What do Black Hole Microstates look like ?

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with

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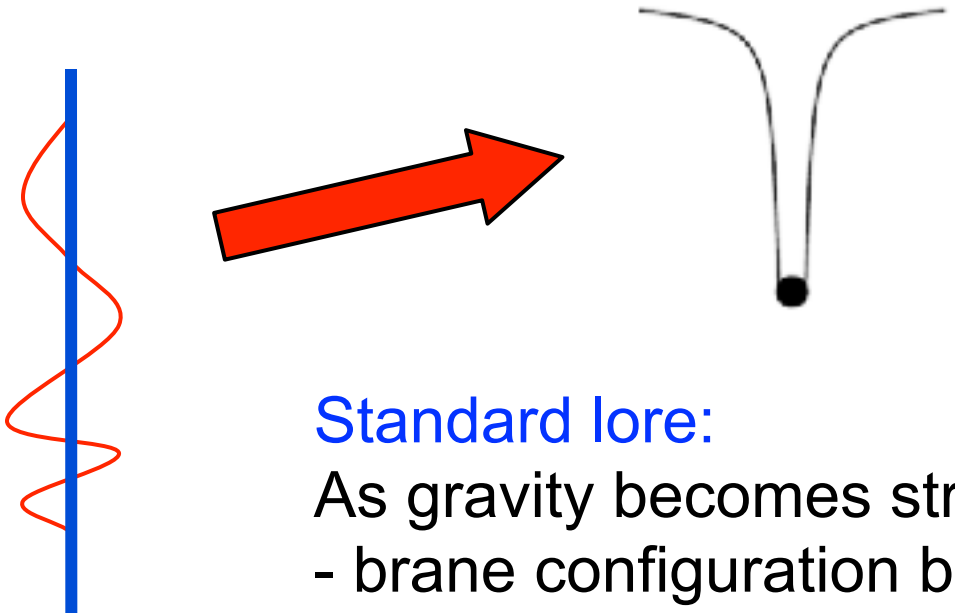
erc FQXi JOHN TEMPLETON FOUNDATION Agence Nationale de la Recherche ANR DE LA RECHERCHE À L'INDUSTRIE cea SACLAY

Strominger and Vafa (1996):

Black Hole Microstates at ***Zero Gravity*** (branes + strings)

Correctly match B.H. entropy !!!

One Particular Microstate at Finite Gravity:



Standard lore:

As gravity becomes stronger,

- brane configuration becomes smaller
- horizon develops and engulfs it
- recover standard black hole

Susskind
Horowitz, Polchinski
Damour, Veneziano

Strominger and Vafa (1996):

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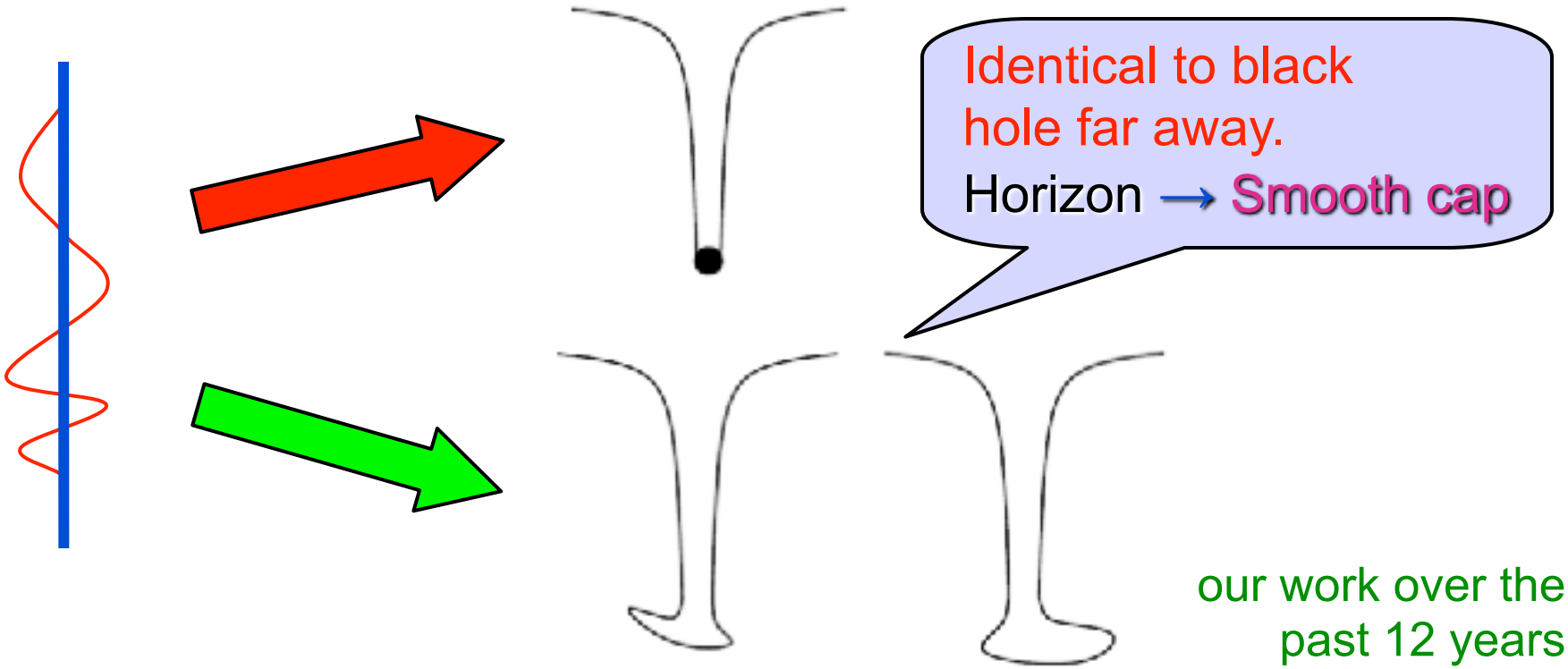


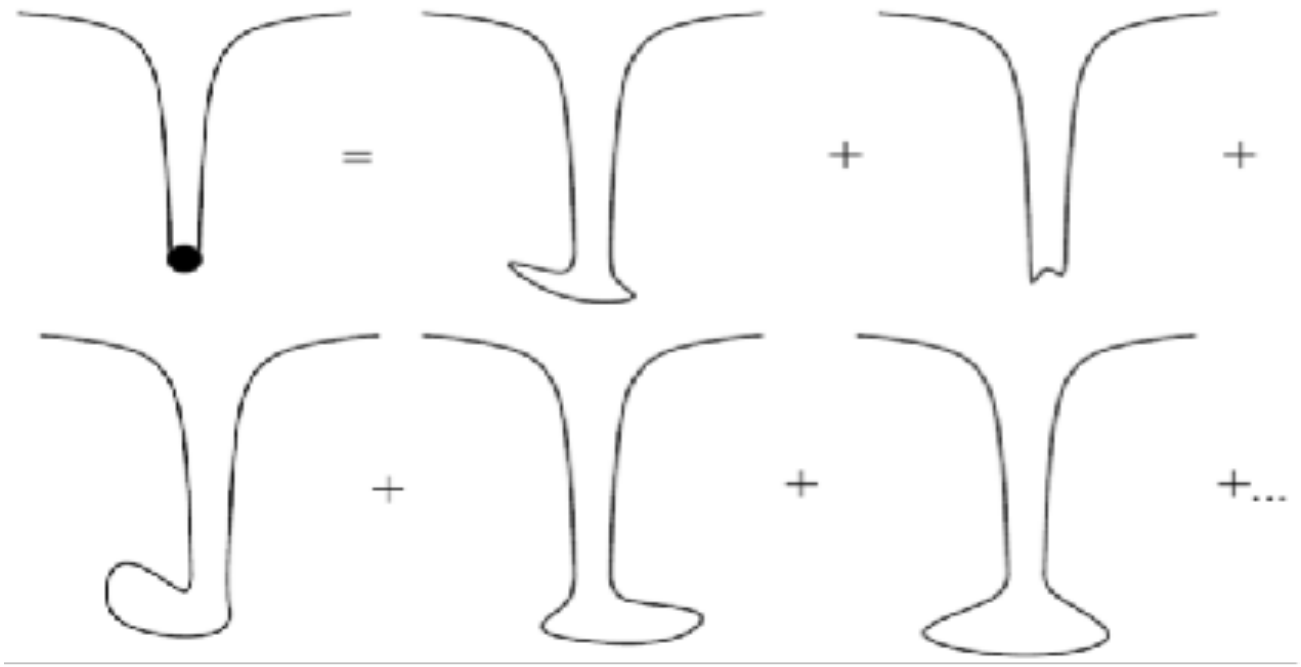
our work over the past 12 years

BIG QUESTION: Are ***all*** black hole microstates becoming geometries with no horizon ?

