Title: Thou shalt not put (ordinary) stuff at the horizon

Date: Nov 09, 2017 10:30 AM

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Abstract: Black holes appear to lead to information loss, thus violating one of the fundamental tenets of Quantum Mechanics. Recent Information-Theory-based arguments imply that information loss can only be avoided if at the scale of the black hole horizon there exists a structure (commonly called fuzzball or

# Thou shalt not put (ordinary) stuff at the horizon


## Iosif Bena

### IPhT, CEA Saclay

with

Nick Warner, Emil Martinec, Jan deBoer, Micha Berkooz, Simon Ross, Gianguido Dall'Agata, Stefano Giusto, Rodolfo Russo, Guillaume Bossard, Masaki Shigemori, Monica Guică, Nikolay Bobev, Bert Vercnocke, Andrea Puhm, David Turton, Stefanos Katmadas, Johan Blåbäck, Pierre Heidmann



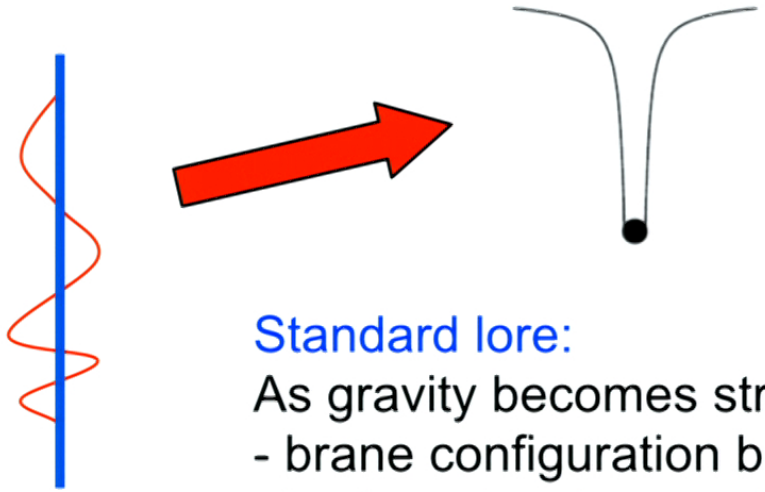
erc FQXi JOHN TEMPLETON FOUNDATION Agence Nationale de la Recherche ANR DE LA RECHERCHE À L'INDUSTRIE cea SACLAY

