Physics at the horizon

Mind the Cap !

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with

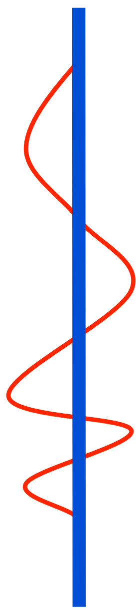
Nick Warner, Emil Martinec, Jan deBoer, Micha Berkooz, Simon Ross, Gianguido Dall'Agata, Stefano Giusto, Rodolfo Russo, Guillaume Bossard, Masaki Shigemori, Monica Guică, Nikolay Bobev, Bert Vercnocke, Andrea Puhm, David Turton, Stefanos Katmadas, Johan Blåbäck, Pierre Heidmann

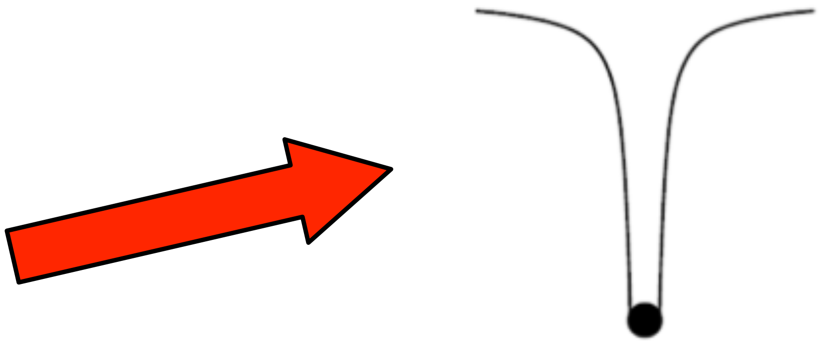
Strominger and Vafa (1996):

