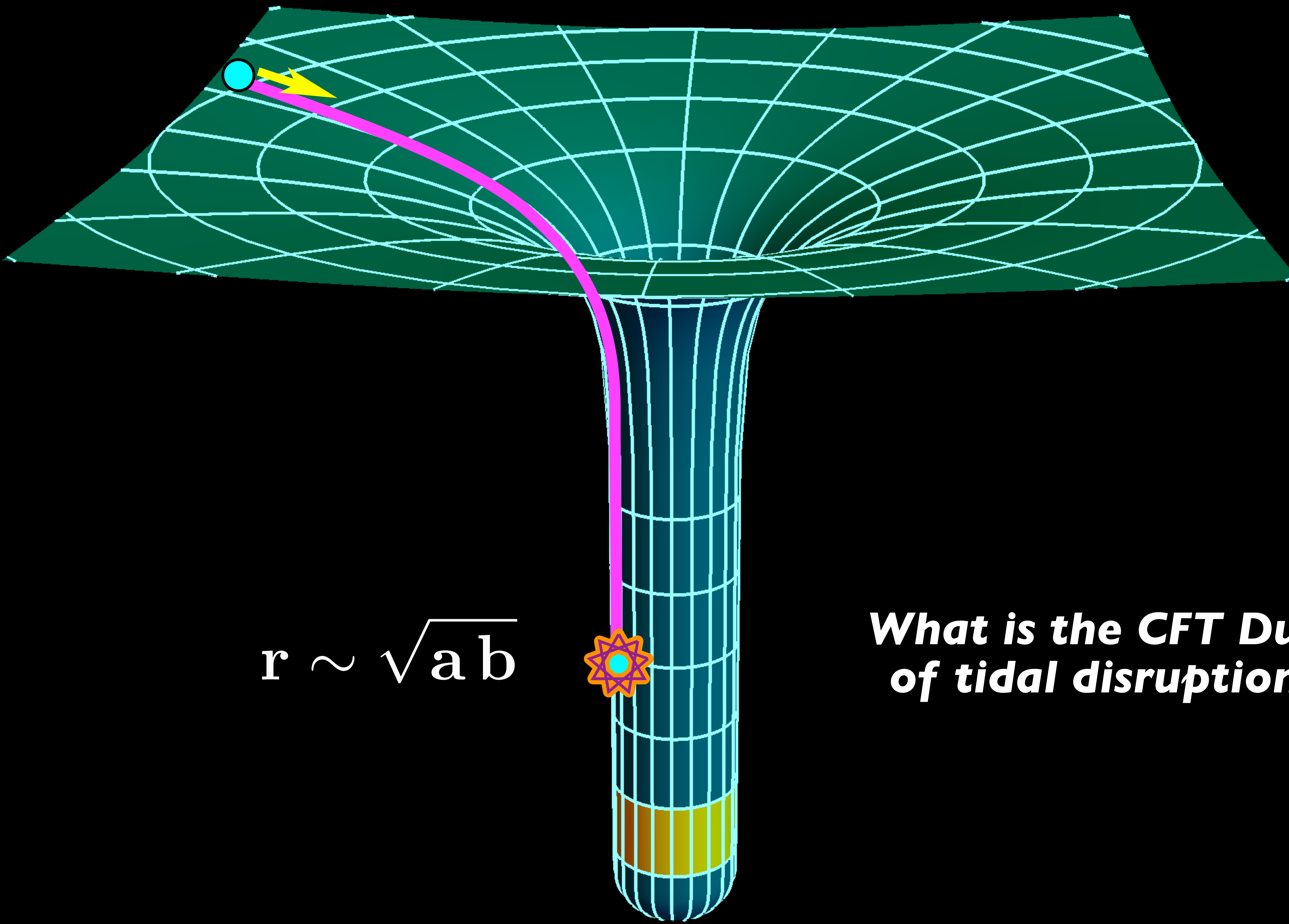
⇒ Exponentially growing mode ..

