Black hole μ-state geometries, antibranes & the dS landscape

Iosif Bena

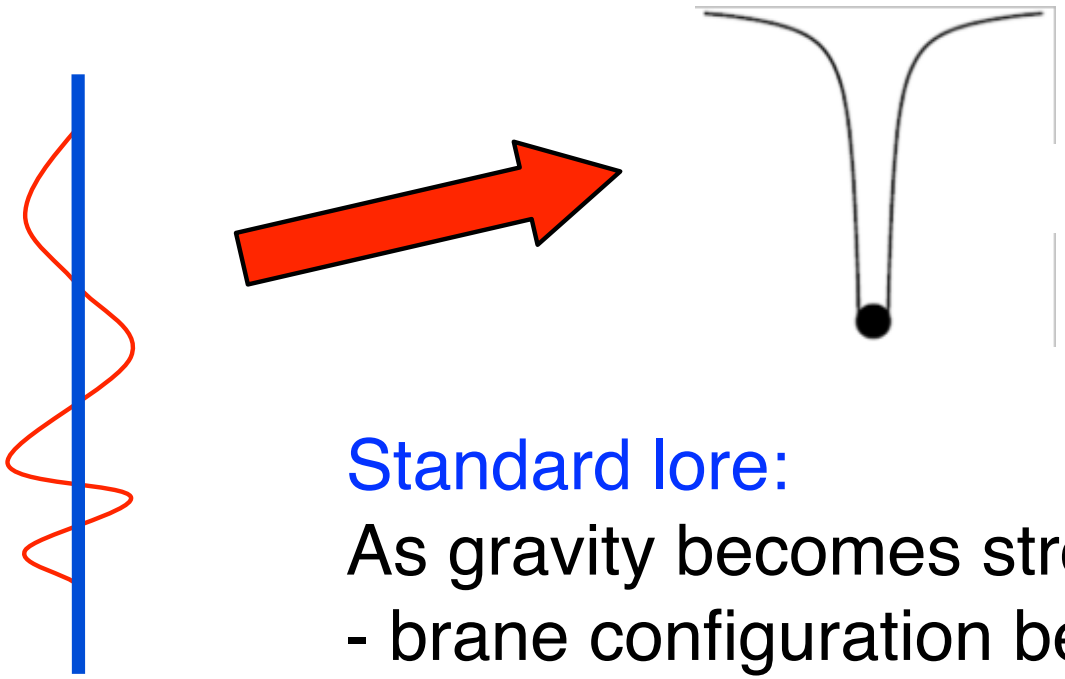
IPhT, CEA Saclay

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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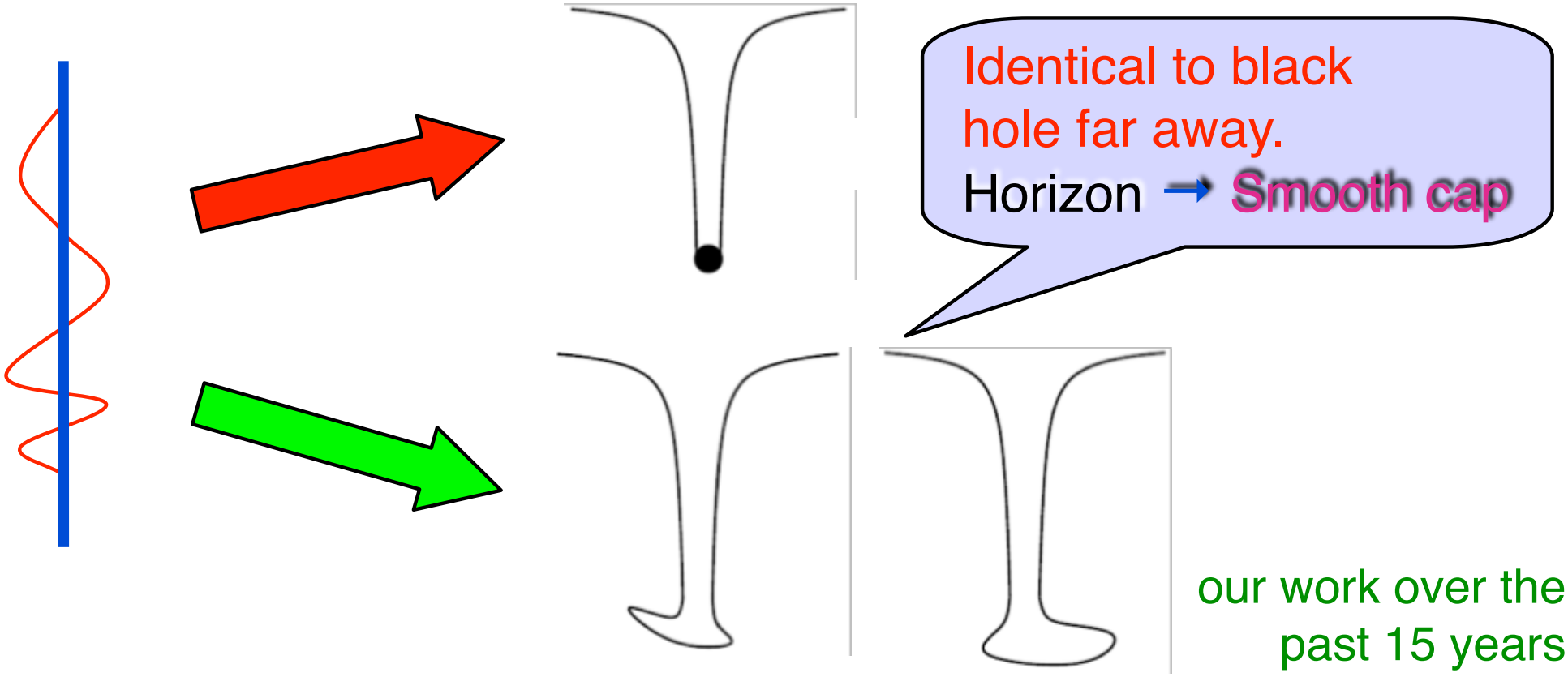
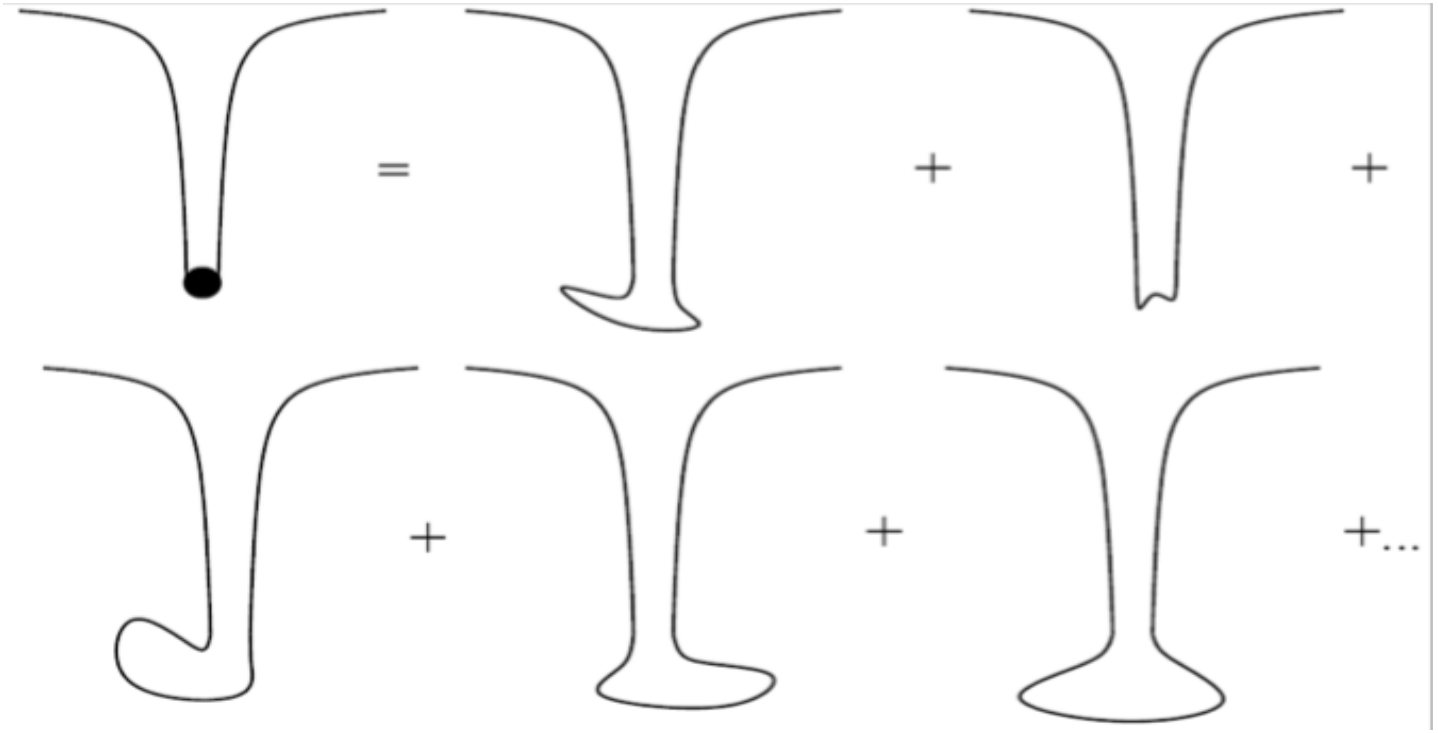


our work over the past 15 years

BIG QUESTION: Are all black hole microstates given by configurations with no horizon ?