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

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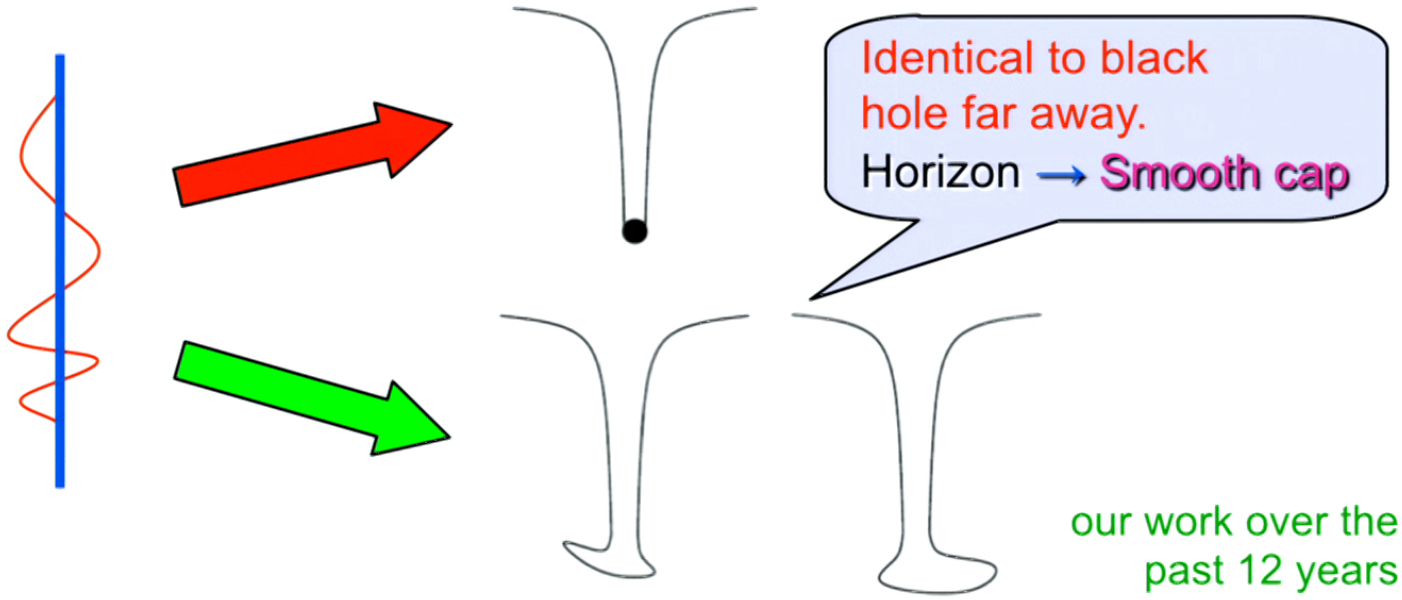
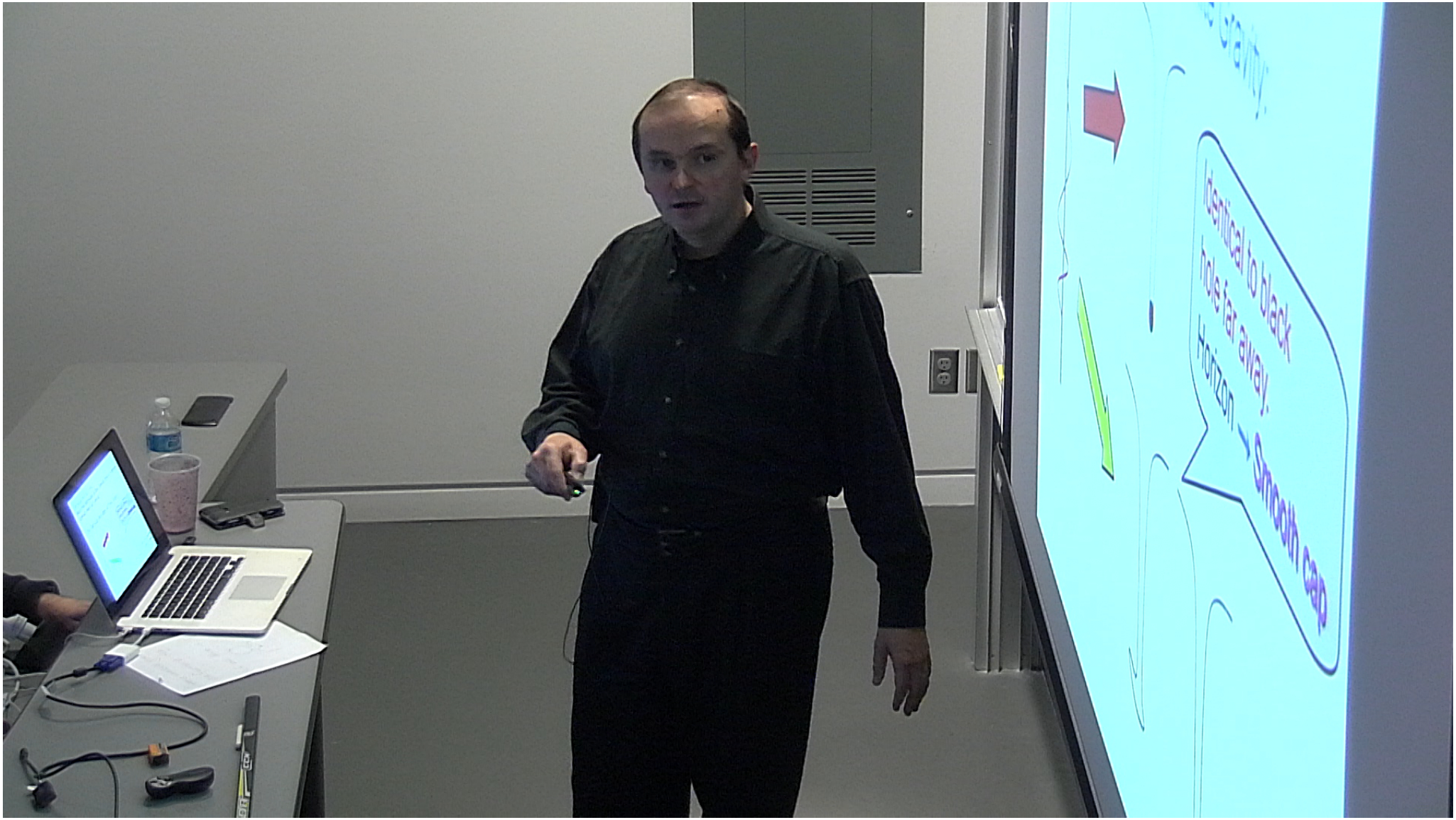



our work over the past 12 years

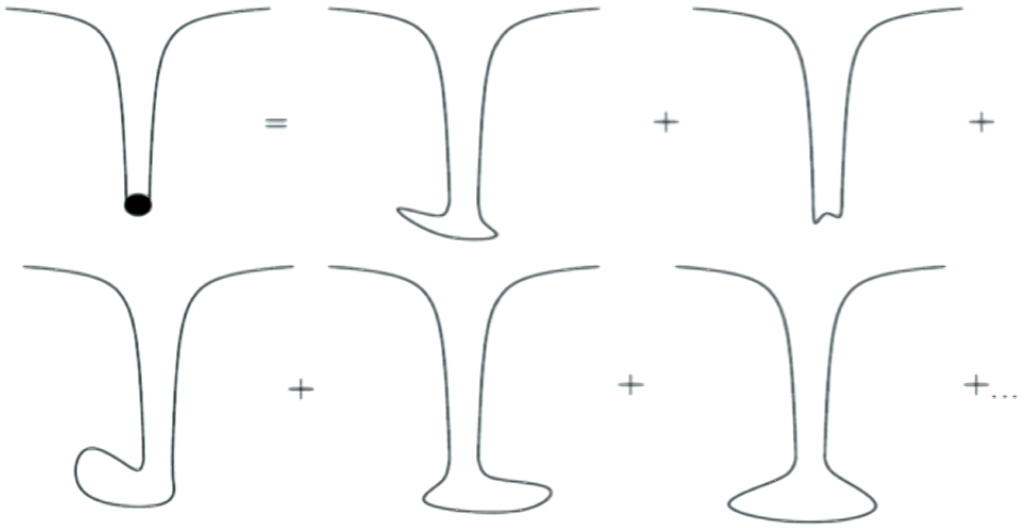

Identical to black
holes far away.
Horizon → Smooth cap

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

?