?

Black hole = ensemble of horizonless microstate configurations

Mathur 2003



Analogy with ideal gas

Thermodynamics

(Air = ideal gas)

$P\,V = n\,R\,T$

$dE = T\,dS + P\,dV$

Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Thermodynamics

Black Hole Solution

Statistical Physics

Microstate geometries

Long distance physics

Gravitational lensing

Physics at horizon

Information loss

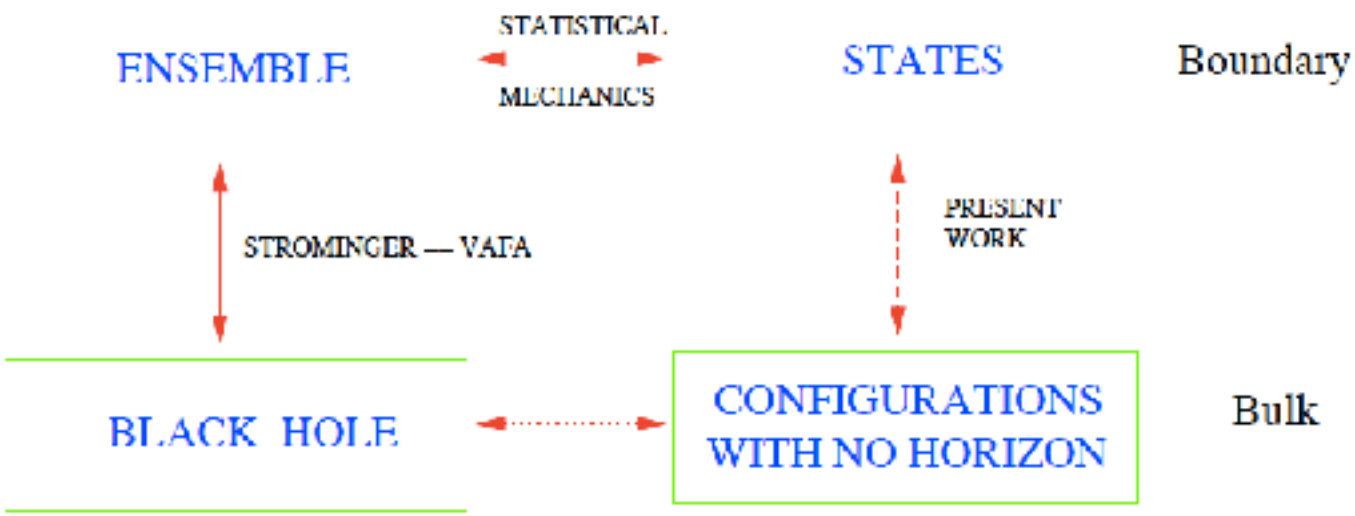
Gravity waves ?

Other formulations:

e.g. Bena, Warner, 2007

- **Thermodynamics (EFT)** breaks down at horizon. New low-mass d.o.f. kick in.

- No spacetime inside black holes. **Quantum superposition** of microstate geometries.



Not some hand-waving idea - provable by rigorous calculations in String Theory

Word of caution

- To replace classical BH by BH-sized object
  - Gravastar
  - Infinite density firewall hovering above horizon
  - LQG configuration
  - Quark-star, you name it …

  satisfy 3 very stringent tests:

1. Same growth with G_N !!!

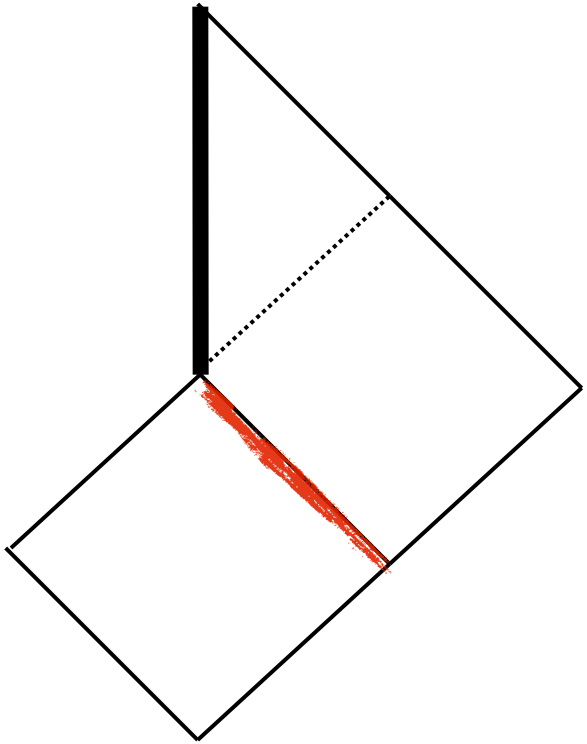
Horowitz

- BH size grows with G_N
- Size of objects in other theories becomes smaller

- BH microstate geometries pass this test
- Highly nontrivial mechanism:
- D-branes = solitons, tension ~ $1/g_s$ ➔ lighter as G_N increases

2. Mechanism not to fall into BH

Very difficult !!!



GR Dogma:

Thou shalt not put anything at the horizon !!!

- Null ➔ speed of light.
- If massive: ∞ boost ➔ ∞ energy
- If massless: dilutes with time

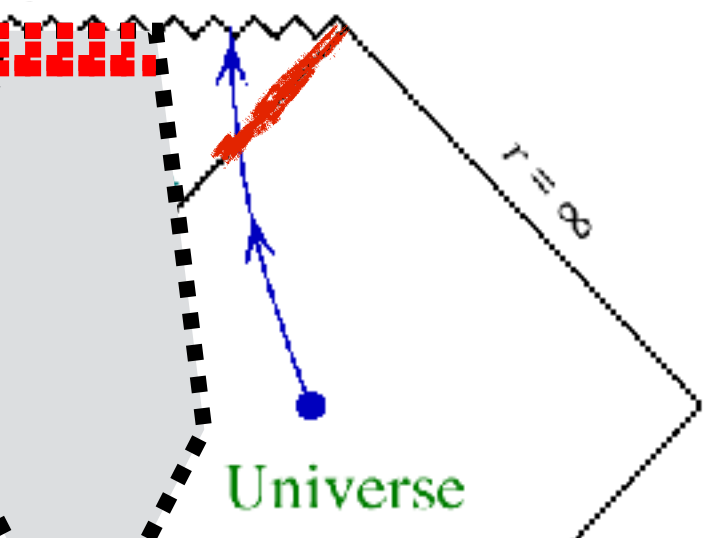
- Nothing can live there !
  (or carry degrees of freedom)
- No membrane, no spins
- No (fire)wall

Otherwise b.s.

Must have a support mechanism !

3. Avoid forming a horizon

- Collapsing shell forms horizon Oppenheimer and Snyder (1939)
- If curvature is low, no reason not to trust classical GR
- By the time shell becomes curved-enough for quantum effects to become important, horizon in causal past



Go backwards in time !

BH has e^S microstates with no horizon

Small tunneling probability = e^{-S}

Will tunnel with probability **ONE** !!!

Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

Only e^S horizon-sized microstates can do it !

BPS Microstates geometries - 11D SUGRA / T^6

5D 3-charge BH (Strominger-Vafa)

Linear system
4 layers:

Bena, Warner
Gutowski, Reall

$\mathbb{R}^4$ base (4D Hyper Kahler)

$$*G^I = G^I$$

$$d * dZ_1 = G^2 \wedge G^3$$

$$d\vec{k} + *d\vec{k} = G^1 Z_1 + G^2 Z_2 + G^3 Z_3$$

Focus on Gibbons-Hawking (Taub-NUT) base:

$$\begin{aligned} ds^2 &= V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2 \\ \nabla \times \vec{A} &= \nabla V \end{aligned}$$

8 harmonic functions

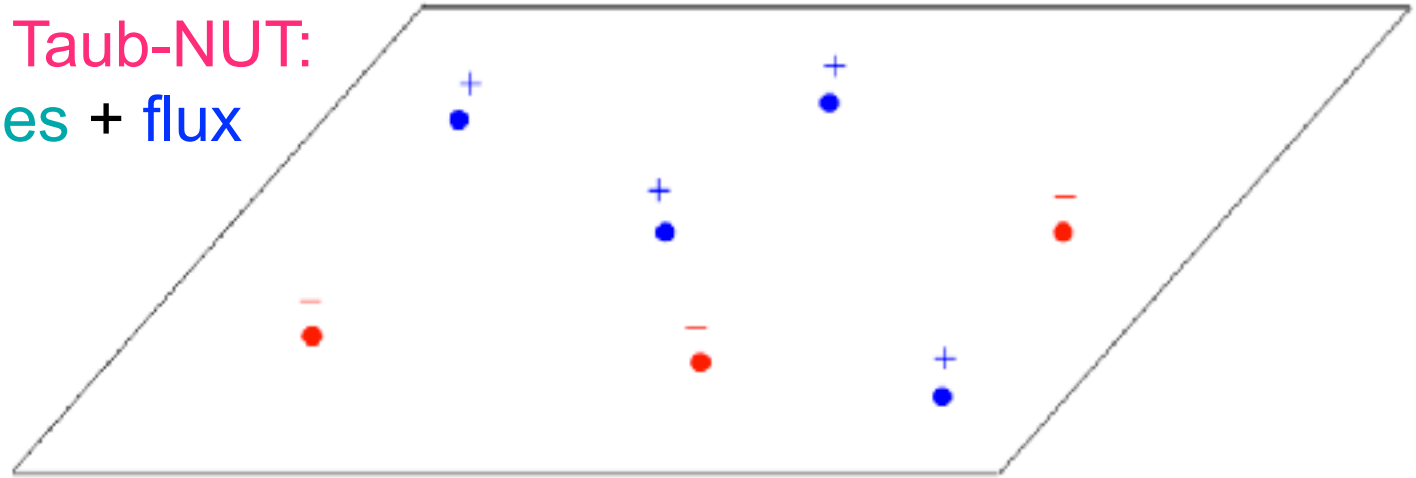
$V = \frac{1}{r}$ $\mathbb{R}^4$

$V = 1 + \frac{1}{r}$ Taub-NUT

Gauntlett, Gutowski,
Bena, Kraus, Warner

Simplest Microstate Geometries

Multi-center Taub-NUT:
many 2-cycles + flux



Base singular (signature changing sign)

Full solution smooth (@ Taub-NUT centers ~ R^4)

Same mass, charge, J, size as BH with large horizon area

Lots of solutions !

Microstates geometries

- Where is the BH charge ?

$L = q\, A_0$

magnetic

$L = \ldots + A_0\, F_{12}\, F_{34} + \ldots$

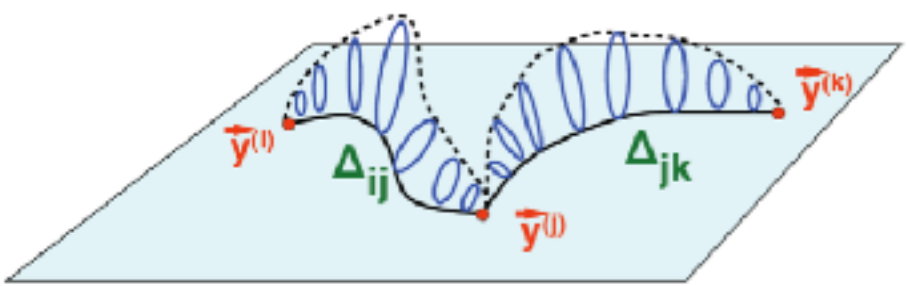
- Where is the BH mass ?

$E = \ldots + F_{12}\, F^{12} + \ldots$

- BH angular momentum

$J = E \times B = \ldots + F_{01}\, F_{12} + \ldots$

2-cycles + magnetic flux



Bubbling Geometries

Black Hole Solitons

beautiful GR story behind

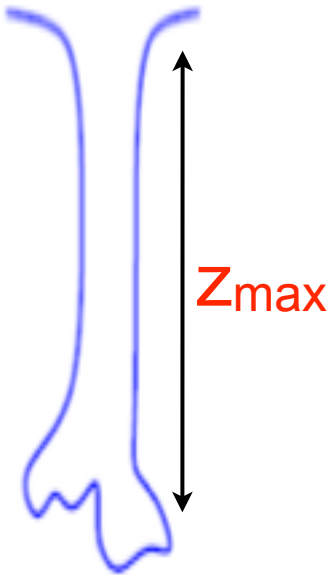
Gibbons, Warner

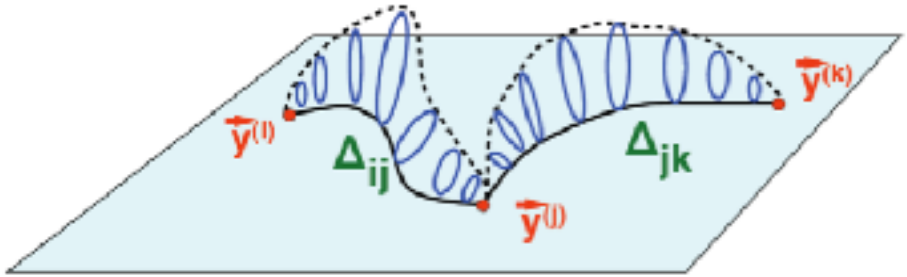
The charge is dissolved in magnetic fluxes. No singular sources.

Klebanov-Strassler

Four Scales

- Classical BH has 2 scales:
  - Mass / Horizon Size
  - Planck Length
- Microstate geometries have 2 more
  - Redshift from the bottom of the throat, z_{max}
  - Size of bubbles: $\lambda_T \sim k\,\ell_P$





More general bubbling solutions

- Add supertubes
  - supersymmetric brane configs
  - arbitrary shape Mateos, Townsend

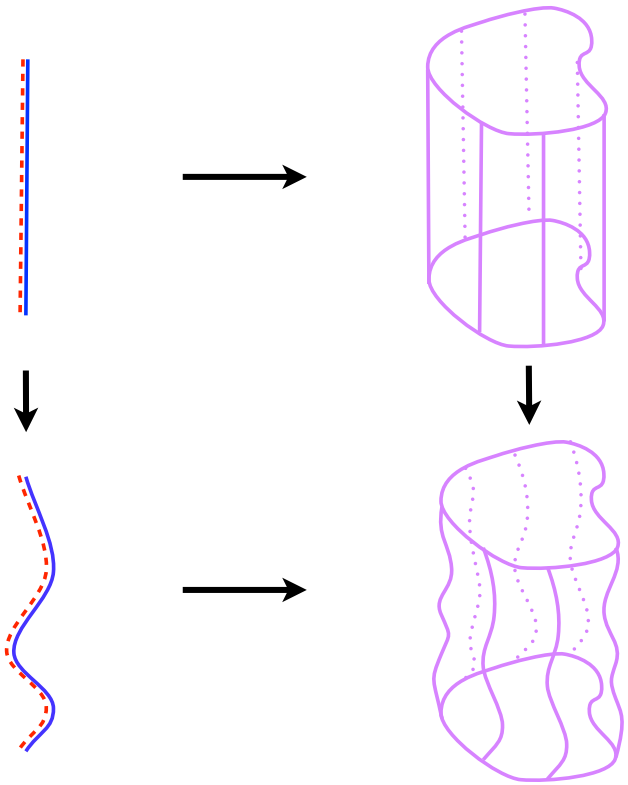
- Construct backreacted solution
  - Taub-NUT Page Green's functions (painful)
- Smooth !
  - exactly as in flat space
    Lunin, Mathur; Emparan, Mateos, Townsend
    Lunin, Maldacena, Maoz

- Entropy: $S \sim (Q^{5/2})^{1/2}$
- Not yet black-hole-like ($Q^{3/2}$)
- Need more degrees of freedom !