Black hole $\stackrel{?}{=}$ ensemble of horizonless microstate configurations

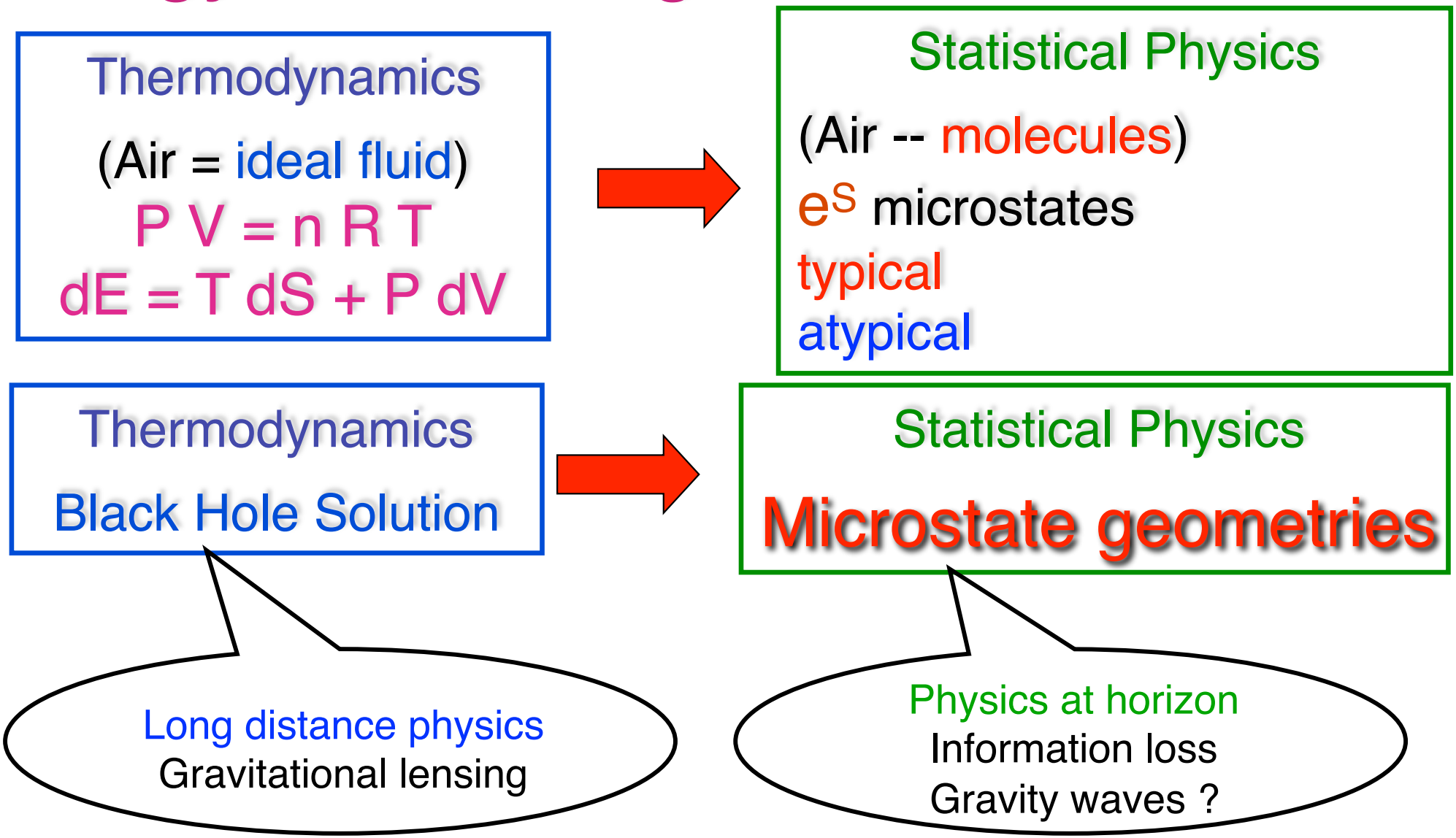
Mathur 2003



Only way to solve QM-GR conflict

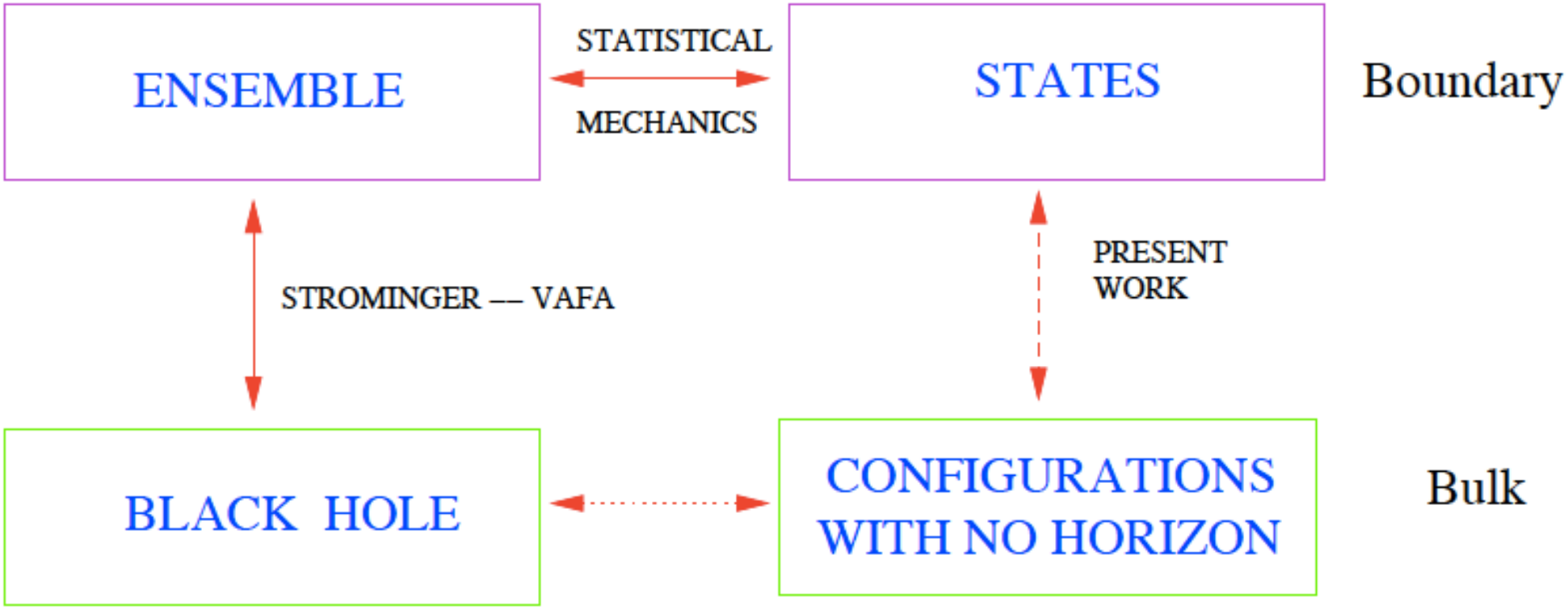
Mathur 2009, Almheiri, Marolf, Polchinski, Sully 2012

Analogy with ideal gas:



AdS-CFT formulation:

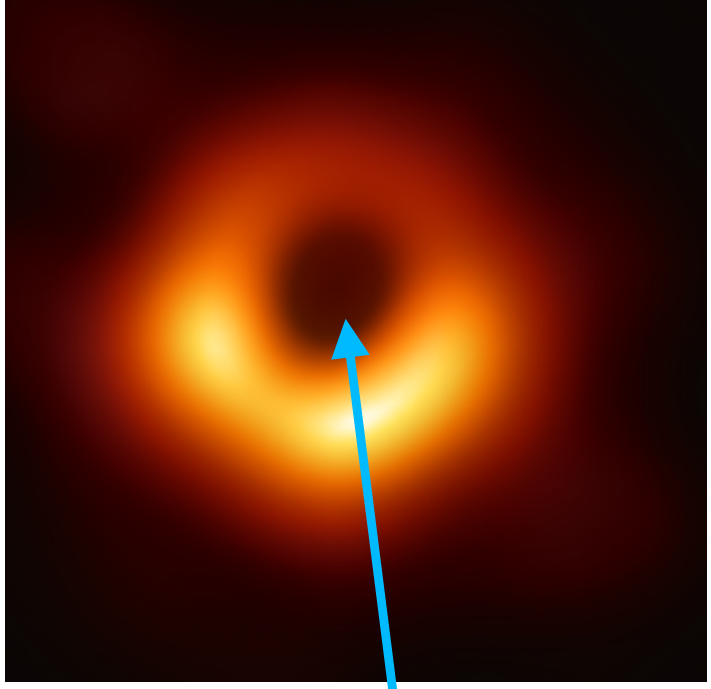
e.g. Bena, Warner, 2007



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

Structure@horizon

in vogue these days



– Gravastars
– Quark-stars
– Boson-stars
– Gas of wormholes (ER=EPR)
– Quantum Black Boxes
– BMS / Soft hair & horizon
– Quantum Pixie Dust
– Modified gravity
– Bose-Einstein condensate of gravitons
– Infinite density firewall hovering just above horizon