Black hole = ensemble of horizonless microstate configurations

Mathur 2003



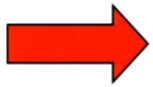
# Analogy with ideal gas

**Thermodynamics**

(Air = ideal gas)

$P V = n R T$

$dE = T dS + P dV$



**Statistical Physics**

(Air -- molecules)

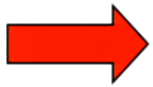
$e^S$ microstates

typical

atypical

**Thermodynamics**

Black Hole Solution



**Statistical Physics**

Microstate geometries

**Long distance physics**

Gravitational lensing

**Physics at horizon**

Information loss

Gravity waves ?

# Word of caution

- To replace classical BH by BH-sized object
  - Gravastar, quark-star, boson-star
  - Infinite density firewall hovering just above horizon
  - Gas of wormholes
  - Bose-Einstein condensate of gravitons
  - LQG configuration…

must satisfy 3 very stringent tests:

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1. Same growth with $G_N$ !!!

Horowitz

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1. Same growth with $G_N$ !!! — Horowitz

BH size grows with $G_N$ ; "normal objects" shrink

- BH microstate geometries pass this test
- Highly nontrivial mechanism: $G_N = g_s^2$
- D-branes = solitons, tension ~ $1/g_s$ → lighter as $G_N$ increases

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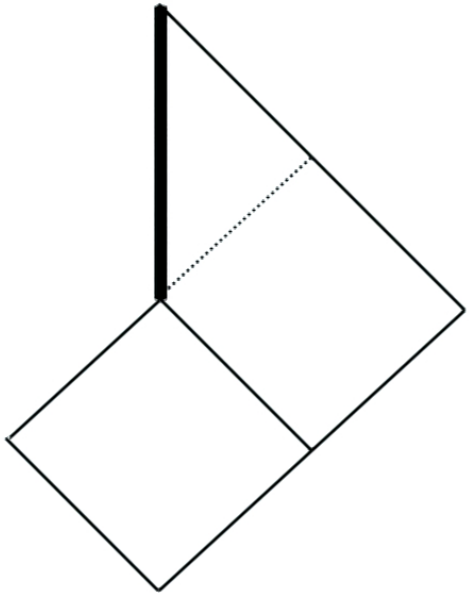
*To build structure@horizon, non-perturbative degrees of freedom you must use !*

# 2. Mechanism not to fall into BH

Very difficult !!!



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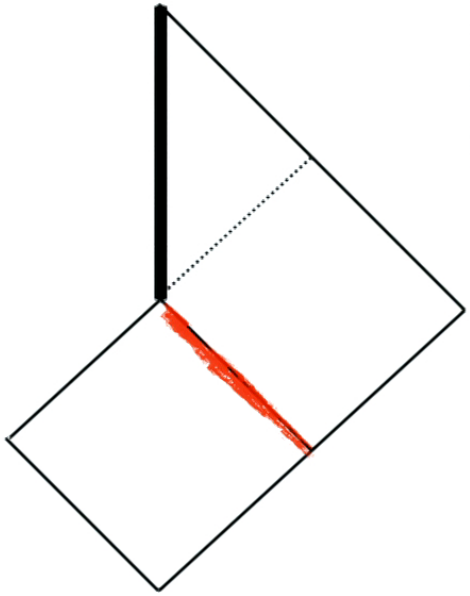

**GR Dogma:**

**Thou shalt not put anything at the horizon !!!**

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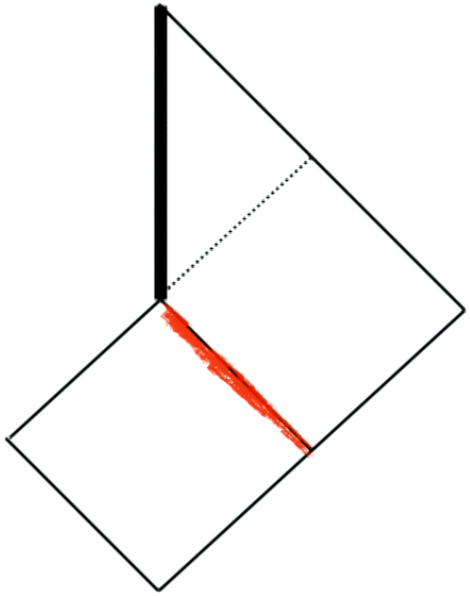

**GR Dogma:**

**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 “quantum stuff”
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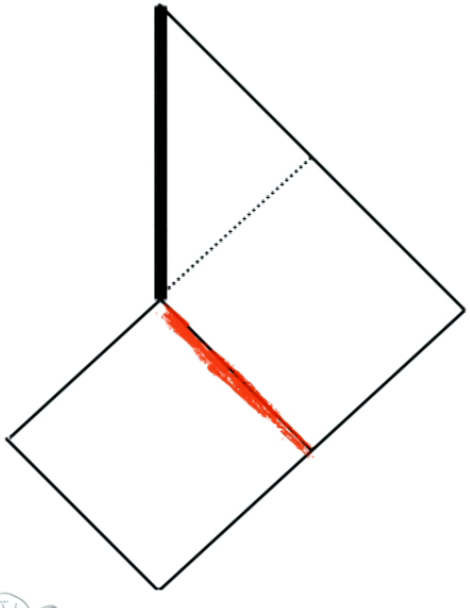