Even more general solutions

Bena, de Boer, Shigemori, Warner

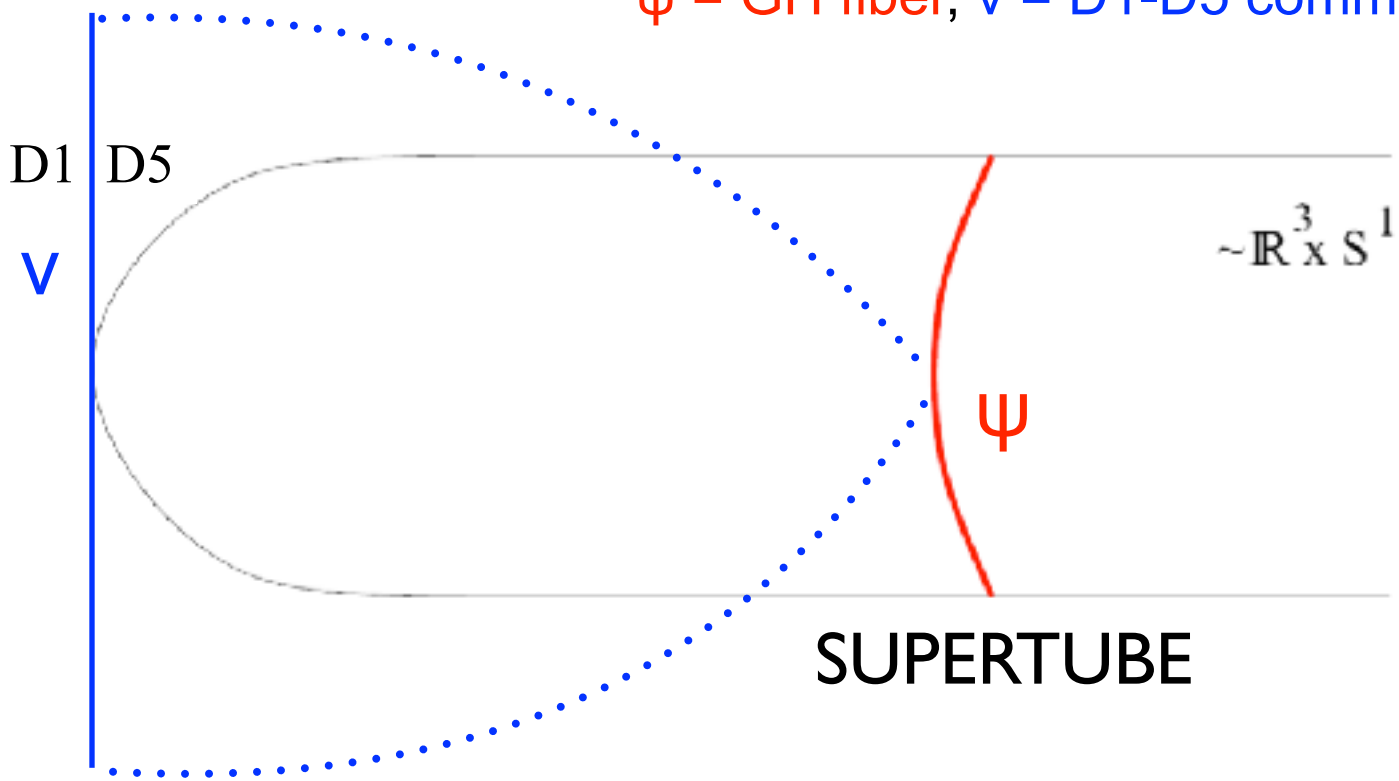
- Supertubes (locally 16 susy) - 8 functions of one variable (c = 8)
- Superstrata (locally 16 susy) - 4 functions of two variables (c= ∞)
- Double supertube transition:



Should be Smooth !!!

Habemus Superstratum

ψ = GH fiber, v = D1-D5 common direction



- ψ-dependent solutions=supertubes Lunin, Mathur; Taylor, Skenderis
  interchange fibers: v-dependent solutions
- Constructed smooth solution parameterized by arbitrary function of 2 variables F(ψ,v)
  Bena, Giusto, Russo, Shigemori, Warner

String Theory to the rescue

- Superstrata conjectured in 2011 constructed in 2015
- 5D microstates with GH bubbles: $U(1)^3$
- Oscillations $\longrightarrow$ singularities
- Precision Holography: Skenderis, Taylor, Kanitscheider
- Open string emission: Giusto, Russo, Turton
- *There is another Skywalker !*
- At least $U(1)^4$
- Metric depends on $Z_1 Z_2 - Z_4^2$ Coiffuring Bena, Ross, Warner
- Singularities cancel - solution smooth !!!

Largest family of solutions known to mankind

- Functions of two variables: ∞ X ∞ parameters

$$ds_{10}^2 = \frac{1}{\sqrt{\alpha}}\, ds_6^2 + \sqrt{\frac{Z_1}{Z_2}}\, ds_4^2 ,$$

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\left[du+\omega+\frac{\mathcal{J}}{2}(dv+\beta)\right] + \sqrt{\mathcal{P}}\, ds_4^2 ,$$

$$e^{2\phi} = \frac{Z_1^2}{\mathcal{P}} ,$$

$$B = \frac{Z_4}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_4\wedge(dv+\beta) + b_2 ,$$

$$C_0 = \frac{Z_4}{Z_1} ,$$

$$C_2 = \frac{Z_2}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_1\wedge(dv+\beta) + \gamma_2 ,$$

$$C_4 = \frac{Z_4}{Z_2}\,\widehat{\mathrm{vol}}_4 - \frac{Z_4}{\mathcal{P}}\gamma_2\wedge(du+\omega)\wedge(dv+\beta) + x_3\wedge(dv+\beta) + \mathcal{C}$$

$$C_6 = \widehat{\mathrm{vol}}_4\wedge\left[-\frac{Z_1}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_2\wedge(dv+\beta) + \gamma_1\right] - \frac{Z_4}{\mathcal{P}}\mathcal{C}\wedge(du+\omega)\wedge(dv+\beta) ,$$

$$\alpha \equiv \frac{Z_1 Z_2}{Z_1 Z_2 - Z_4^2} \qquad \mathcal{P} \equiv Z_1 Z_2 - Z_4^2 .$$

$$\omega_r^{(2)} = -\frac{Rr}{\sqrt{2}\,k_2(m_1^2-1)}\,\frac{m_1(k_2+m_1+1)\Delta_{k_2+m_1-1,m_1-1} + (k_2+m_1-1)\Delta_{k_2+m_1}}{(r^2+a^2)^2}$$