Three Very Stringent Tests

1. Growth with G_N ↔ BH size for any mass

Horowitz

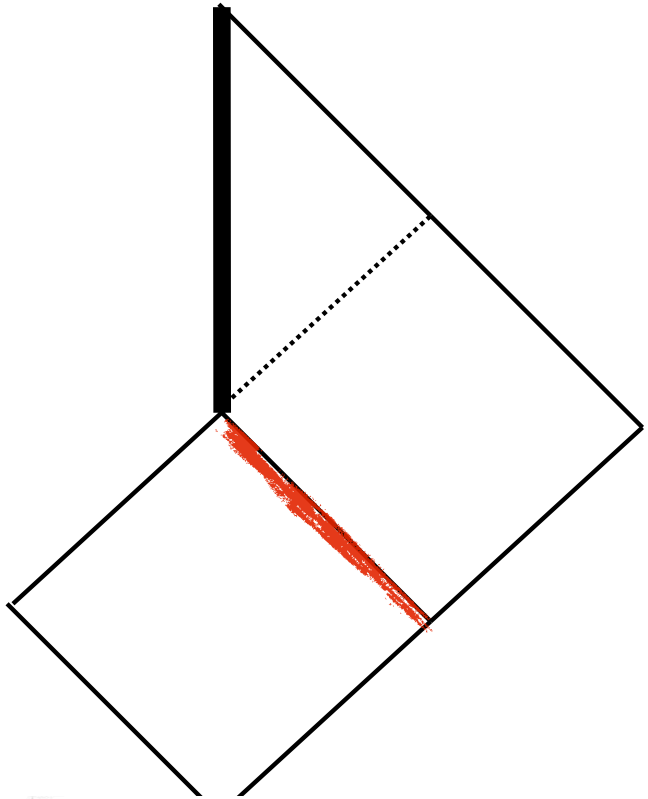
- Normal objects shrink; BH horizon grows
- BH microstate geometries grow like BH
- Highly nontrivial mechanism: $G_N = g_s^2$
- D-branes = solitons, tension ~ $1/g_s$ ➞ lighter as G_N increases

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

- Boson stars need scalar fields of different masses to replace various BH's: One field for M☉, another for 30 M☉, etc.
- String theory non-perturbative d.o.f. ➞ fields whose mass decreases for larger BH

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 “quantum stuff”
- No (fire)wall

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

“Quantum Coyote principle”

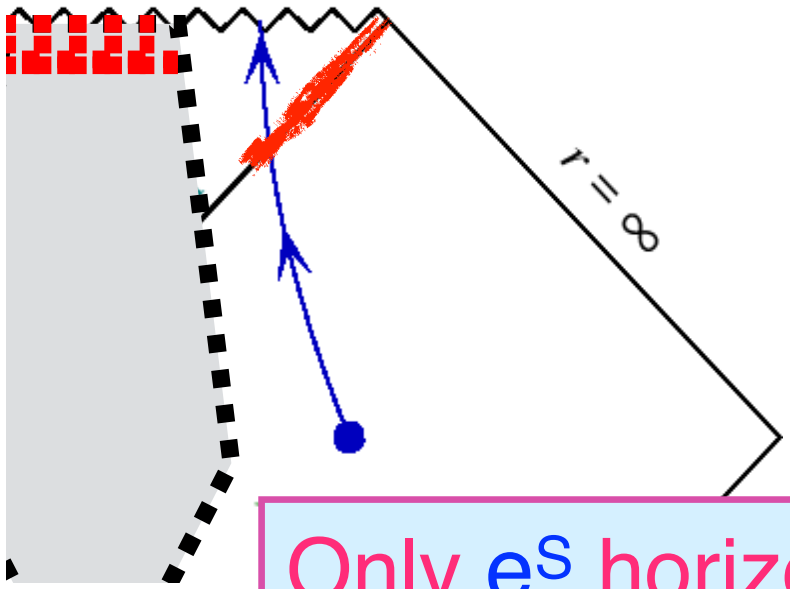
Quantum Coyote Principle

GRAVITY DOES NOT WORK
`TILL YOU LOOK DOWN ….


Such is the fate of
Firewalls, quantum black boxes, Mirrors & their brothers

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 (180 hours for TON618 BH)



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

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

Black hole entropy the structure must have

Rules out gravastars

Microstate geometries

M2	0	1	2					
M2	0			3	4			
M2	0					5	6	

3-charge 5D black hole Strominger, Vafa; BMPV

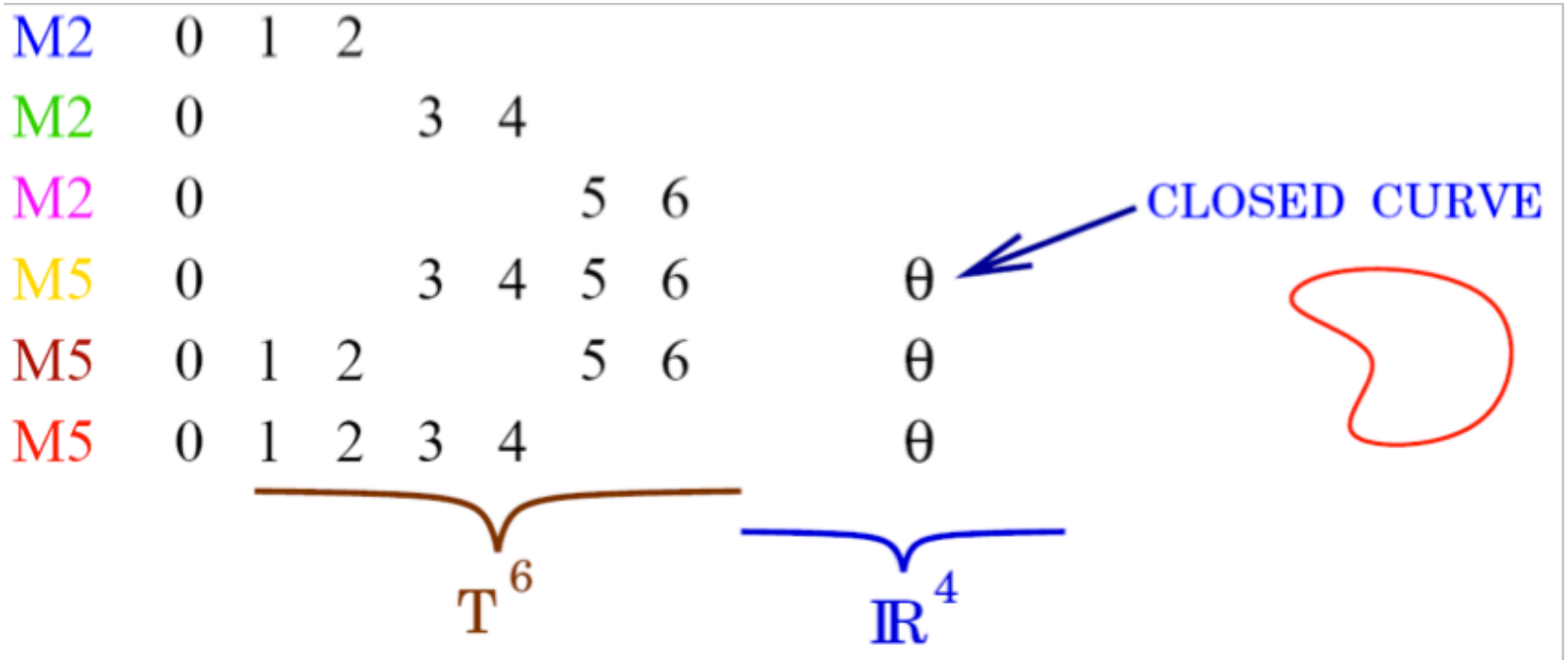
$$S_{BMPV} = 2\pi\sqrt{N_1 N_5 N_P - J^2}$$

$$ds^2 = -Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx^2_{\mathbb{R}^4} + ds^2_{T^6}$$

$$F_{120i} = \partial_i Z_1^{-1} \qquad F_{340i} = \partial_i Z_2^{-1} \qquad F_{560i} = \partial_i Z_3^{-1} \qquad \text{electric}$$

Want solutions with same asymptotics, but no horizon

Microstate geometries



$$ds^2 = -Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx^2_{\mathbb{R}^4} + ds^2_{T^6}$$

$F_{120i} = \partial_i Z_1^{-1}$ $F_{340i} = \partial_i Z_2^{-1}$ $F_{560i} = \partial_i Z_3^{-1}$ electric

$F_{12ij} = G^1_{ij}$ $F_{56ij} = G^2_{ij}$ $F_{56ij} = G^3_{ij}$ magnetic

Solution depends on G^1 G^2 G^3 Z_1 Z_2 Z_3 $\vec{k}$

Bena, Warner
Gutowski, Reall

Microstates geometries: M2-M2-M2 frame

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:

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

$$\nabla \times \vec{A} = \nabla V$$

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

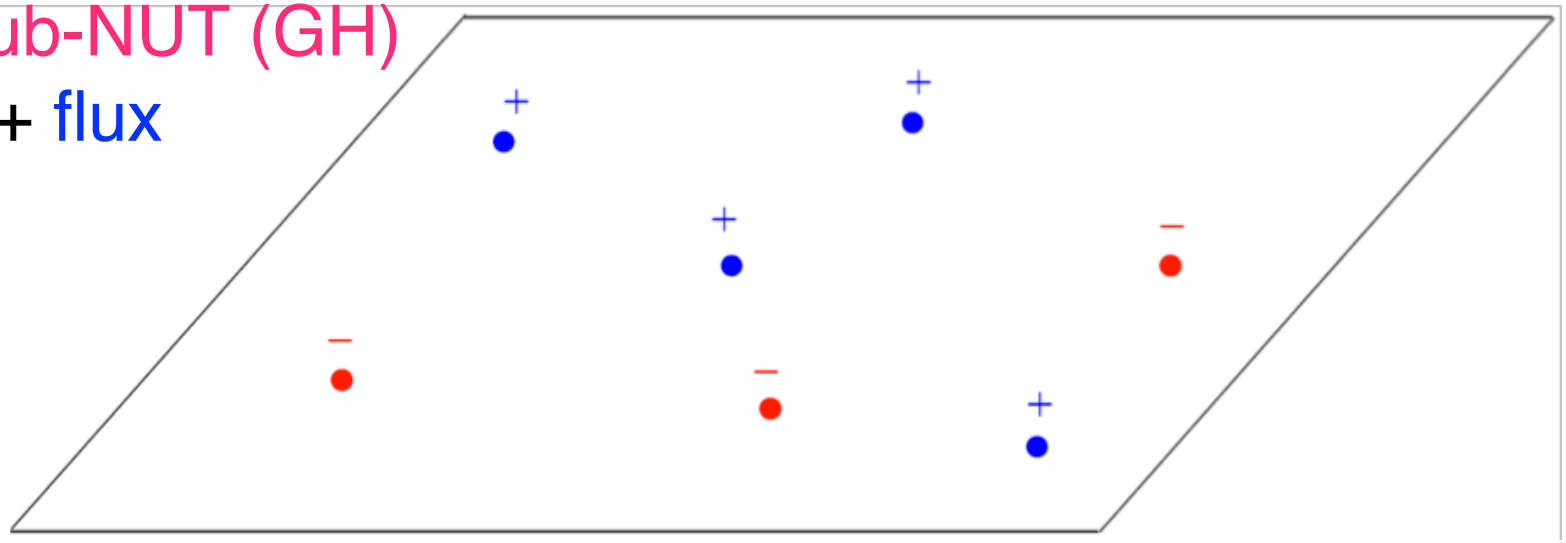
$V = 1 + \frac{1}{r}$ Taub-NUT

8 harmonic functions

Gauntlett, Gutowski,
Bena, Kraus, Warner

Simplest Microstate Geometries

Multi-center Taub-NUT (GH)
many 2-cycles + flux



Compactified to 4D → multicenter configuration Denef

- $+$ GH center $\Leftrightarrow$ $D6$ brane
- $-$ GH center $\Leftrightarrow$ $\overline{D6}$ brane