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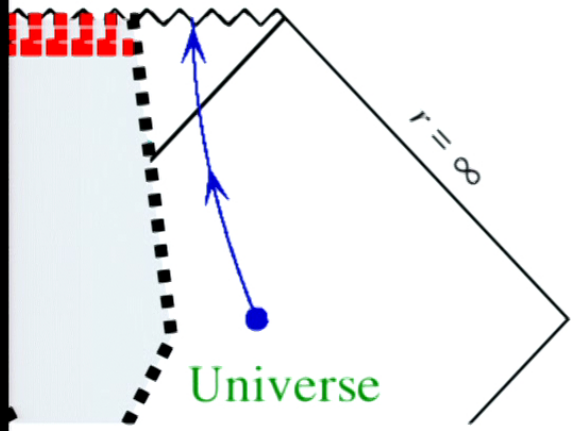
*If support mechanism have you not, go home and find one*

# 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



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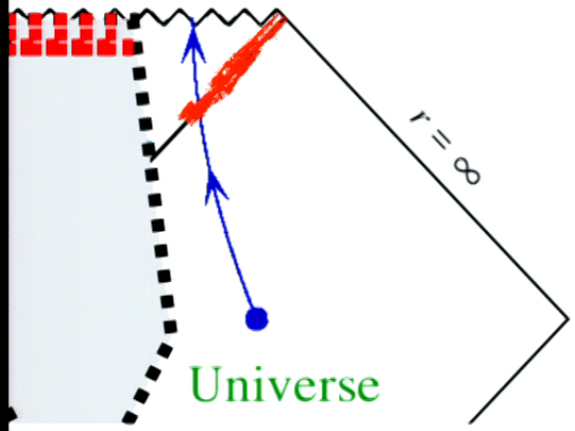

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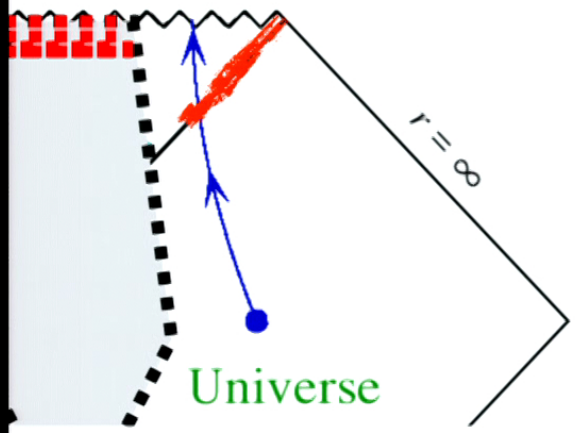


Backwards in time - illegal !

BH has $e^{S}$ microstates with no horizon

Small tunneling probability = $e^{-S}$

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

Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

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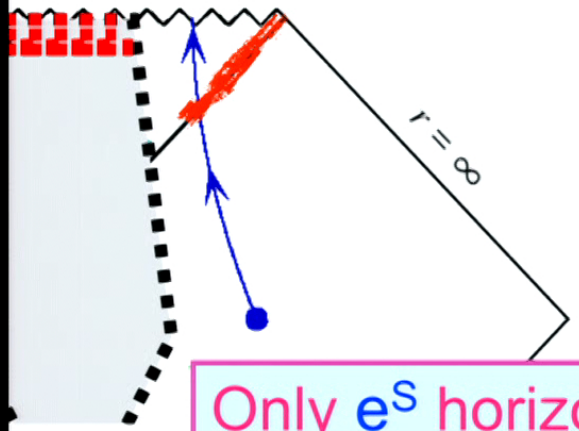


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Only $e^S$ horizon-sized microstates can do it !

*If quantum tunneling you are brushing aside,*
*great mistake you are making*

# Microstates geometries

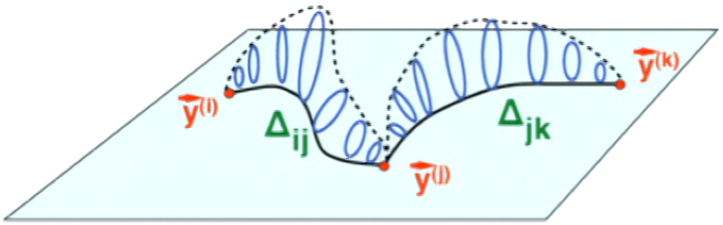
5D 3-charge (Strominger-Vafa) BH

blow-up (2)-cycles
add magnetic flux

- BH charge:

$L = q\, A_0$ (magnetic)

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




- BH mass:

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

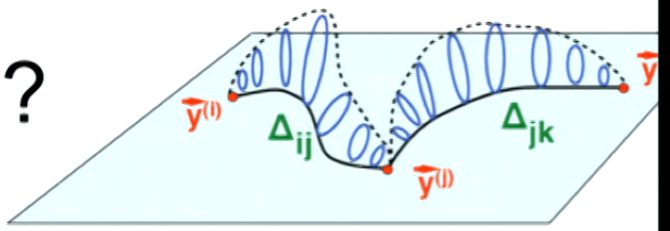
- BH angular momentum

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

Bubbling Geometries
Black Hole Solitons
beautiful GR story behind
Gibbons, Warner

The charge is dissolved in magnetic fluxes. No singular sources.
Klebanov-Strassler

# Why not collapsing ?



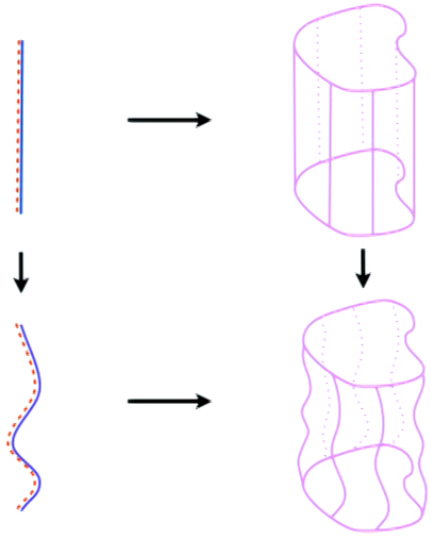

- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller ⟶ increases energy
  - bubbling = only mechanism to avoid collapse in semiclassical limit Gibbons, Warner
  - If any state in the $e^S$-dimensional BH Hilbert space has a semiclassical limit, 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); nowhere else
  - **Highly unusual** matter from a 4d perspective
  - Usual matter does not hang around, just falls in BH