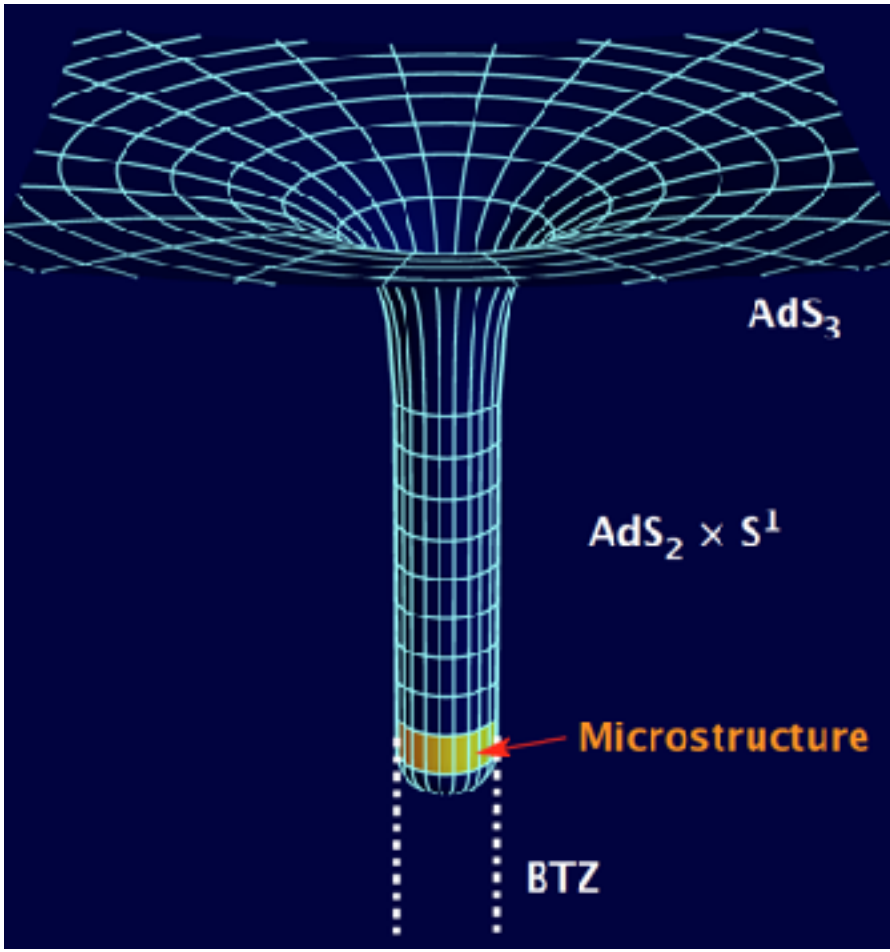
$$\omega_\theta^{(2)} = -\frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2\sin\theta\cos\theta}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} + (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1} - m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1^2(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big] ,$$

$$\omega_\phi^{(2)} = -\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\sin^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} + (m_1^2-2m_1+k_2-1)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1} + m_1(k_2-m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (k_2(m_1^2+m_1-1)-m_1(m_1+1))\Delta_{k}$$

$$\omega_\phi^{(2)} = -\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\cos^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[(k_2-1)(m_1-1)\Delta_{k_2+m_1-}$$
$$-2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} + (m_1-1)(k_2-3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1-1)(m_1(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big] .$$

Deep superstrata

- BH microstates with GH bubbles - very large J
- Typicaly ~ 99% Heidmann
- 85% of maximal value
  Bena, Wang, Warner
- Impossible to lower by playing with GH bubbles
- Build deep superstrata: J can be arbitrarily small
  Bena, Giusto, Martinec Russo, Shigemori, Turton, Warner
  (PRL editor's selection)
- First BTZ microstates



Superstrata

Entropy:

- D1-D5 supertube - dimension of moduli space
  - classically: dimension = ∞
  - quantize: dimension = $4 N_1 N_5$ = number of momentum carriers
- Counting (+ fermions) (à la Maldacena Strominger Witten)

  $S=2\pi(N_1 N_5 N_p)^{1/2}$!!! Bena, Shigemori, Warner

It remains to dot the i's and cross the t's :

- We have AdS-CFT duals. Solutions more and more messy as one approaches typical states (long strings). Recursive construction
- D1-D5 CFT - fractional momentum carriers. Have some, not all.
- Fluxes + warping: Small & Crumply $\longrightarrow$ Big & Fluffy & Smooth
- Are typical microstates spanned by smooth solutions ?

MSW Superstrata

Bena, Martinec, Turton, Warner

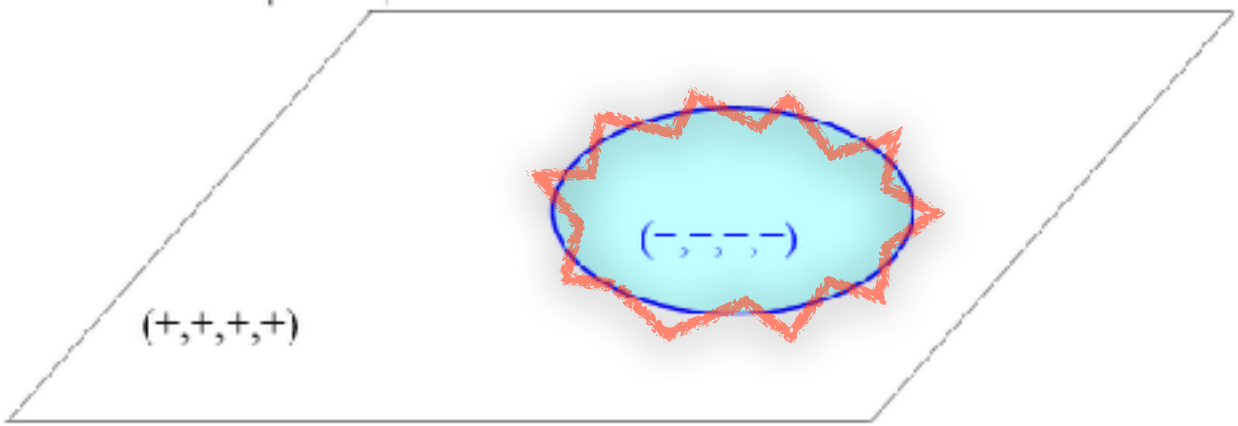
- D1-D5 solution: $AdS_3 \times S^3 \times T^4$
  - T-dualize on the Hopf fiber of S^3+ few more times
  - $AdS_3 \times S^2 \times T^6$: NS vacuum of the MSW CFT
- Central charges match
- subsector of MSW CFT $\Leftrightarrow$ subsector of D1-D5 CFT !!!
- One arbitrary function worth of smooth solutions to $U(1)^4$ 5D ungauged supergravity

Why did we miss them solutions for past 12 years ?!?

Singular 4D ambipolar bases have one function worth of singular fluxes that gives rise to smooth 5D solutions

$$ds^2 = V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2$$

$$V = \frac{1}{r} - \frac{Q}{|\vec{r} - \vec{a}|} + \frac{Q}{|\vec{r} - \vec{b}|}$$



- Signature of base changes from $(+,+,+,+)$ to $(-,-,-,-)$
- Z_i blow up and change sign at interface:

$$d * d\, Z_1 = G^2 \wedge G^3 \qquad \Rightarrow \qquad Z_i \sim \frac{1}{V}(\ldots)$$

- Full 11D metric is smooth:

$$ds^2 = -Z^{-2}(dt + \vec{k})^2 + Z\left[V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2\right] + ds^2_{T^6}$$

Extra singular wiggly G^i sourced at the interface

SUSY microstates – the story:

- We have a huge number of them
  - Arbitrary continuous functions of 2 variables
  - Smooth solutions. 4 scales !
  - Superstrata reproduce black hole entropy ☺

    Bena, Shigemori, Warner
- Dual to CFT states in typical sector
  - This is where BH states live too ☺
  - AdS-CFT perspective: highly weird if BH microstates had horizon

    Bena, Wang, Warner; Taylor, Skenderis
- Two non-backreacted calculations:
  - BH entropy - scaling multicenter config ☺

    Denef, Moore; Denef, Gaiotto, Strominger, Van den Bleeken, Yin
  - Higgs-Coulomb map.