Abelian worldvolume flux
Each: 16 supercharges
4 common supercharges
(D2,D2,D2)

Lots and lots of solutions !
No singular sources or horizons
Completely smooth (@ Taub-NUT centers geometry ~ R^4)
Same mass, charge, size as BH with large horizon area

Microstates geometries: M2-M2-M2 frame

- 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

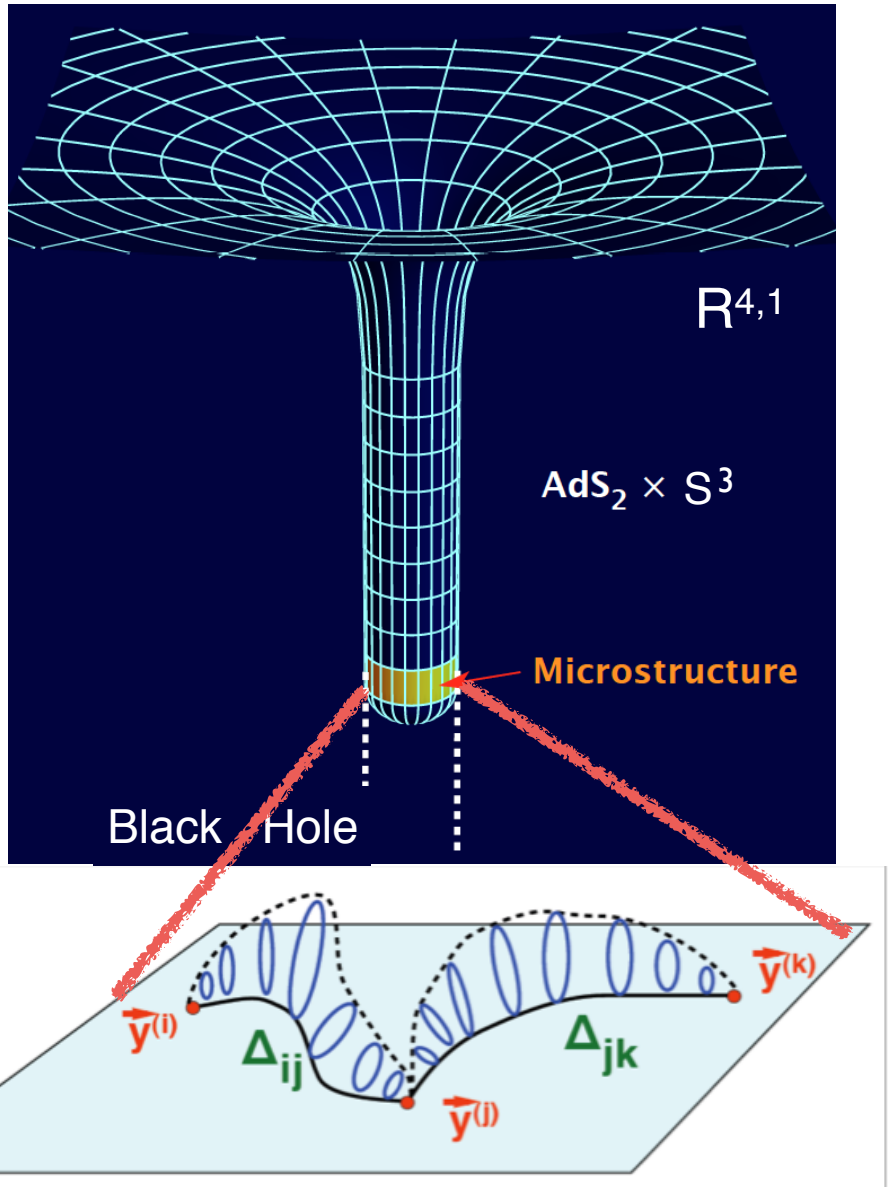
$J = E \times B = \ldots + F_{01}\, F_{12} + \ldots$

Charge dissolved in fluxes.

No singular sources.

Klebanov-Strassler

11d/CY - black hole in 5d

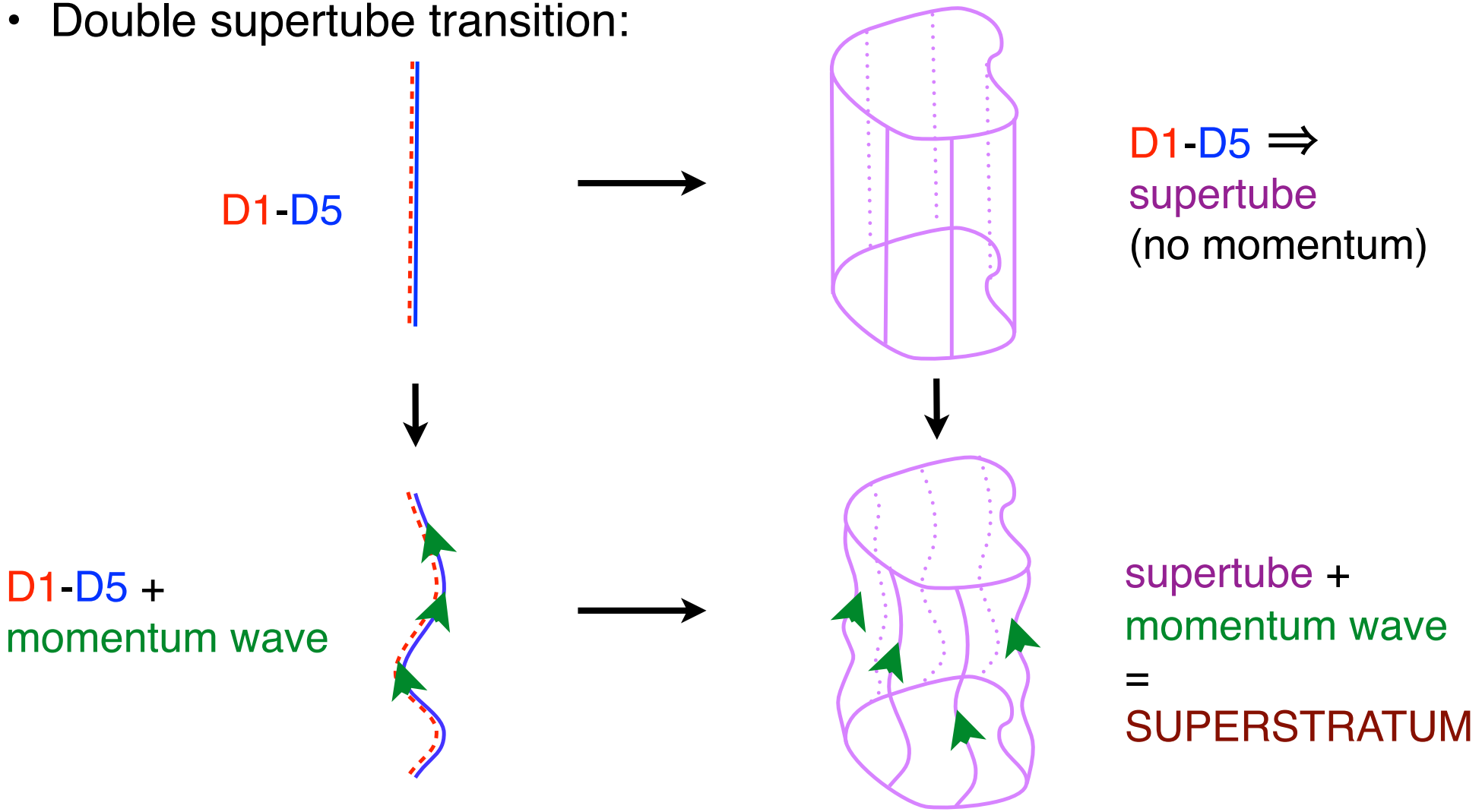


2-cycles + magnetic flux

Even more general solutions

Bena, deBoer, 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:

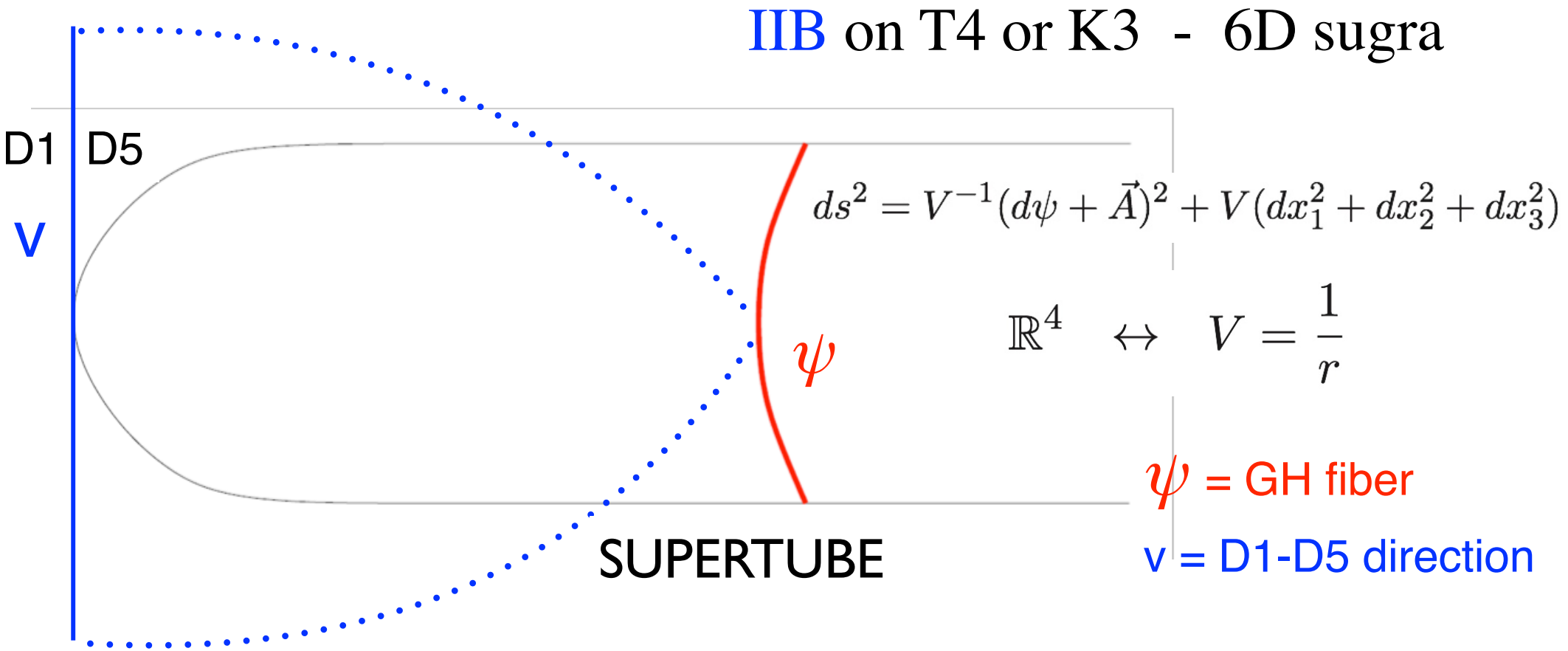


Superstrata

architect’s plan

actual construction

Microstates geometries: D1-D5-P frame



- Starting solution: $AdS_3 \times S^3$ Add wiggles
- Arbitrary $F(\psi)$ - 8 supercharges - supertube
  Lunin, Mathur; Lunin, Maldacena, Maoz; Taylor, Skenderis
- Arbitrary $F(\psi, v)$ - 4 supercharges - superstratum
  Bena, Giusto, Russo, Shigemori, Warner

Largest family of solutions known to mankind

Arbitrary fns. of 3 variables: ∞ X ∞ X ∞ parameters !

Cohomogeneity - 5 !

Bena, Giusto, Russo, Shigemori, Warner, 2015

Heidmann, Mayerson, Walker, Warner, 2019

$$
\begin{aligned}
ds_{10}^2 &= \frac{1}{\sqrt{\alpha}}\, ds_6^2 + \sqrt{\frac{Z_1}{Z_2}}\, d\hat{s}_4^2\,,\\
ds_6^2 &= -\frac{2}{\sqrt{\mathcal{P}}}\,(dv+\beta)\left[du+\omega+\frac{\mathcal{F}}{2}(dv+\beta)\right] + \sqrt{\mathcal{P}}\, ds_4^2\,,\\
e^{2\Phi} &= \frac{Z_1^2}{\mathcal{P}}\,,\\
B &= -\frac{Z_4}{\mathcal{P}}\,(du+\omega)\wedge(dv+\beta) + a_4\wedge(dv+\beta) + \delta_2\,,\\
C_0 &= \frac{Z_4}{Z_1}\,,\\
C_2 &= -\frac{Z_2}{\mathcal{P}}\,(du+\omega)\wedge(dv+\beta) + a_1\wedge(dv+\beta) + \gamma_2\,,\\
C_4 &= \frac{Z_4}{Z_2}\,\widehat{\mathrm{vol}}_4 - \frac{Z_4}{\mathcal{P}}\,\gamma_2\wedge(du+\omega)\wedge(dv+\beta) + x_3\wedge(dv+\beta) + \mathcal{C}\,,\\
C_6 &= \widehat{\mathrm{vol}}_4\wedge\left[-\frac{Z_1}{\mathcal{P}}\,(du+\omega)\wedge(dv+\beta) + a_2\wedge(dv+\beta) + \gamma_1\right]\\
&\qquad - \frac{Z_4}{\mathcal{P}}\,\mathcal{C}\wedge(du+\omega)\wedge(dv+\beta)\,,\\
&\qquad \mathcal{P} \equiv Z_1 Z_2 - Z_3^2\,.
\end{aligned}
$$

$$
\begin{aligned}
\omega_r^{(2)} &= -\frac{R\,r}{\sqrt{2}\,k_2(m_1^2-1)}\,\frac{m_1(k_2+m_1+1)\Delta_{k_2+m_1-1,m_1-1} + (k_2+m_1-1)\Delta_{k_2}}{(r^2+a^2)^2}\\
\omega_\theta^{(2)} &= \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2\sin\theta\cos\theta}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1}\\
&\quad + (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}\\
&\quad - m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1^2(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big],\\
\omega_\phi^{(2)} &= -\frac{R}{\sqrt{2}}\,\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\sin^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m}\\
&\quad + (m_1^2-2m_1+k_2-1)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}\\
&\quad + m_1(k_2-m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (k_2(m_1^2+m_1-1) - m_1(m_1+1)\\
\omega_\psi^{(2)} &= -\frac{R}{\sqrt{2}}\,\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\cos^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[(k_2-1)(m_1-1)\Delta_{k_2}\\
&\quad - 2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1}\\
&\quad - (m_1-1)(k_2-3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1}\\
&\quad - (m_1-1)(m_1(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big]\,.
\end{aligned}
$$

String theory input crucial

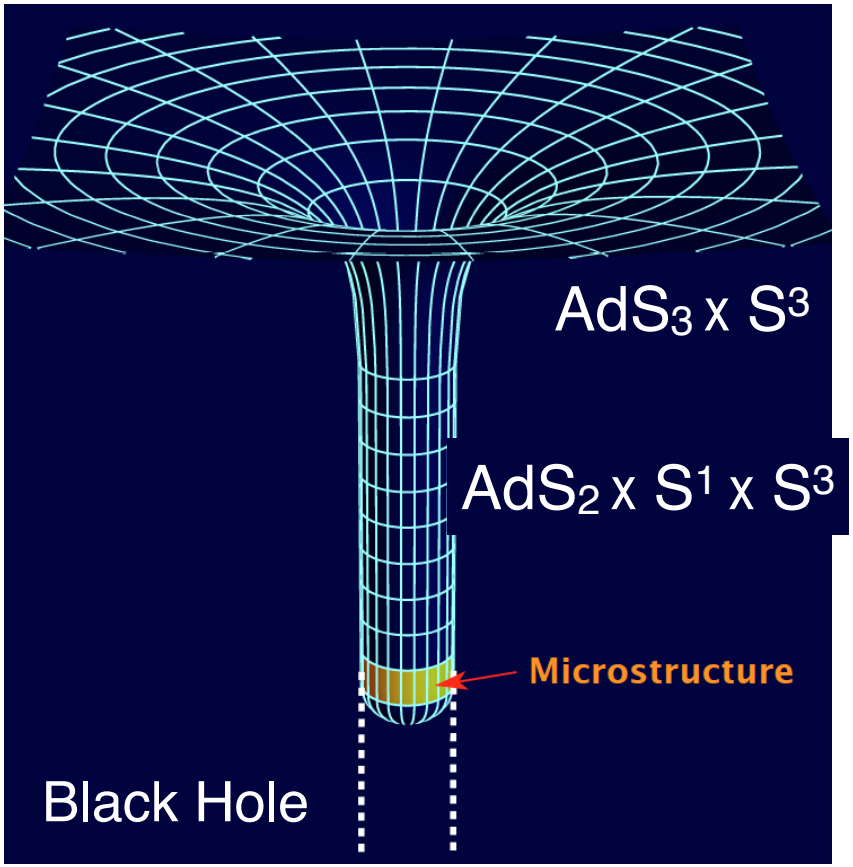
Giusto, Russo, Turton

Habemus Superstratum !!!