# Add wiggles - increase entropy

- Supertubes Mateos, Townsend; Lunin, Mathur
  - supersymmetric, arbitrary shape
  - 8 functions of one variable (c = 8)
  - In bubbling geometries $S \sim (Q^{5/2})^{1/2}$
  - Lots, but not yet black-hole-like $(Q^{3/2})$
- Superstrata Bena, de Boer, Shigemori, Warner
  - 4 functions of two variables (c = $\infty$)
  - quantize: c = $4N_1N_5$ momentum carriers
  - Counting (+ fermions) (à la MSW)

    **$S=2\pi(N_1N_5N_p)^{1/2}$ !!!**

    Bena, Shigemori, Warner



# Largest family of solutions known to mankind

## Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

$$ds_{10}^2 = \frac{1}{\sqrt{\alpha}}\, ds_6^2 + \sqrt{\frac{Z_1}{Z_2}}\, d\hat{s}_4^2\,,$$

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

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

$$B = -\frac{Z_4}{\mathcal{P}}\,(du+\omega)\wedge(dv+\beta) + a_4\wedge(dv+\beta) + \delta_2\,,$$

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

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

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

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

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

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

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

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

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

# SUSY microstates – the story:

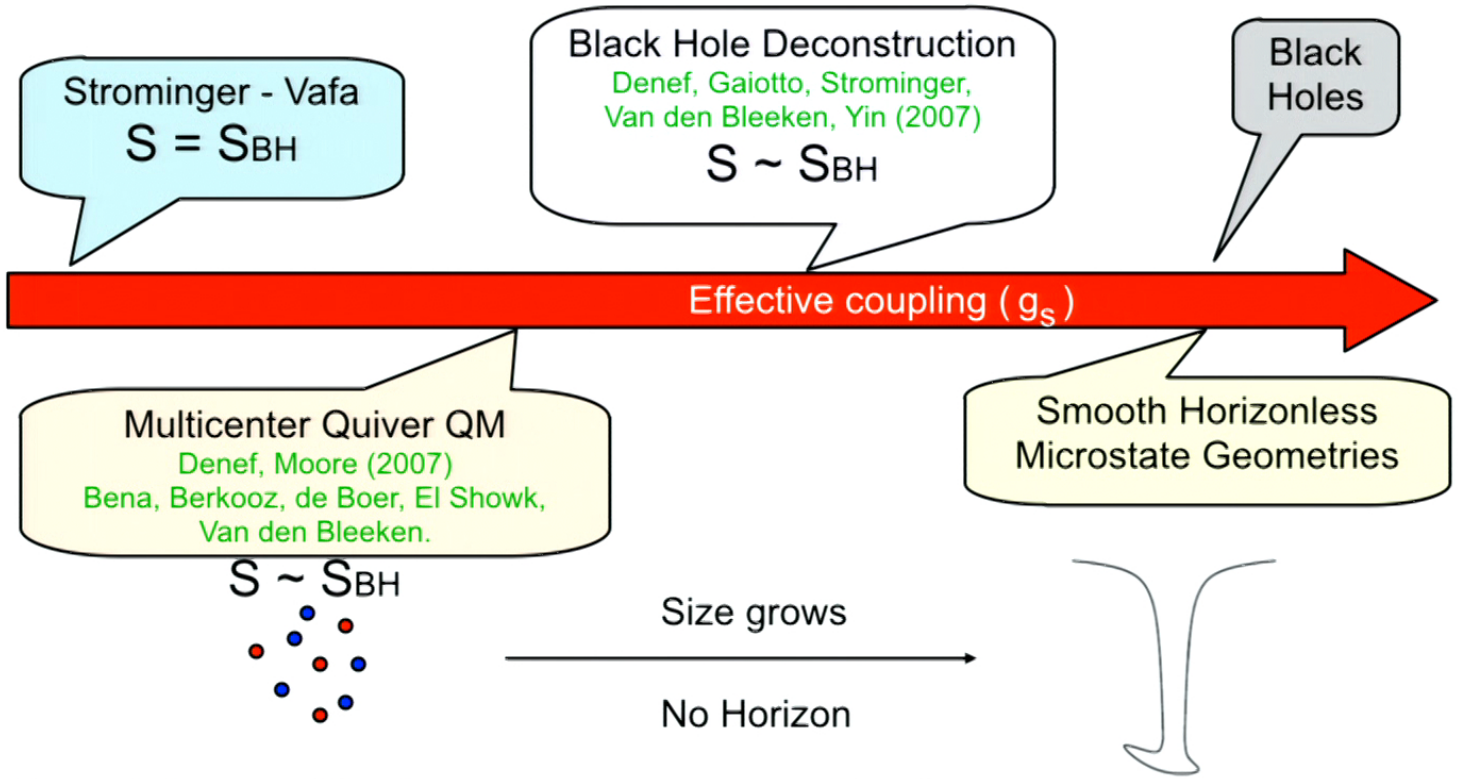
- We have a huge number of them
  - Arbitrary continuous functions of 2 variables
  - Superstrata can reproduce black hole entropy ☺