*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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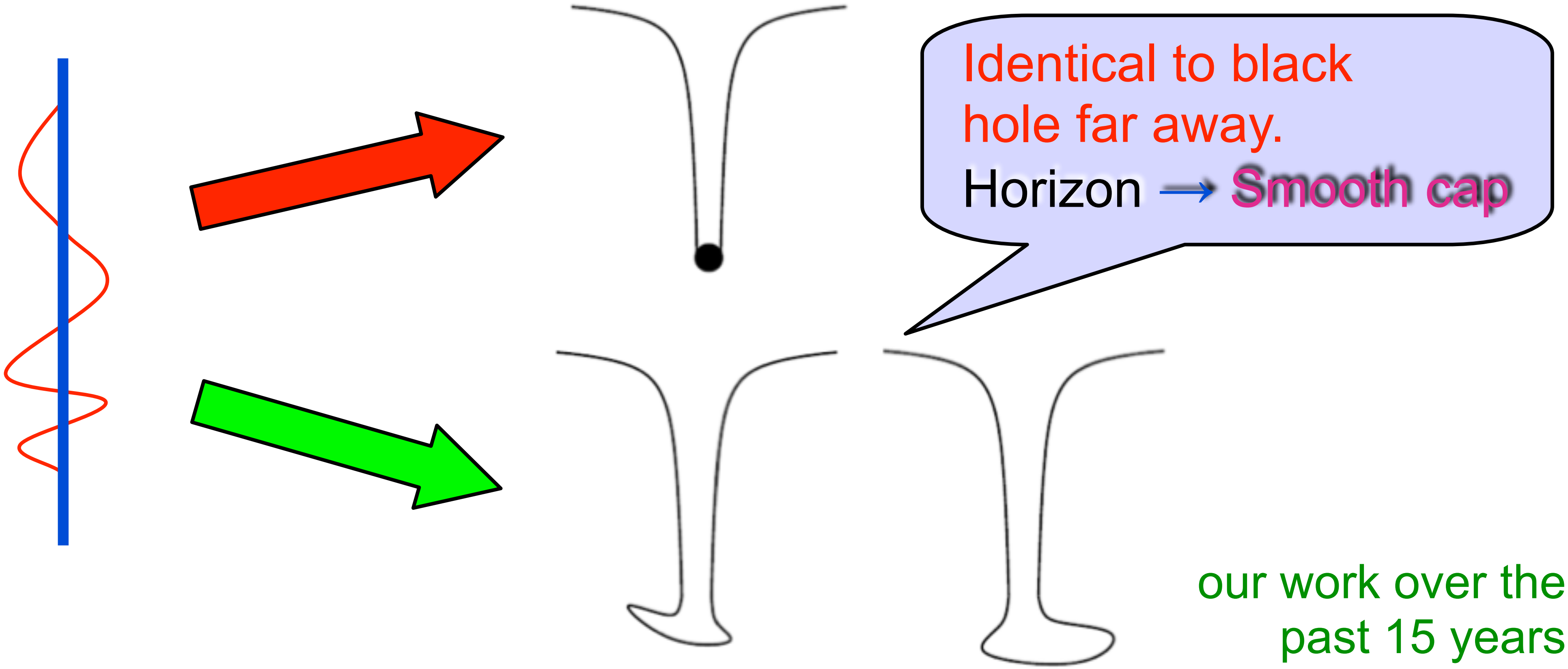
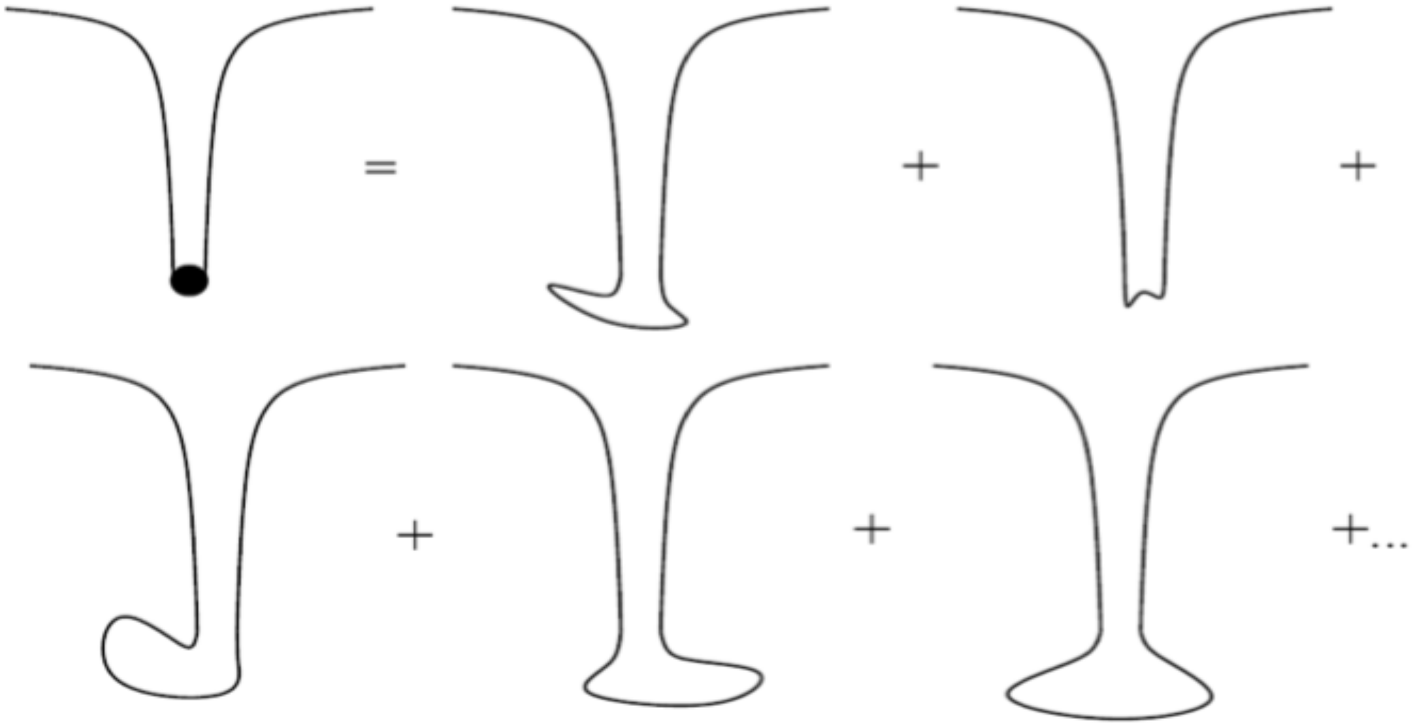