Deep superstrata

D1-D5-P black string in 6D

- J can be arbitrarily small
  Bena, Giusto, Martinec Russo, Shigemori, Turton, Warner '16 (PRL editor's selection)
- First BTZ microstates
- CFT dual state known
- Certain superstrata (1,0,n)
  Wave equation separable !
  Bena, Turton, Walker, Warner
- Can compute many things:
  Geodesics Tyukov, Walker, Warner
  Mass gaps Bena, Heidmann, Turton
  Wightman functions Raju, Shrivastava
  Green fns, Thermalization, Chaos, dip-ramp-plateau

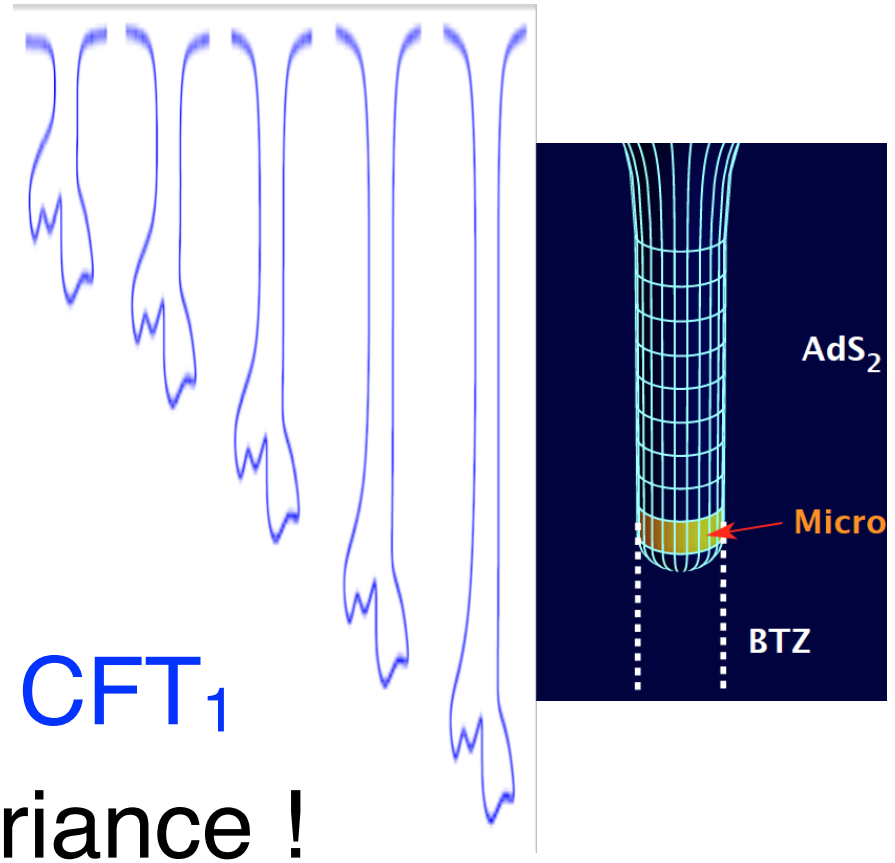


Quantum Gravity in AdS_2

Bena, Heidmann, Turton

- Deep microstate geometries have long AdS_2 throat
- Limit when length → ∞
- Disconnect from AdS_3
- Solutions above → asymptotically-AdS_2

  Bena, Heidmann, Turton
- Dual to ground states of CFT_1
- All break conformal invariance !



Quantum Gravity in AdS_2

Bena, Heidmann, Turton

- $\exists$ finite-energy time-dependent excitations $\rightarrow$

Paulos

- CFT_1 has no conformally-invariant ground state !!!
- Un-capped empty Poincaré AdS_2 is not dual to any ground state of CFT_1 (similar to Poincaré AdS_3)
- All CFT_1 ground states break conf. symmetry
- Tower of finite-energy excitations above each and every one of them

- Claims: CFT_1 has no excitations - looking at the wrong ground state
- Work assuming conformally-invariant IR (JT, etc) — nothing to do with AdS_2/CFT_1 in String Theory

SUSY microstates – the story:

- We have a huge number of them
  - Arbitrary continuous functions of 3 variables
  - Smooth solutions. $S \sim (Q_1 Q_5)^{1/2} (Q_p)^{1/4} < (Q_1 Q_5 Q_p)^{1/2}$
  - Can give black hole entropy Bena, Shigemori, Warner
- Dual to CFT states in typical sector
  - This is where BH states live too
  - Green Function - same thermal decay as BH but with Information Recovery Bena, Heidmann, Monten, Warner
  - CFT_1 dual to AdS_2 has no conformally-invariant ground state ! Bena, Heidmann, Turton
  - Hence extremal BH microstates in AdS_2 have no horizon —formal proof of fuzzball proposal for extremal Black Holes !

Strominger - Vafa

$S = S_{BH}$

Black Hole Deconstruction

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

$S \sim S_{BH}$

Black Holes

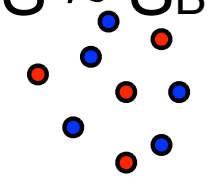
Effective coupling (g_s)

Multicenter Quiver QM

Denef, Moore (2007)

Bena, Berkooz, de Boer, El Showk, Van den Bleeken.

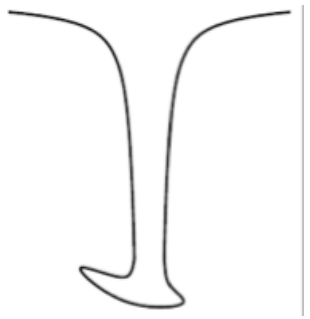
$S \sim S_{BH}$



Size grows

No Horizon

Smooth Horizonless Microstate Geometries



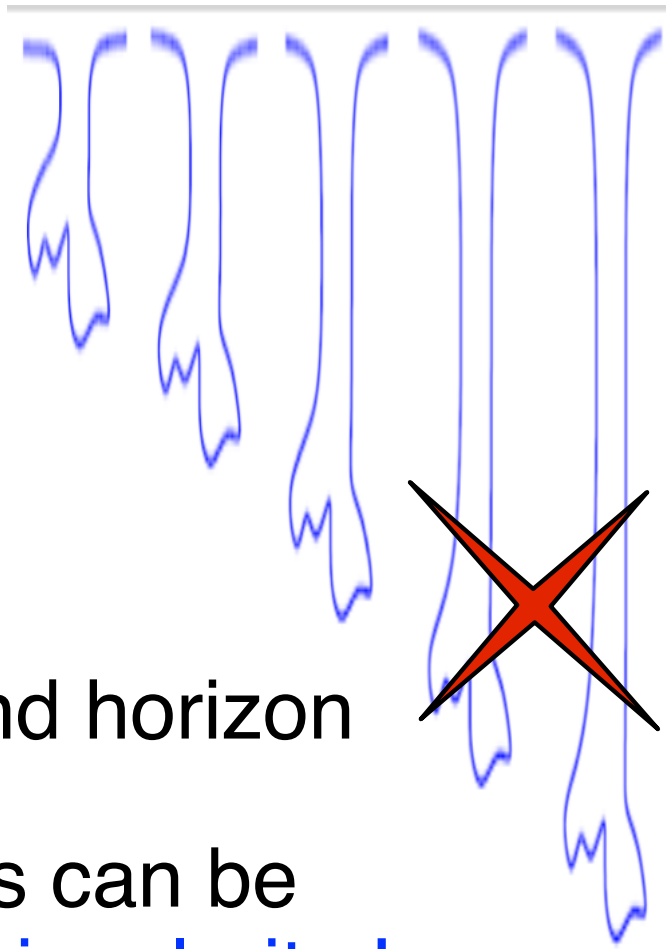
Punchline: Typical states grow as G_N increases.
Horizon never forms.
Quantum effects from singularity extend to horizon

Similar story for non-SUSY extremal black holes

Goldstein, Katmadas; Bena, Dall'Agata, Giusto, Ruef, Warner

Why destroy horizon ? Low curvature !

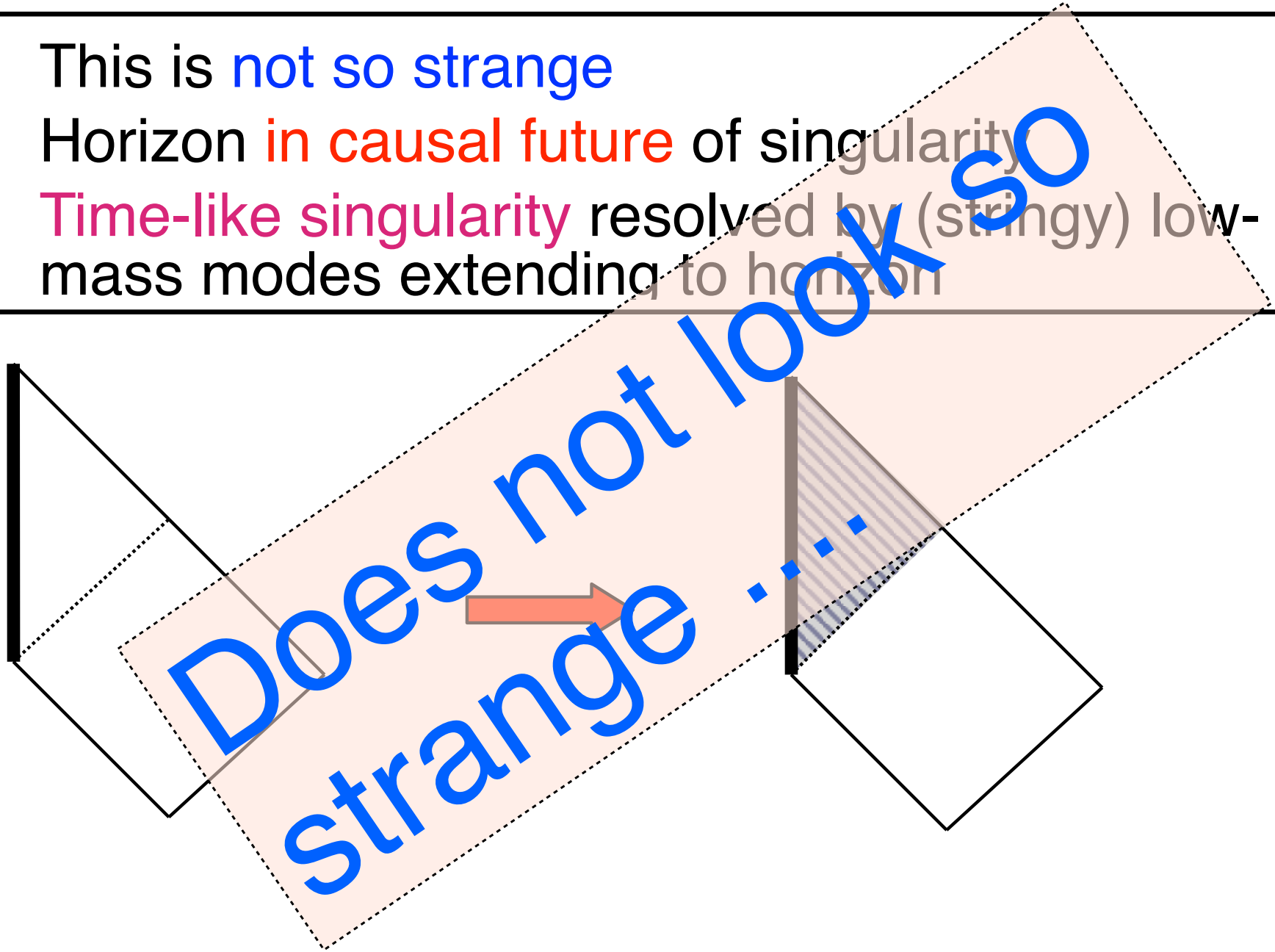
- Answer: space-time has singularity:
  - low-mass degrees of freedom
  - change physics on long distances
- Very common in string theory !!!
  - Polchinski-Strassler
  - Klebanov-Strassler
  - Giant Gravitons + LLM
  - D1-D5 system