    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, W-branes ☺

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

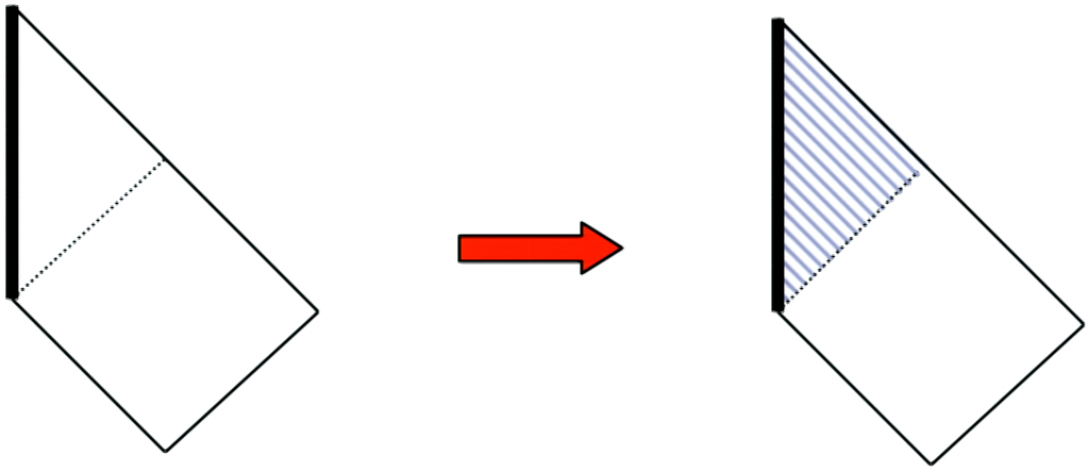
    Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi




Punchline: Typical states grow as $G_N$ increases.
Horizon never forms
Pure black hole states have no horizon

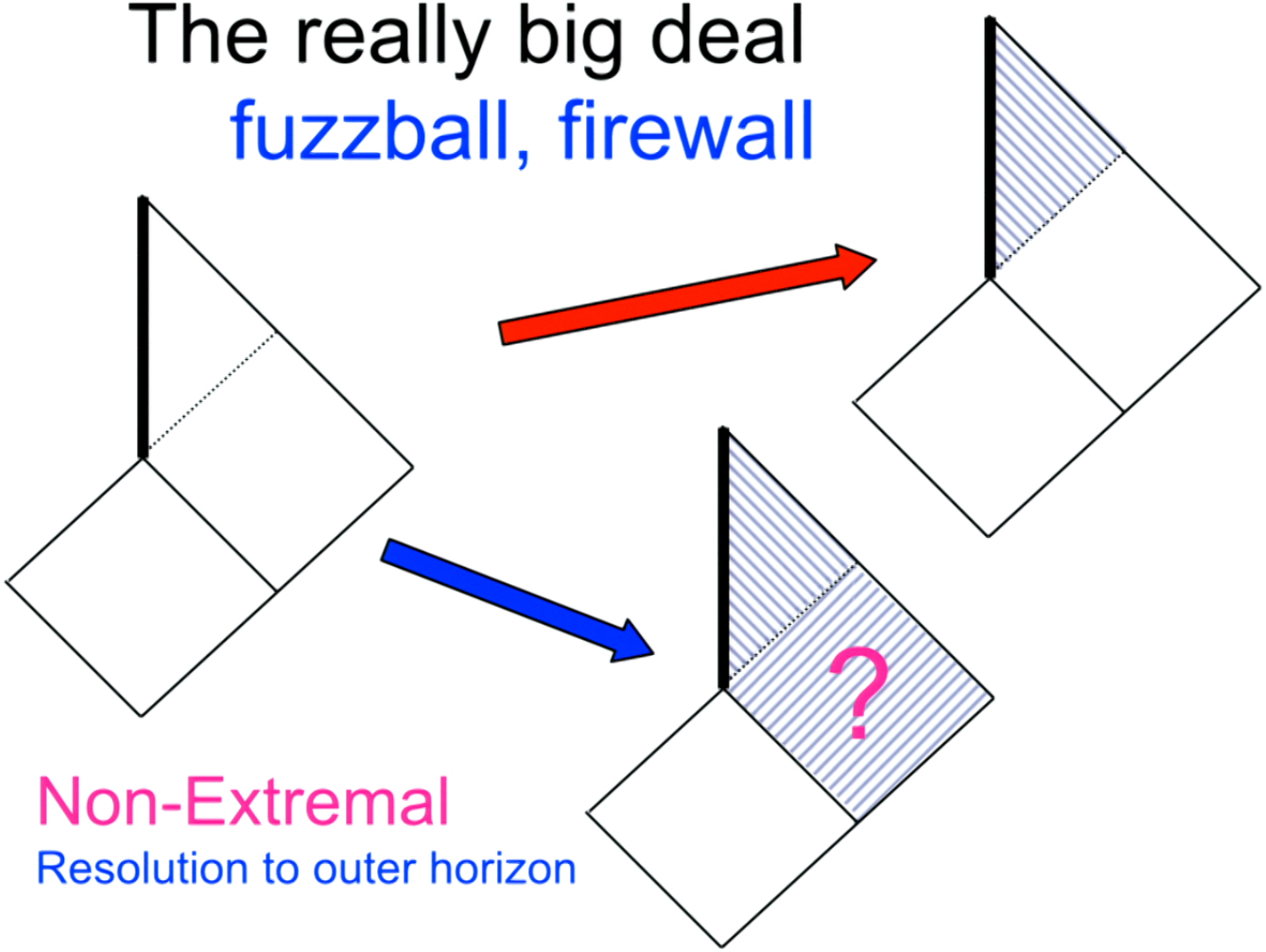
# BPS Black Hole = Extremal

- Horizon in causal future of singularity
- Time-like singularity resolved by (stringy) low-mass modes extending to horizon
- Common in String Theory (PS, KS, LLM, Myers effect)



# The really big deal

## fuzzball, firewall




Non-Extremal

Resolution to outer horizon

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...