BIG QUESTION: Are ***all*** black hole microstates becoming geometries with no horizon ?

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

Thermodynamics

(Air = ideal fluid)

$P V = n R T$

$dE = T dS + P dV$

→

Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Thermodynamics

Black Hole Solution

→

Statistical Physics

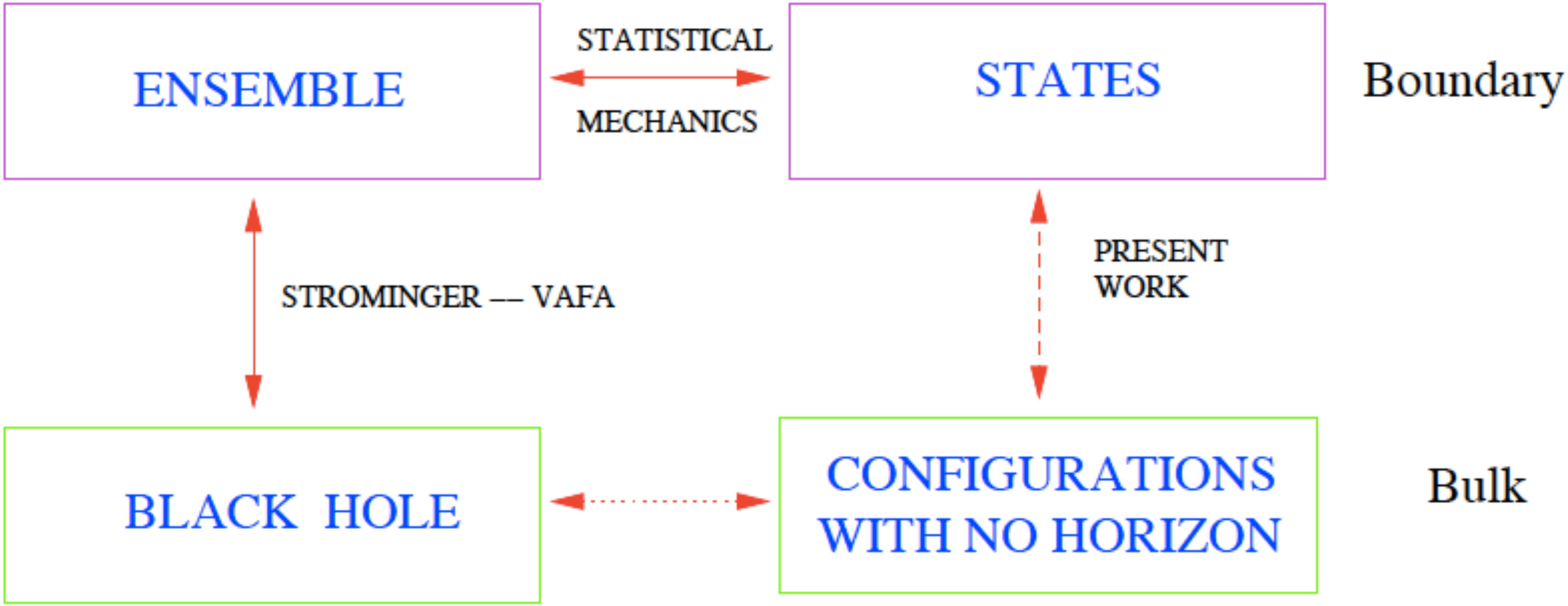
Microstate geometries

Long distance physics
Gravitational lensing

Physics at horizon
Information loss
Gravity waves ?