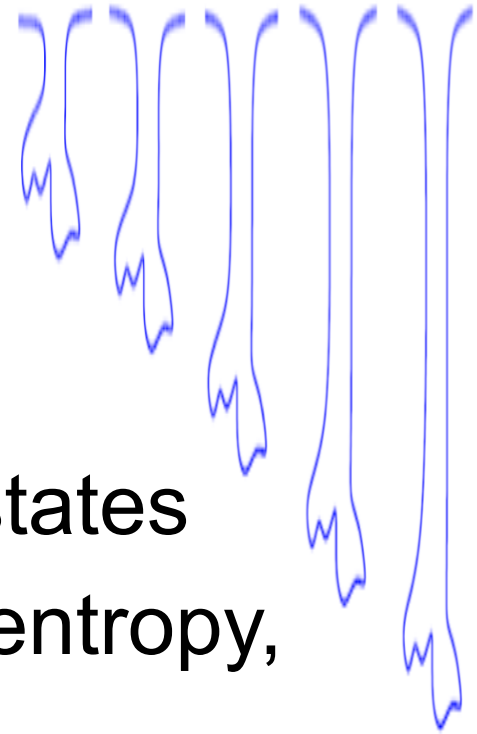
    Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi

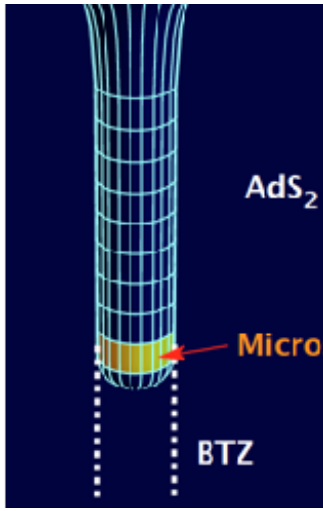
Quantum Gravity in AdS_2

- Everybody & their brother & SYK
- AdS_2 - no finite-energy excitations
  Maldacena, Strominger
- backreaction of particle in AdS_2 either
  - destroys UV
  - singularity in IR
    (? $\leftrightarrow$ SYK 4-pt. function not conformally invariant)
- Singularities in String Theory and AdS-CFT solved by string and brane dynamics involving extra dimensions 20 years of examples

Quantum Gravity in AdS_2

- Typical microstate geometries have long AdS_2 throat
- Limit when length $\rightarrow \infty$
- Solutions above $\rightarrow$ asymptotically-AdS_2
  Bena, Heidmann, Turton
- Same entropy as microstates
- If superstrata count BH entropy, so do these solutions !
- Ground states of QM dual to AdS_2 Sen





Strominger - Vafa

$S = S_{BH}$

Black Hole Deconstruction

Denef, Gaiotto, Strominger,
Van den Bleeken, Yin (2007)

$S \sim S_{BH}$

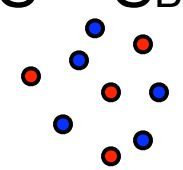
Black Holes

Effective coupling (g_s)

Multicenter Quiver QM

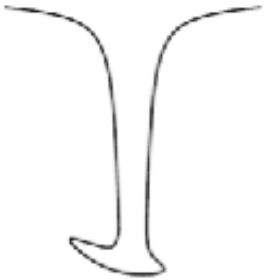
Denef, Moore (2007)
Bena, Berkooz, de Boer, El Showk,
Van den Bleeken.

$S \sim S_{BH}$



Size grows

No Horizon



Smooth Horizonless
Microstate Geometries

Punchline: Typical states grow as G_N increases.

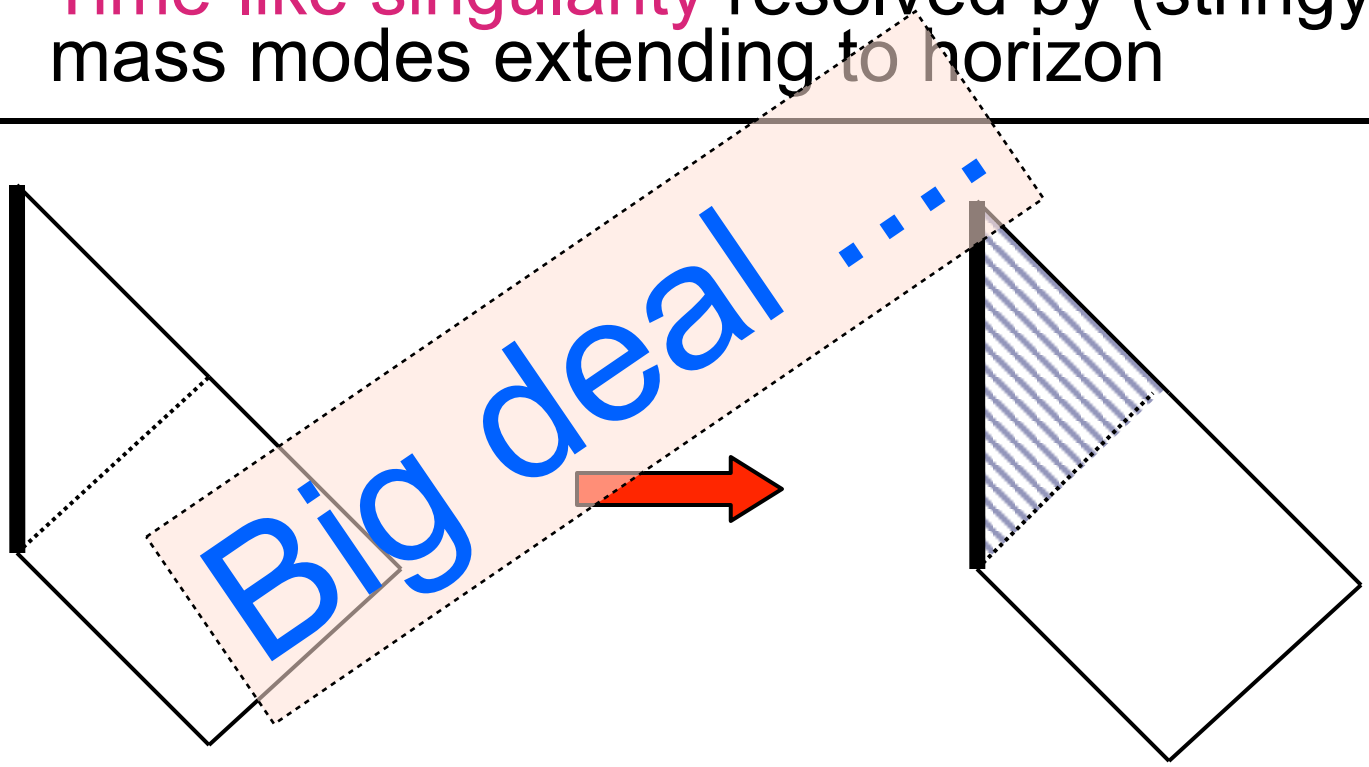
Horizon never forms.