Recall tidal tensor: $|\mathcal{A}|_{\text{throat}} \sim \frac{a^2\, b^2\, E^2}{r^6}$ with $E \sim \alpha' p^+$

Ultra-relativistic speeds enhance multipole moments of microstate geometries

⇒ Tidal forces scramble infalling matter* into stringy excitations

***falling from a large distance**



$$r \sim \sqrt{a\,b}$$

What is the CFT Dual of tidal disruption?

Next steps and open problems ...

Tidal forces and viscosity

(*Why you should care about Microstate Geometries* **III**)

Supergravity can be a powerful tool in understanding the *large-scale effective hydrodynamics* of strongly coupled quantum systems ….

e.g.
- ✦ *Viscosity and jet-quenching in quark-gluon plasmas*
- ✦ *Trailing strings and viscous drag from microstate geometries*

I. Bena, A. Tyukov: 1911.12821

★ Tides ⇒ Energy transfer to probes

★ Back-reaction of tidal effects on probes
→ Energy transfer between probes and background

★ Use D1-brane probes
→ background/probe on same footing

★ Estimate energy exchange with background as probe scrambles
→ effective viscosity of interactions with microstates

★ ***What is the CFT analogue of this tidal disruption?***

Twisted sector states: The bulk of black hole entropy

- Very limited supergravity examples from orbifolds
- "W-branes:" wrapping branes around cycles of microstate geometries

Martinec and Niehoff, 1509.00044

Entropy of such states grows as $\sim \; Q^{3/2}$

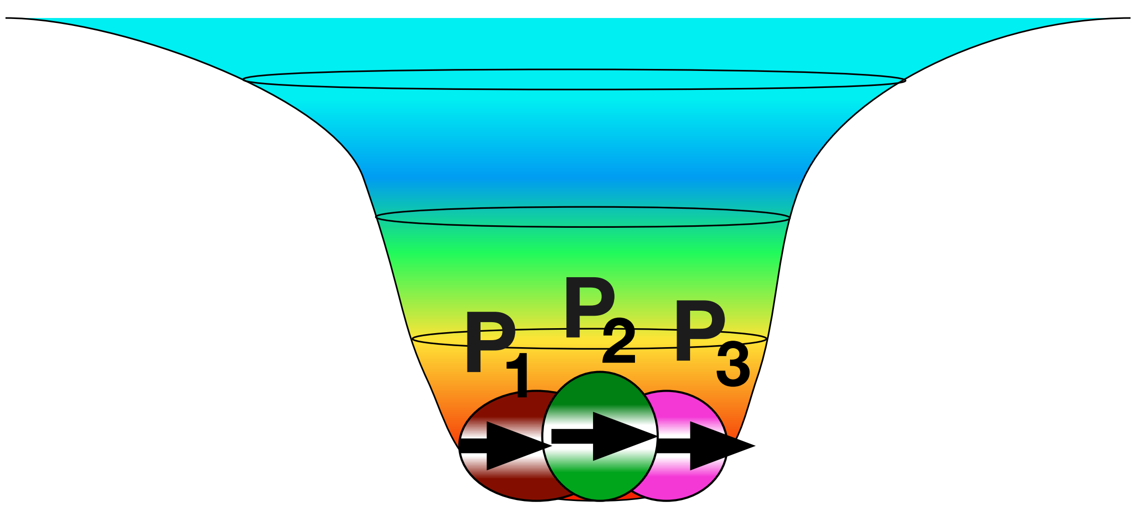
Massless limit ➞ *Semi-classical description of black-hole microstructure*

Generic coherent twisted sector excitations should be visible in supergravity.

- States of open strings stretched between branes ➞ *Magnons*

Related to (?) open problem on the gravity side:

The holography of multi-centered microstate geometries: multi-superstrata



UV: *D1-D5 CFT with c = 6* $N_1 N_5$

Holographic RG flow

IR: *State/Phase of D1-D5 CFT*
Complex "product of CFTs" each with some momentum excitation

Magnon condensates?