AdS-CFT formulation:

e.g. Bena, Warner, 2007



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

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…

3 very stringent tests:

1. Same growth with G_N !!!

Horowitz

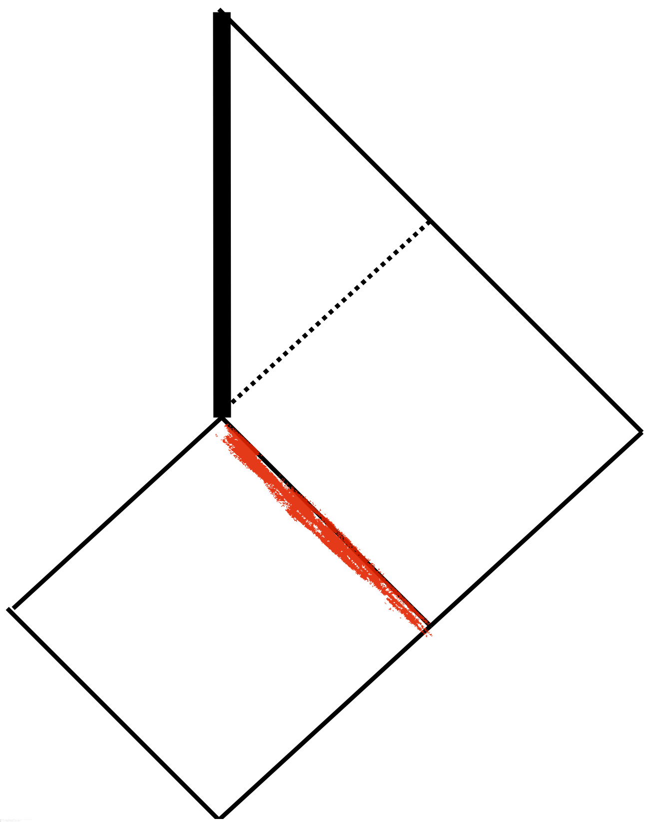
BH size grows with G_N ; "normal objects" shrink

- 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

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

2. Mechanism not to fall into BH

Very difficult !!!



GR Dogma:

Thou shalt not put anything at the horizon !!!

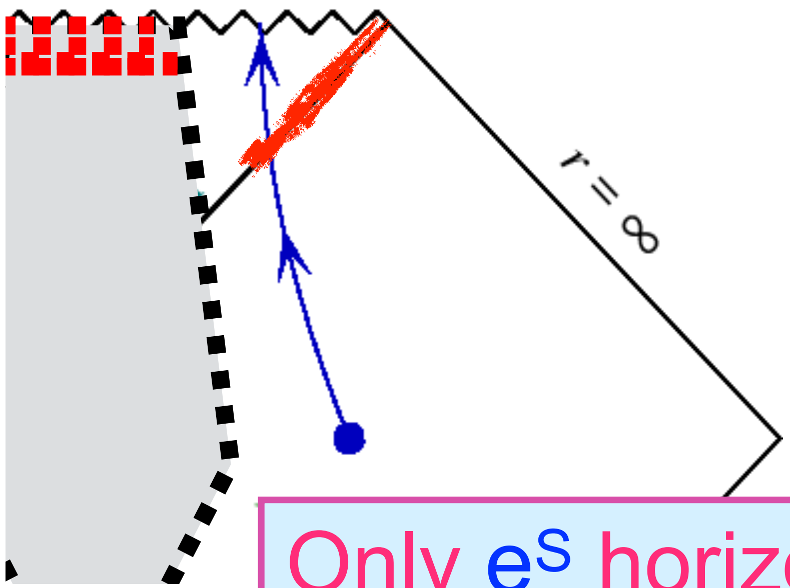
- Null → speed of light.
- If massive: ∞ boost → ∞ energy
- If massless: dilutes with time

- 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

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



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 !