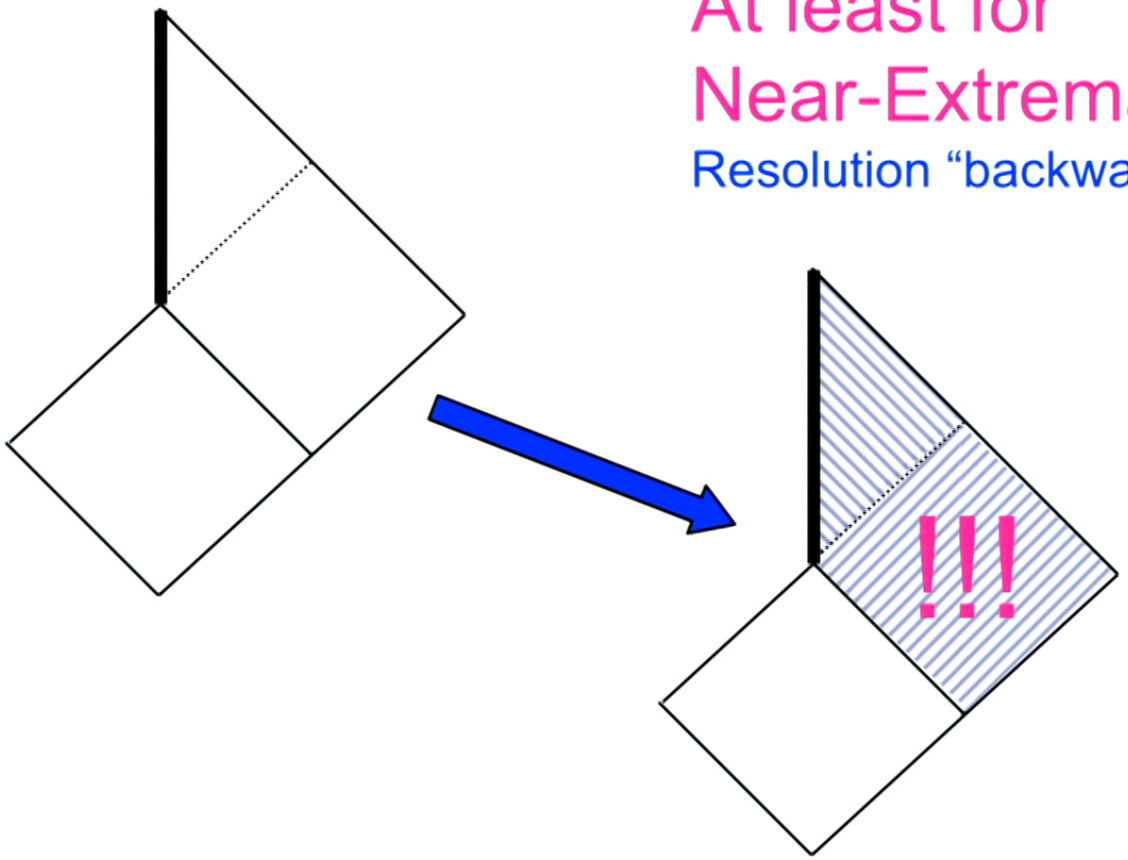
– Coupled nonlinear 2‘nd order PDE’s do not factorize

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 talk by Turton
- Method can get us far from extremality.
- How far ? How generic ? Antibranes ?

# The really big deal

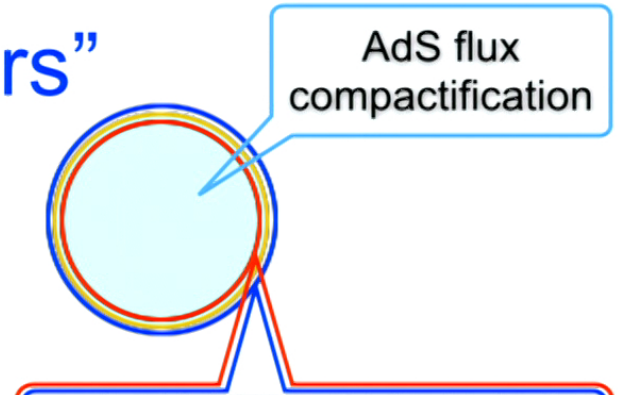
At least for
Near-Extremal
Resolution “backwards in time!”