Quantum effects from singularity extend to horizon

Similar story for non-SUSY extremal black holes

BPS Black Hole = Extremal

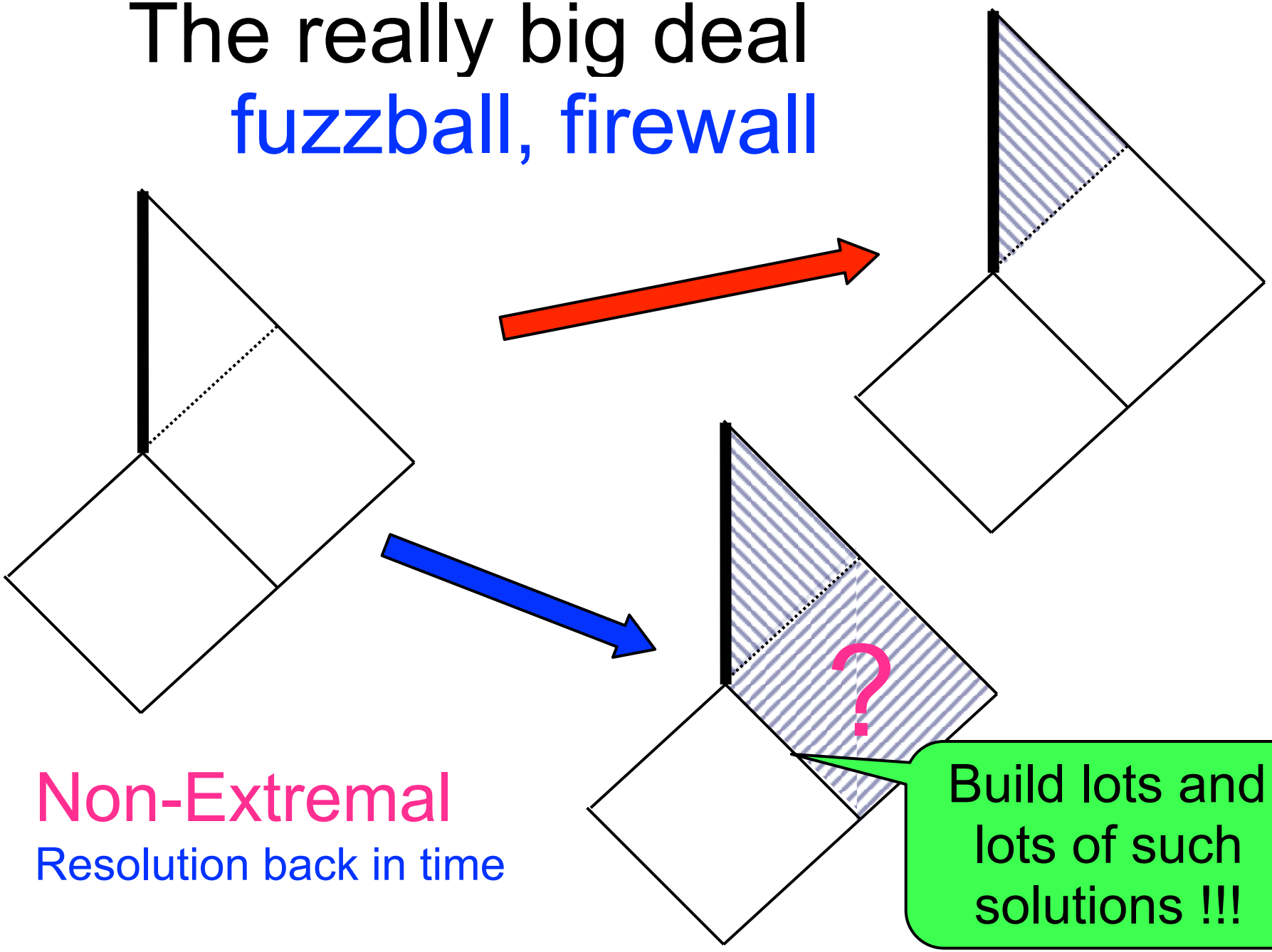
- This is not so strange
- Horizon in causal future of singularity
- Time-like singularity resolved by (stringy) low-mass modes extending to horizon



Penrose
Poisson, Israel
Dafermos
Marolf

The really big deal

fuzzball, firewall



Non-Extremal

Resolution back in time

Very few known. Extremely hard to build...

– Coupled nonlinear 2‘nd order PDE’s do not factorize

Do not pray to the saint who does not help you ! Romanian proverb

- Idea: perturbative construction - near-BPS
- Add antibranes to BPS bubbling sols.
  Kachru, Pearson, Verlinde
- Metastable minima Bena, Puhm, Vercnocke
- Decay to susy minima:
  brane-flux annihilation - Hawking radiation
- Microstates of near-extremal BH

Very few known. Extremely hard to build...

– Coupled nonlinear 2‘nd order PDE’s do not factorize

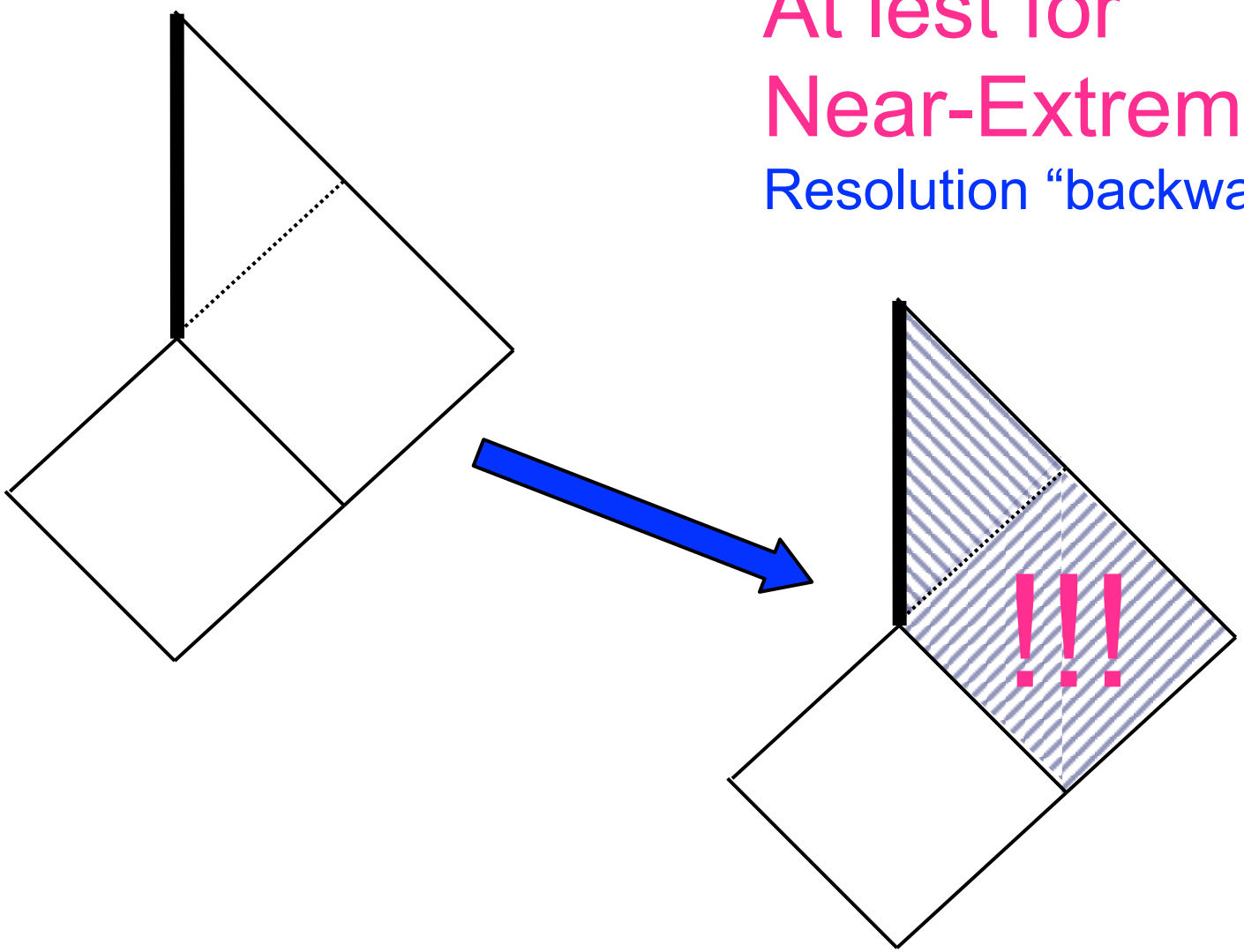
When a bird is blind, God sometimes makes its nest ! another Romanian proverb

- For some solutions the 2‘nd order PDE’s do factorize !!! Bossard, Katmadas
- We can build analytically certain classes of non-extremal solutions Bena, Bossard, Katmadas, Turton
- Add extra cycles to JMART
- Method can get us far from extremality.
- How far ? How generic ? Antibranes ?