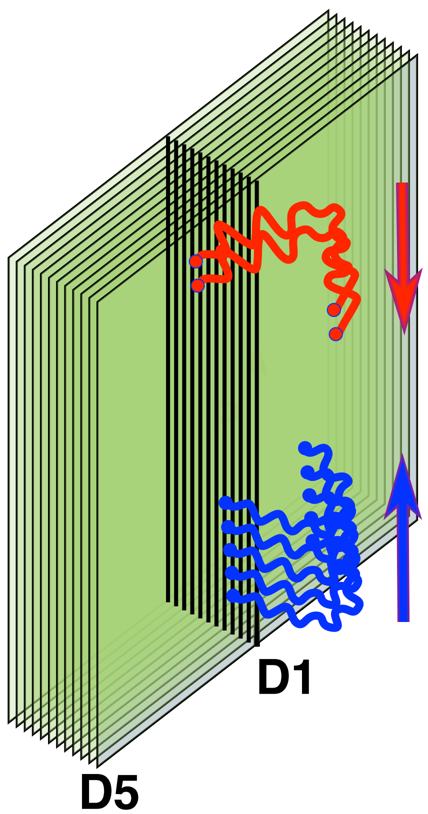
Bena, Shigemori, NPW

Non-extremal microstate geometries:

Colliding superstrata

Following the results of Strominger and Vafa in 1996, there was an industry analyzing such *near BPS* states in the CFT and at vanishing string coupling, $g_s \to 0$

Near BPS $\leftrightarrow$ *Small number,* N_{Right}*, of right movers*



- ★ Non BPS: $M \sim N_{Left} + N_{Right}$, $Q_P \sim N_{Left} - N_{Right}$
- ★ State counting worked well, including both left-moving and right-moving states
- ★ Small Hawking Temperature
- ★ Hawking radiation is correctly captured by open string scattering into closed strings
- ★ Grey-body factors work nicely …

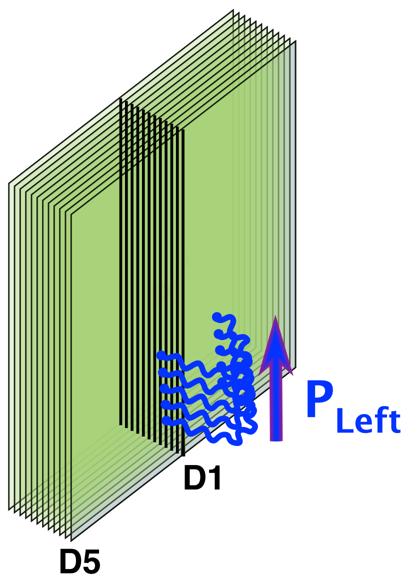
Beautifully controlled supersymmetry breaking.

All of this was done in the CFT and with $g_s \to 0$

Can we find the gravity dual with finite g_s*?*

The BPS story gave us a precise holographic dictionary …

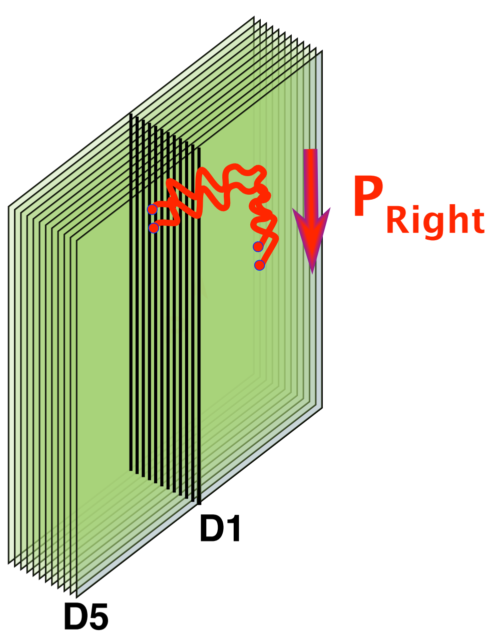
Setting up the scattering problem in gravity