- Nothing holy about singularity behind horizon
  Bena, Kuperstein, Warner
- It can be even worse – these effects can be significant even without horizon or singularity !
  Bena, Wang, Warner; de Boer, El Showk, Messamah, van den Bleeken

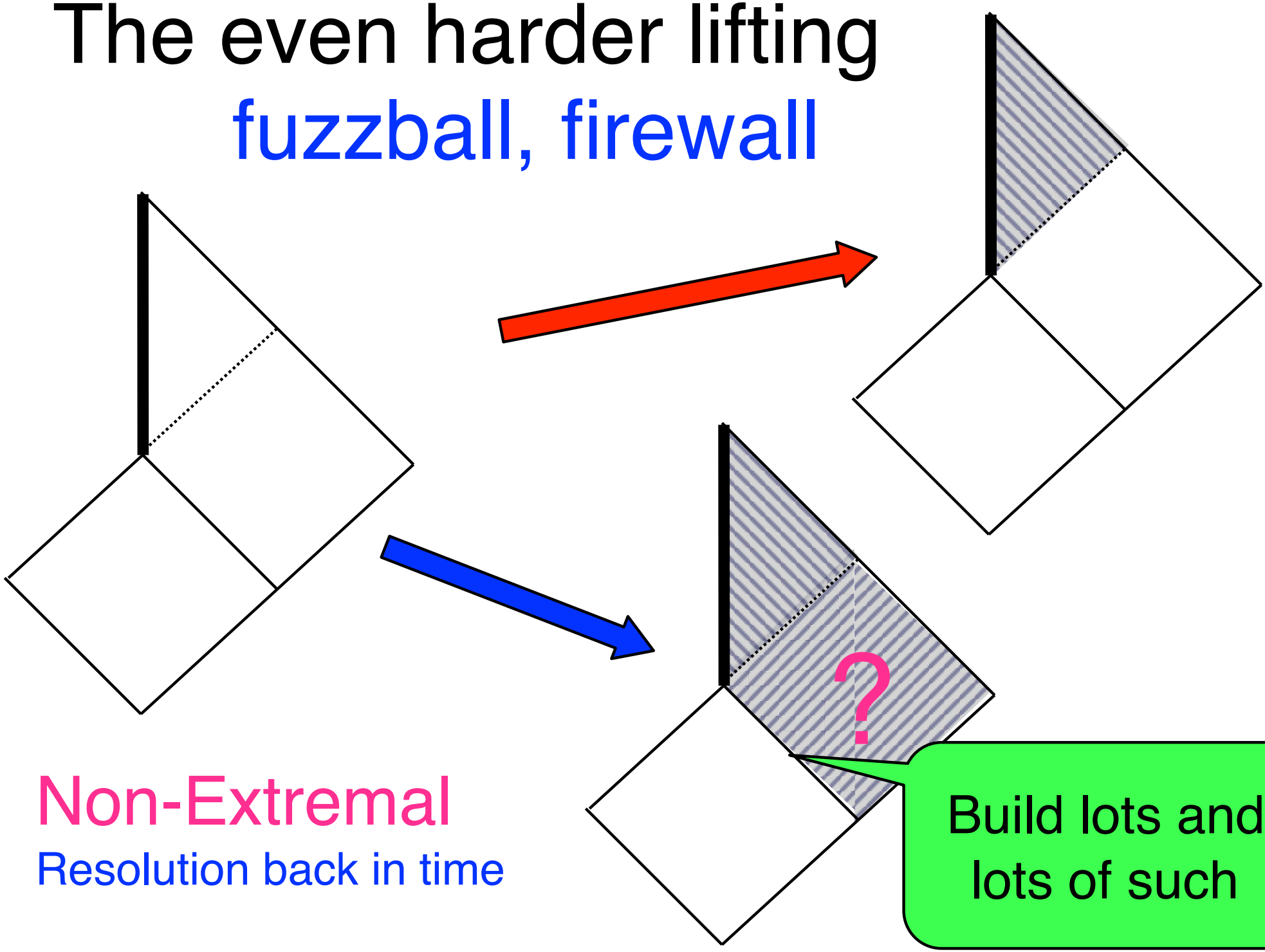
BPS Black Hole = Extremal

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



The even harder lifting

fuzzball, firewall



Non-Extremal

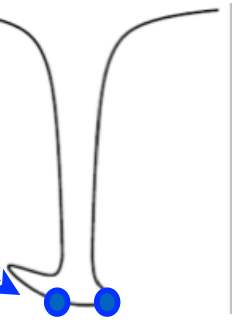
Resolution back in time

Extremely hard to build non-extremal microstates

– 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 probes
  Bena, Puhm, Vercnocke
- Decay to susy minima:
  - Brane-Flux annihilation
- Microstates of near-extremal BH

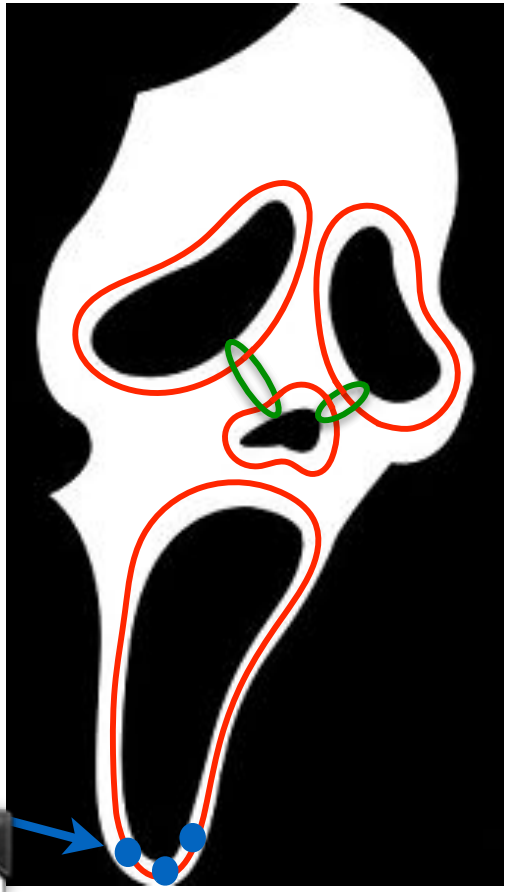


Exactly as in String Cosmology

Flux compactifications → 10^{500} vacua with negative cosmological constant: AdS

add fluxes + gaugino cond. → stabilize moduli → AdS

anti-D3 down long throats → redshift → very-small energy → lift AdS to dS KKLT, ~2500 others



THE LANDSCAPE

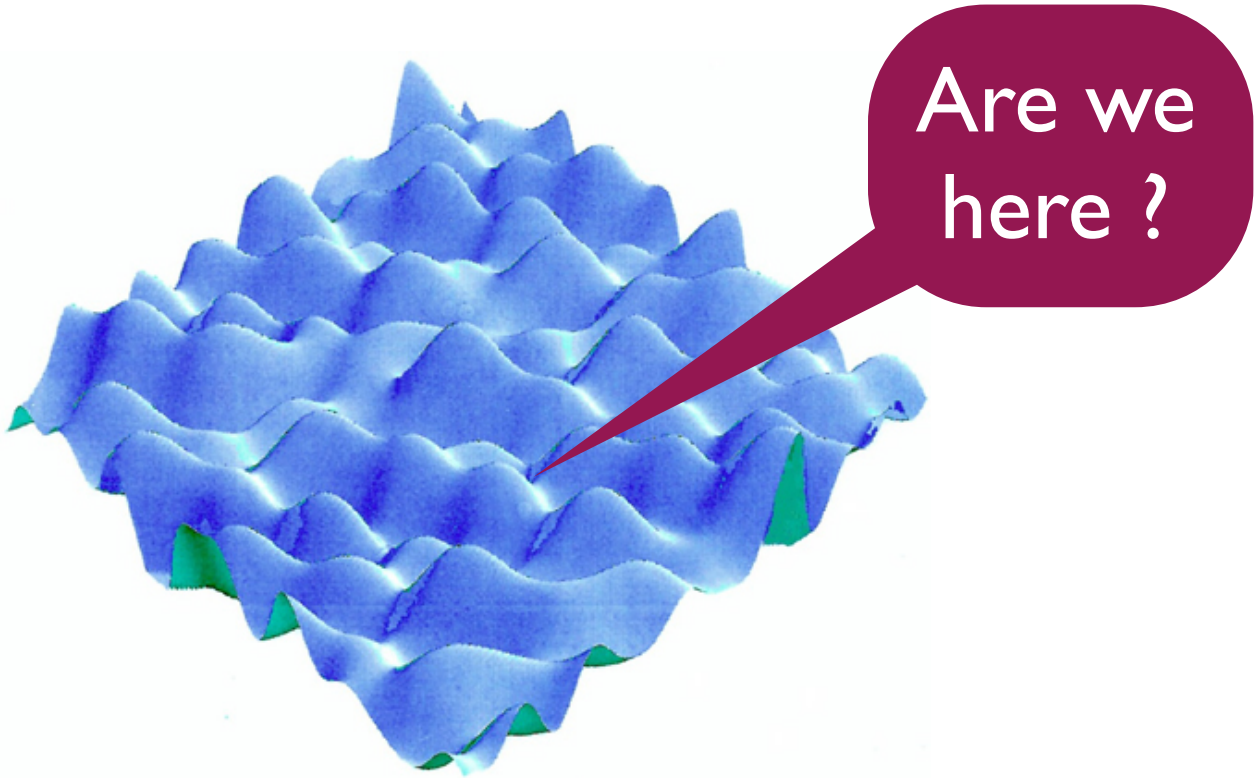
Huge fine-tuning in laws of physics:
10^{-120} cosmological constant,
10^{-24} electroweak,
10^{-10} inflation