If quantum tunneling you are brushing aside, incorrect physics you are doing

Microstates geometries

- Where is the BH charge ?

$\mathcal{L} = q\, A_0$ (magnetic)

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

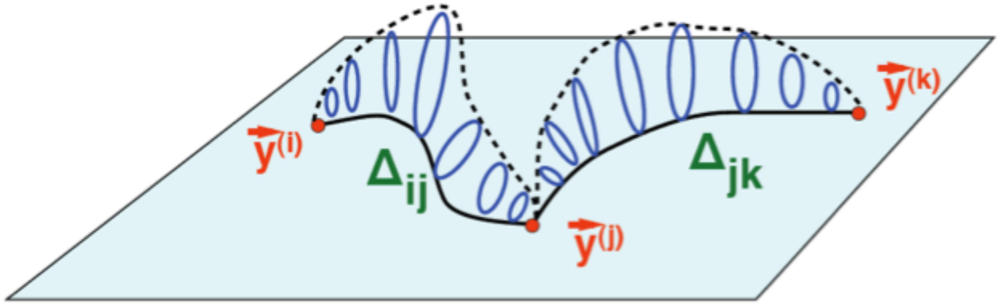
- Where is the BH mass ?

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

- BH angular momentum

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

2-cycles + magnetic flux



Bubbling Geometries

Black Hole Solitons

beautiful GR story behind

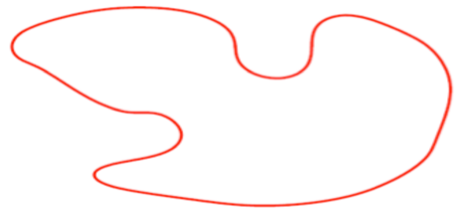
Gibbons, Warner

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

Klebanov-Strassler

Add wiggles - increase entropy

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

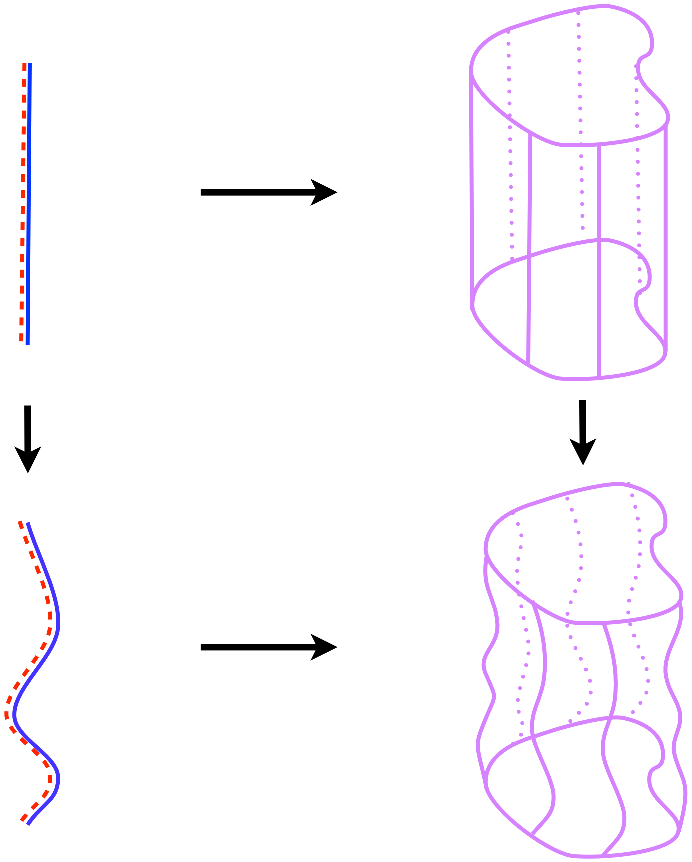


- Construct backreacted solution
  - Taub-NUT Page Green’s functions (painful)
- Smooth !
  - exactly as in flat space
    Lunin, Mathur; Emparan, Mateos, Townsend
    Lunin, Maldacena, Maoz
- Entropy: $S \sim (Q^{5/2})^{1/2}$
- Huge but not yet black-hole-like ($Q^{3/2}$)
- Need more degrees of freedom !