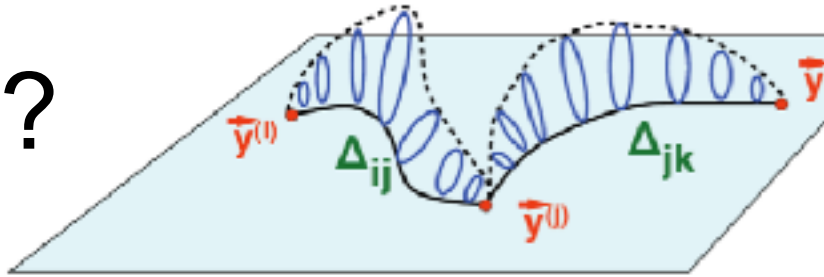
The really big deal

At lest for
Near-Extremal

Resolution “backwards in time!”

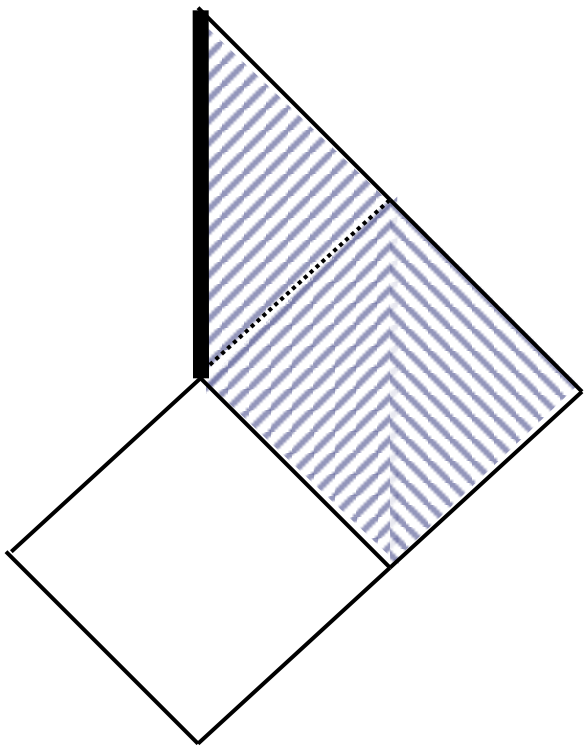


Why not collapsing ?



- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller ⟶ increases energy
  - bubbling = only mechanism to avoid collapse in semiclassical limit Gibbons, Warner
  - If any state in the e^S-dimensional BH Hilbert space has a semiclassical limit, it **must** be a microstate geometry !
- 4(+6)d : multicenter solutions Denef
  - smooth GH centers with negative charge ⟶ centers with negative D6 charge and negative mass
  - common in String Theory (e.g. orientifolds)
  - **Highly unusual** matter from a 4d perspective
  - Usual matter does not hang around, just falls in BH

What about other black holes?



- Near Extremal ?
- Schwarzschild + 1 electron ?

Take electron away

Same Penrose diagram !

String theory can resolve BH singularities "backwards in time." Why stop at near-extremal?

Same Mechanism ?

Pure BH states have no horizon - 4 approaches:

(1) Information-theory arguments Mathur 2009, AMPS, etc

– secondary question: firewall ? burn or smooth through ?

(2) Generic AdS-CFT Skenderis, Taylor, AMPS2 (Papadodimas Raju against)

– nontrivial vevs ⇒ no spherical symmetry ⇒ no horizon

Agnostic about theory

No mechanism for Hair !

(3) Follow microstates from weak to strong coupling

– BH deconstruction, String emission, Higgs-Coulomb map

Denef, Gaiotto, Strominger, Van den Bleeken, Yin, Giusto, Russo, Turton

Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi

(4) Lots of BH microstate geometries = Hair !!!

– One mechanism in three hypostases:

Bubbling ⇔ Brane polarization ⇔ NonAbelian

– Can get BH entropy; 2 new scales, E_{gap} , λ_T

A few questions

- Would all microstates be classical ?
  - No, but classical solutions are the only things one can construct
  - Hovering mechanism extrapolates ⇒ brane polarization, non-Abelian
  - Typical states: many small bubbles ($\lambda_T \sim \ell_P$), or just a few ($\lambda_T > \ell_P$)
  - Larger bubbles - more entropy Denef, Moore; Bena, Shigemori, Warner
- Don't people in Saclay say antibranes are bad?
  - Tachyonic ! Bad for cosmology, but not for BH !
  - Instabilities in fact expected for non-extremal black hole microstates; JMaRT (+ bubbles) has them Myers&al, Santos&al
  - D1-D5: BPS left-movers + right movers Mathur
- What about non-linear instabilities ?
  - first-order backreaction of non-BPS perturbation; D1-D5 right movers ⇒ Closed string emission
  - Moduli space of classical solutions. non-BPS ⇒ Motion

Bena, Pasini Marolf, Michel, Puhm

A few questions

- Can you fall through horizon drinking your coffee ? (as GR textbooks say)
- Do you rather go splat at the horizon scale?
- 3 options:
  - Analyze ∞ density shells / membranes / stuff carrying d.o.f. @ horizon (kept from collapsing by the Tooth Fairy)
  - Modify gravity by weird terms and analyze horizon
  - Use actual solutions of String Theory
- Answer likely depends on E_{gap} , λ_T
- Known bubbling solutions or polarized branes have no intention to let you fall through unharmed

How can we observe this ?

Universal feature:

- Low-mass degrees of freedom at horizon.

Collision of two black holes:

Gravitational waves emitted close to horizon:

LIGO, eLISA

Summary and Future Directions

- String theory configurations that hover above horizon.
  Topology + fluxes ⇔ brane polarization ⇔ nonabelian d.o.f.
- BPS black hole microstates = horizonless solitons
  - low-mass modes affect large (horizon) scales
  - Convergence of many research directions
  - BPS superstrata - 2 variables - **Black Hole Entropy !**
- Extensive extremal non-BPS story
- Extend to non-extremal black holes
  - Near-extremal
    - Metastable supertubes Bena, Puhm, Vercnocke
  - Far from extremality — 2'nd order nonlinear coupled PDE
    - Systematic construction Bena, Bossard, Katmadas, Turton
    - Others: numerics? inverse scattering? blackfolds?
  - Maybe start thinking about experimental consequences ?
    - Gravity waves
    - Supermassive BH formation easier

Some speculative connections

- **A.** 10-yr old question: what is the dual of pure Higgs states ?
- Martinec: W-branes - pure Higgs entropy from condensing M2 branes wrapping 2-cycles in GH space (F1 between fluxed D6 in 10D)
- Similar to D0-D4: bi-fundamentals come from F1 between D0 and D4
  - F1's source fields in hypermultiplets of sugra.
  - Long time belief: need sugra solutions with hypermultiplets
    Ortin, Raymaekers, Van den Bleeken
  - Think deeper: hypermultiplets = red herring
- String emission calculations - first order in operators that correspond to going on the Higgs branch
- Going on the Higgs branch turns on (1,1) metric components on the T^6. Same from four-charge system Bianchi, Morales, Pieri
- Makes sense - condensation of F1 between 2 D2's bend them into each other. Source extra (1,1) components

Some speculative connections

- **B.** MSW entropy counting:
- N_1, N_2, N_3 M5 wrapping three T^4's inside T^6. Singular ample divisor.
- Smooth ample divisor = deformation into single M5 brane of length $N_1 \times N_2 \times N_3$; sources (1,1) metric components. Expects them to be present in generic microstate
- **C.** String emission - extra field (1,1) metric on T^6 Giusto, Russo, Turton
- **D.** Smoothness of superstrata - coiffuring - same field
- **E.** Function worth of MSW microstate solutions - same field

- Five different indications we are converging on the right ingredient.