Symmetry explanations (susy) increasingly excluded by LHC data

Anthropic explanations if **>> 10^{120}** universes with all possible laws and constants

String Theory - 10^{500} possible compactifications to 4D

Multiverse



New paradigm: fundamental laws of physics do not come from a deeper underlying theory, but are environmental variables determined by where we happen to be in the multiverse.

Microstates ↔ String

- Antibrane breaks susy and uplifts: $\Lambda > 0$
- Antibrane breaks susy and uplifts: $M > Q$
- However, life is not that simple:
- Antibranes have tachyons and runaways

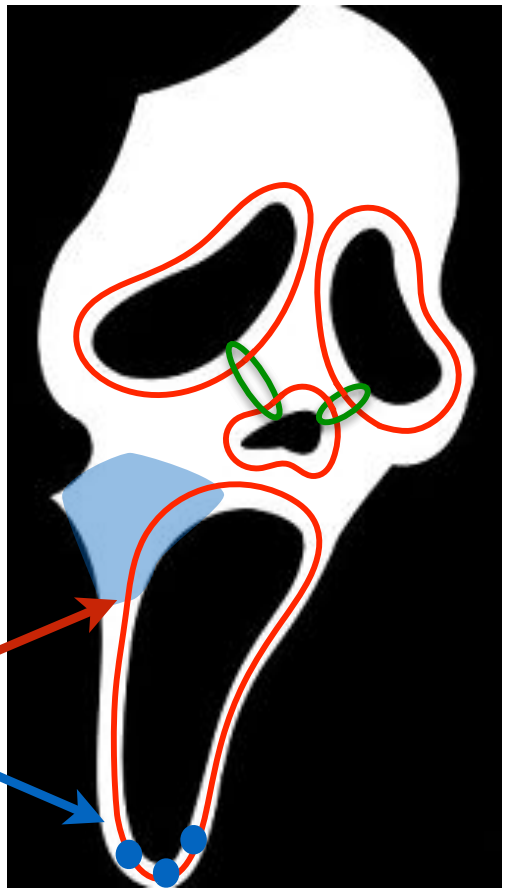
  Bena, Graña, Kuperstein, Massai; Bena, Dudas, Graña, S. Lüst
- Bad for cosmology
- but not for BH !
  - Instabilities in fact expected for non-extremal black hole microstates; JMaRT (+ bubbles) has them

    Cardoso, Dias, Hovdebo, Myers
  - D1-D5: BPS left-movers + right movers

Why instabilities ?

~~anti-D3 down long throats → redshift → very small energy → lift AdS to dS~~ KKLT, ~2500 others

anti-D3 → very strong fields ?
energy not tunably-small →
instabilities + runaways



Runaway mode ↔ jaw becoming longer and longer

Bena, Dudaș, Graña, S. Lüst

Confirmed by numerically-constructed KS black hole

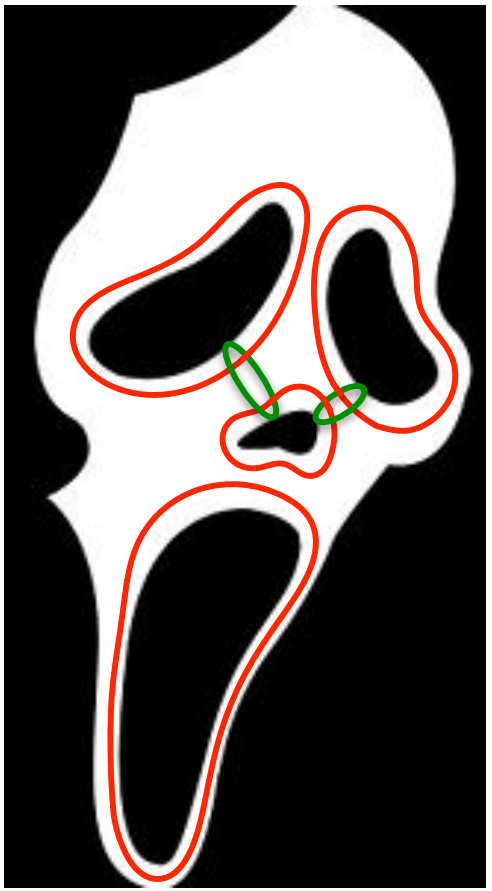
Bena, Buchel, S. Lüst

Goes away if D3 charge dissolved in fluxes in the jaw > 500

But total charge on compact space has to be zero !

How to get -500 units of charge ?

- O3 planes - at most -32
- D7 planes on 4-cycle S with huge Euler number: $\frac{\chi(S)}{24}$
- F-theory compactifications



~500

$$N_{D3} + \frac{1}{2}\int_Z G \wedge G = \frac{\chi(CY_4)}{24}$$

$$\chi(CY_4) = 6(8 + h^{1,1} + h^{3,1} - h^{2,1})$$

∃ χ (CY_4)=1 820

~300 000 4-cycles

Need more fluxes to stabilize these moduli

Large negative tadpoles in F-theory

- Argument / conjecture for large $\chi(CY_4)$:
- Tadpole of fluxes needed to stabilize (3,1) moduli grows like $\chi(CY_4)/12$
- Cannot stabilize all moduli in this limit

  Bena, Blåbäck, Graña, S. Lüst, to appear
- Even before antibranes. K3 x K3 for example
- Similar argument for
  - (2,1) moduli in CY_3 compactifications
  - fluxes on GH bubbles in microstate geometries

A bit of history

2003-now: KKLT + 2500 other articles:

de Sitter + inflation in String Theory

2009: Saclay group: antibranes are singular perturbatively

2011: Singularity is there to all orders

2012: Singularity is unphysical - no horizon cloaking

2014: Tachyon for $g_s N_{antiD3} > 1$

2016: Tachyon for $g_s N_{antiD3} \ll 1$

2009-16: Europe: Saclay, Leuven, Uppsala, Copenhagen

2018: new bottom-up arguments by Vafa&co against de Sitter

- followed by everybody and their brother

2018: new top-down runaway behavior

Pro-landscape: "intuition-based"
Anti-landscape: "equal-sign based"

- Crucial to distinguish between hard calculations and wishful thinking or moving goalposts

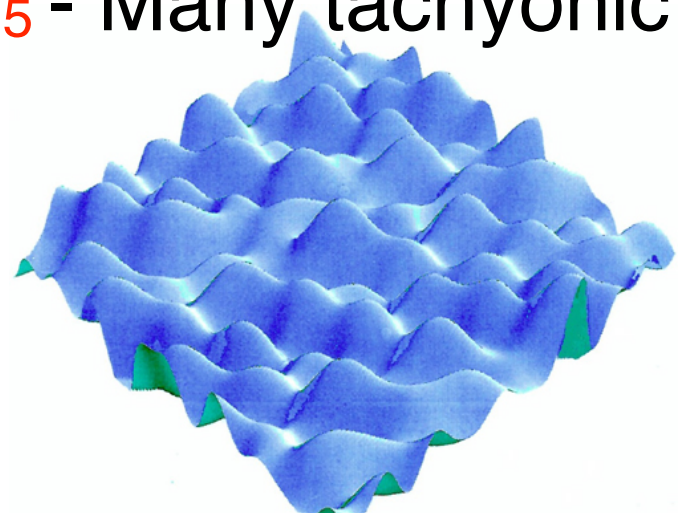
- US $ versus Zimbabwe $

- pro-KKLT goalposts moved from
  - "all antibranes are OK" 2010
  - "$g_s N_{antiD3} \ll 1$ is OK" 2012
  - "a single anti-D3 is OK" 2015
  - "F-theory saves the day" 2018

- de Sitter & nonextremal microstates - not stable !

Implications

- Bad for Landscape
  - Back to drawing board in String Cosmology
  - No controlled construction of de Sitter ☹
  - No string inflation model one can trust ☹
  - Swampland ? Quintessence ? ☹
- Non-extremal μ-state geometry instability
  - Feature not a bug Myers&co, Mathur&co
  - BPS moduli space dim. N_1N_5 - Many tachyonic
- Black hole:
  - messy dynamics in phase space of huge dimension



Antibranes = Bread & butter of 2 fields

String Phenomenology and Cosmology

- Flux compactifications -> AdS landscape
- Antibranes uplift Λ to get de Sitter, String Inflation

Black Hole Information Paradox

- Need Structure @ Horizon
- Constructed for extremal (SUSY) black holes
  $\Rightarrow$ it works !!!
- Antibranes in bubbling geometries - only systematic construction of structure @ non-extremal horizon

  Bena, Puhm, Vercnocke; Gibbons, Warner
- Antibrane instability: what physics it implies ?