# String theory "gravastars"

Danielsson, Dibitetto, Giri

- Neutral 4D BH microstate
- Shell of branes
  ⇒ correct growth with $G_N$
- @ Buchdahl radius




| – | $t$ | $\xi_1$ | $\xi_2$ | $r$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ |
|---|---|---|---|---|---|---|---|---|---|---|
| D8 | ⊗ | ⊗ | ⊗ | – | ⊗ | ⊗ | ⊗ | ⊗ | ⊗ | ⊗ |
| D4 | ⊗ | ⊗ | ⊗ | – | ⊗ | ⊗ | – | – | – | – |
| D4 | ⊗ | ⊗ | ⊗ | – | – | – | ⊗ | ⊗ | – | – |
| D4 | ⊗ | ⊗ | ⊗ | – | – | – | – | – | ⊗ | ⊗ |
| NS5 | ⊗ | ⊗ | ⊗ | – | ⊗ | – | ⊗ | – | ⊗ | – |
| NS5 | ⊗ | ⊗ | ⊗ | – | – | – | – | ⊗ | ⊗ | ⊗ |
| NS5 | ⊗ | ⊗ | ⊗ | – | ⊗ | ⊗ | – | – | – | ⊗ |
| NS5 | ⊗ | ⊗ | ⊗ | – | – | ⊗ | ⊗ | ⊗ | – | – |
| KK5 | ⊗ | ⊗ | ⊗ | – | ⊗ | – | ⊗ | – | iso | ⊗ |
| KK5 | ⊗ | ⊗ | ⊗ | – | ⊗ | ⊗ | iso | – | ⊗ | – |
| KK5 | ⊗ | ⊗ | ⊗ | – | iso | – | ⊗ | ⊗ | ⊗ | – |
| KK5 | ⊗ | ⊗ | ⊗ | – | – | ⊗ | – | ⊗ | iso | ⊗ |
| KK5 | ⊗ | ⊗ | ⊗ | – | – | ⊗ | iso | ⊗ | – | ⊗ |
| KK5 | ⊗ | ⊗ | ⊗ | – | iso | ⊗ | – | ⊗ | – | ⊗ |
| KK5 | ⊗ | ⊗ | ⊗ | – | – | ⊗ | ⊗ | – | ⊗ | iso |
| KK5 | ⊗ | ⊗ | ⊗ | – | ⊗ | – | – | iso | ⊗ | ⊗ |
| KK5 | ⊗ | ⊗ | ⊗ | – | ⊗ | iso | ⊗ | – | – | ⊗ |

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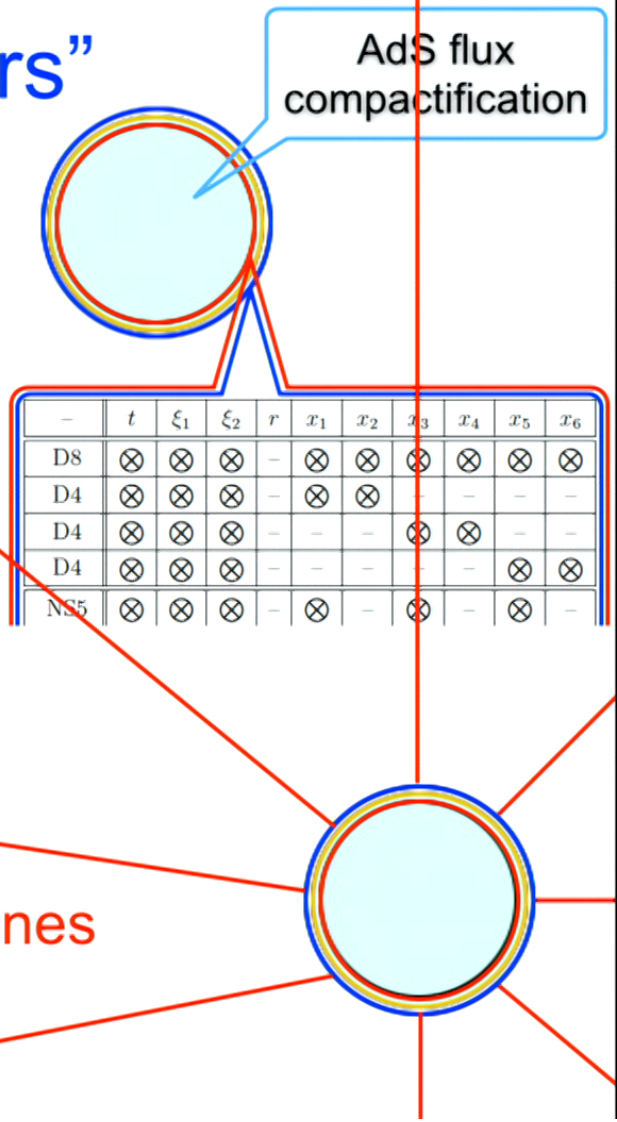
- Simpler incarnation:
  Bena, Blåbäck, Katmadas, to appear
- Locally 2 supercharges
- Fluxes ⇒ D8 Freed-Witten anomaly ⇒ need extra D6 branes
- More work needed



# Pure BH states have no horizon - 4 approaches:

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

– secondary question: firewall ? burn or skip through ?

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

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Agnostic about theory

No mechanism for Hair !

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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 capture typical BH states; can get BH entropy

# A few questions

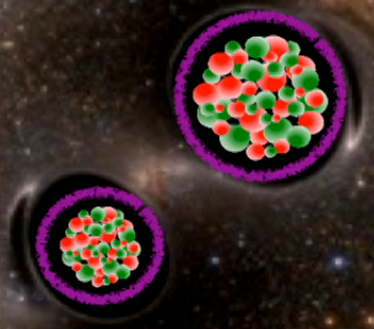
- Would all microstates be classical ?
  - Only constructions that include gravity and one can trust.
  - Hovering mechanism extrapolates ⇒ brane polarization, non-Abelian
  - Classical geometries - basis vectors that span BH Hilbert space
  - Typical states: many small bubbles or just a few ?
- Don't 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
- Can you fall through horizon drinking your coffee ? (as GR textbooks say) … Or do you go splat ?

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

# How can we observe this ?

Universal feature:

- Low-mass degrees of freedom at horizon.



**LIGO, eLISA:**

**Extra d.o.f. : new dissipative terms ?**

**Distortion of the Kerr multipole moments**