(0,4) supersymmetry

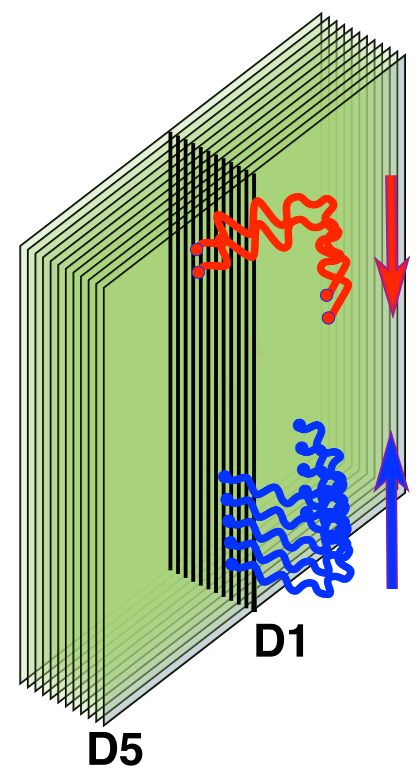
These BPS solutions are exactly known - localizable momentum waves

Holographic dictionary is also known

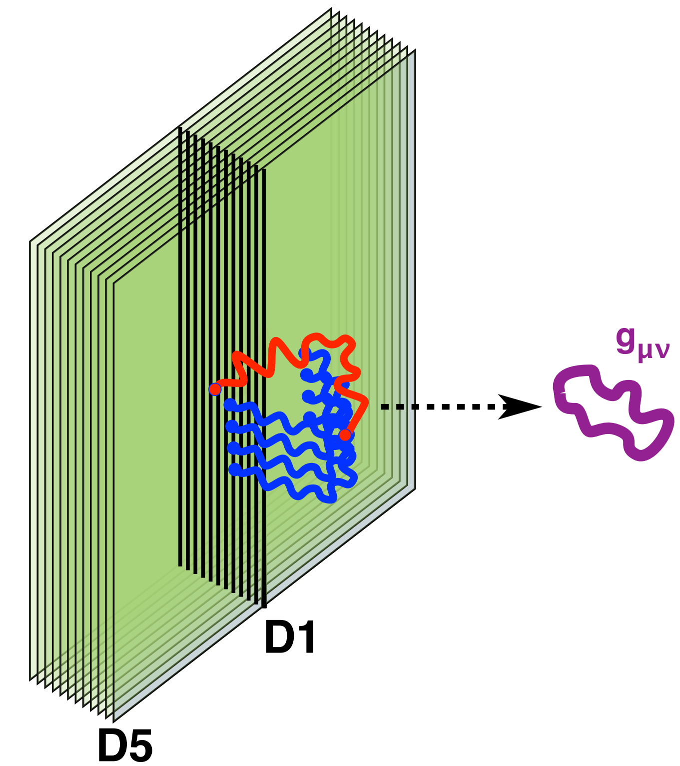


(4,0) supersymmetry

Holomorphic waves in superstrata: *Accurate approximations to solutions with* ***localized regions*** *with (0,4) and (4,0) supersymmetry*



The really hard part: The waves collide.



BPS elements → *Precisely-posed initial value problem ….*

Still depends on all coordinates: (u,v,r,θ,ψ,ϕ)

Colliding superstratum states:

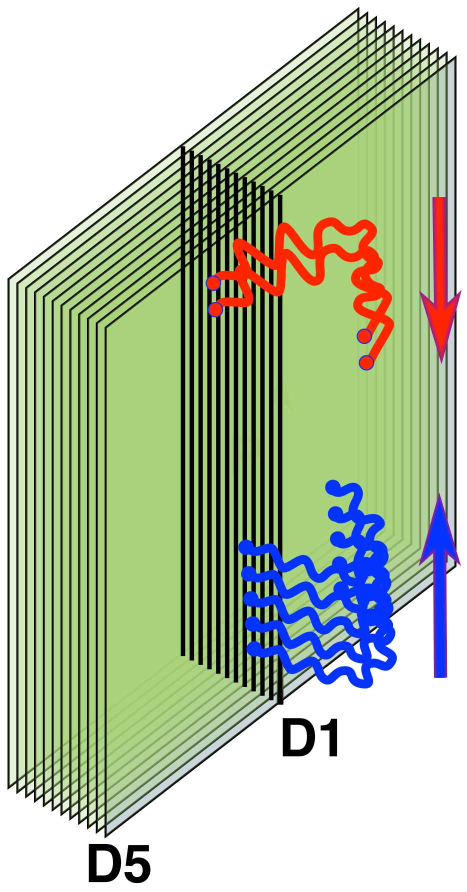
Options:

★ Treat the anti-BPS, right-moving states perturbatively …
in the exactly-known, left-moving superstratum background

★ Numerical simulations

- *Precisely-posed initial value problem for explicitly known D1-D5 CFT microstates*
- *One can do the dual computation in the CFT*

Perturbative calculations: Mathur; Bombini

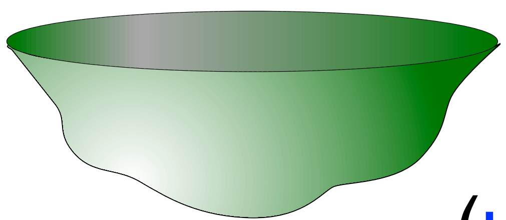


Gravity side:

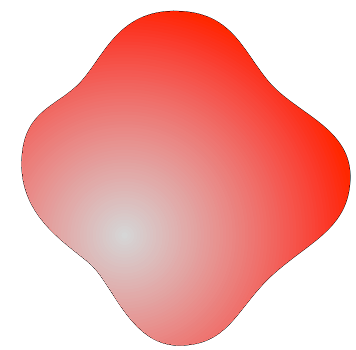
In principle, the solution depends on all six coordinates: (u,v,r,θ,ψ,ϕ)

However, exact results on superstrata have led to a huge bonus …

In the underlying six-dimensional supergravity theory, *colliding superstrata* can be described in terms of harmonic deformations of $AdS_3 \times S^3$



(u, *v*, *r*)



(θ, ψ, ϕ)

- There are still very rich families of both purely left-moving and purely right-moving superstrata that *only involve the lowest harmonics of* S^3.
- Restricting to these modes ***seems*** to be a *consistent truncation* of six-dimensional supergravity to a ***three-dimensional gauged supergravity***

D. Mayerson, R. Walker and NPW

Such superstrata, *and their collisions* **could** be described entirely in a gauged supergravity in three-dimensions (*u*, *v*, *r*):

All degrees of freedom described by a gauged non-linear σ-model (*SO(5,4)*) depending on only three space-time variables

Conclusions

- ★ To understand black-hole microstructure we need to apply all that we have learned from holographic field theory ⇒ *Microstate geometries*
- ★ *Microstate geometries: a laboratory for studying horizon-scale microstructure*
- ★ Superstrata: holographic dual of "supergraviton gas"
  - ★ Capped BTZ geometries
  - ★ Supergravity solutions that depend on arbitrary holomorphic functions of three variables
- ★ Infall and tidal scrambling
  - ★ Infall from large distances ⇒ scrambling half-way down the throat
  - ★ Viscosity/hydrodynamics of the microstructure: *Supergravity is good at this!*
  - ★ CFT dual of tidal disruption?

Important open problems

- ★ Systematics of twisted sector states; *W-branes;*

  Magnon condensates ?↔? Holography of multi-centered geometries
- ★ Non-BPS/Near-BPS ★ *Perturbation theory* ★ *Numerical simulations*
  - ★ We are in a position to address this problem because the study of BPS microstate geometries has given us the *holographic dictionary* and the ability to *localize waves*
  - ★ non-BPS scattering can be compared to CFT computations
  - ★ Gauged supergravity in three dimensions might lead to huge simplifications …