Get even more entropy

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 !!!

Largest family of solutions known to mankind

Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

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

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

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

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

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

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

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

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

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

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

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

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

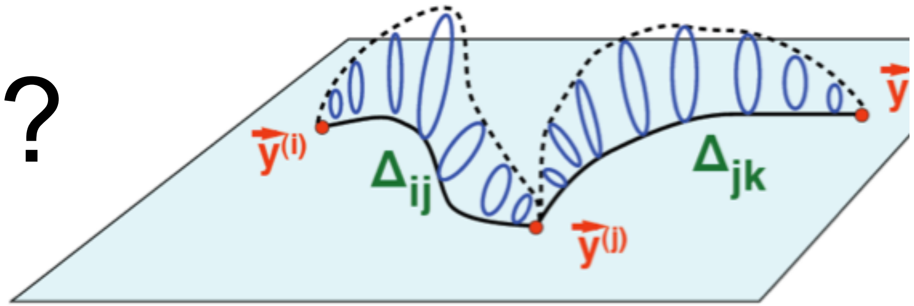
$$= -\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\cos^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[(k_2-1)(m_1-1)\Delta_{k_2+m_1+} - 2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} - (m_1-1)(k_2-3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1}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

Habemus Superstratum !!!

What took us so long ?

- 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 !!!

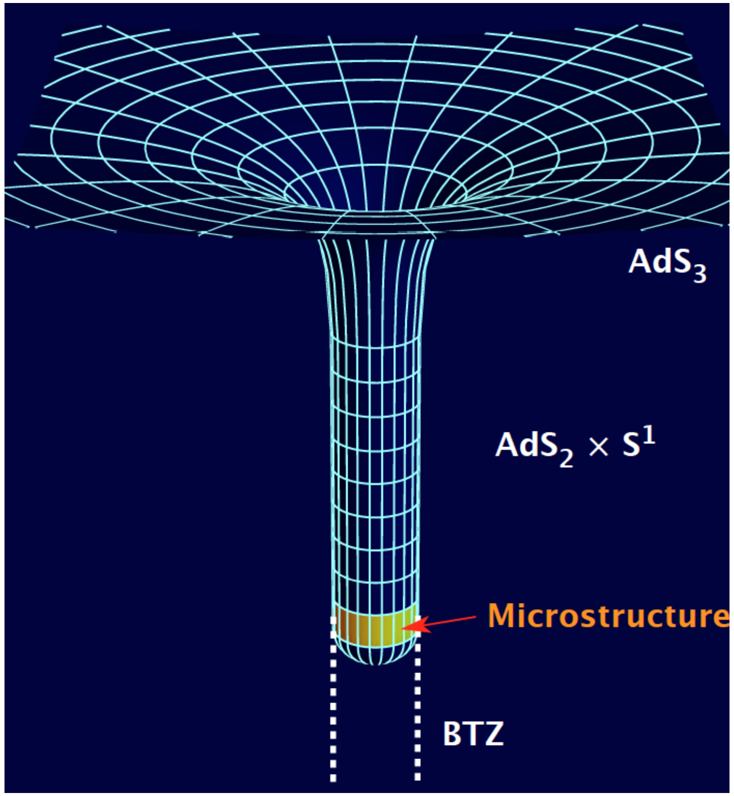
Why not collapsing ?



- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller $\longrightarrow$ 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 $\longrightarrow$ 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

Deep superstrata

- BH microstates with GH bubbles - very large J
- Typicaly ~ 99% of c.c. bound   Heidmann
- With a lot of pain ~ 85%
  Bena, Wang, Warner ’06; Bena, Heidmann, Ramírez ’17
- Build deep superstrata:
  J can be arbitrarily small
  Bena, Giusto, Martinec Russo, Shigemori,
  Turton, Warner ‘16 (PRL editor’s selection)
- First BTZ microstates
- CFT dual state known
- More recent low-J solutions
  with 3 GH centers + supertube
  Bena, Heidmann, Ramírez
  or with 1001 GH bubbles
  Ávila, Ramírez, Ruipérez



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 ?

Quantum Gravity in AdS_2

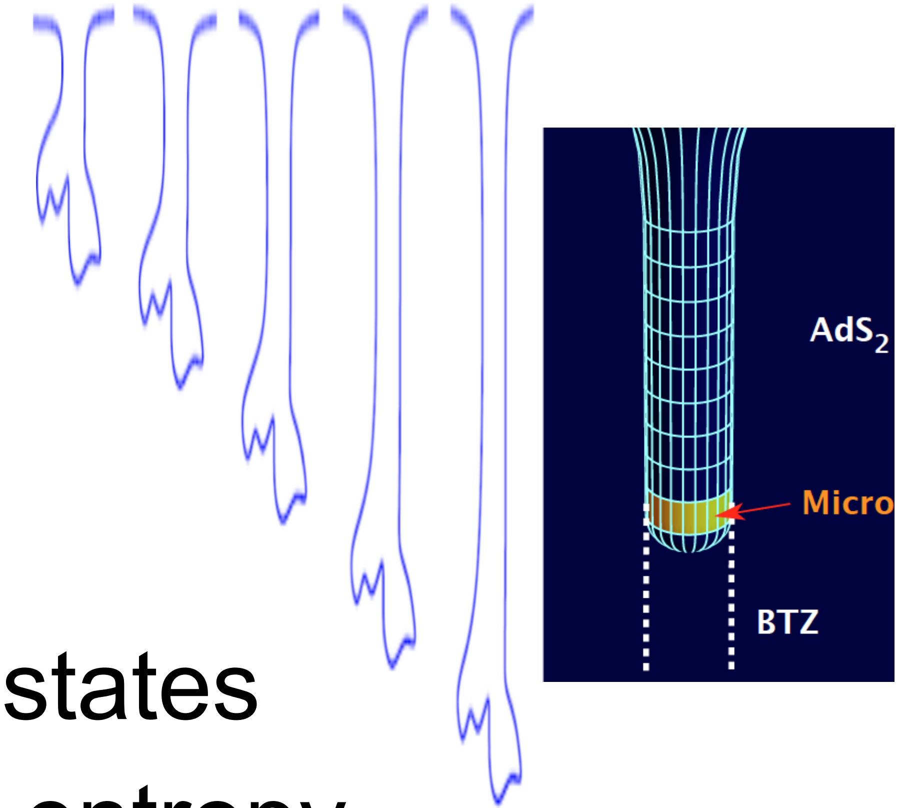
Bena, Heidmann, Turton, to appear

- Everybody & their brother & SYK & JT
- AdS_2 - no finite-energy excitations
  Maldacena, Michelson, Strominger
- backreaction of particle in AdS_2 either
  – destroys UV (work instead with *near-AdS_2*)
  – destroys IR - singularity
  (? ↔ singularity in SYK 4-pt. function)
- 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

Bena, Heidmann, Turton, to appear

- Typical microstate geometries have long AdS_2 throat
- Limit when length $\rightarrow \infty$
- Disconnect from AdS_3
- Solutions above $\rightarrow$ asymptotically-AdS_2
  Bena, Heidmann, Turton
- Same entropy as microstates
- If superstrata count BH entropy, so do these solutions !



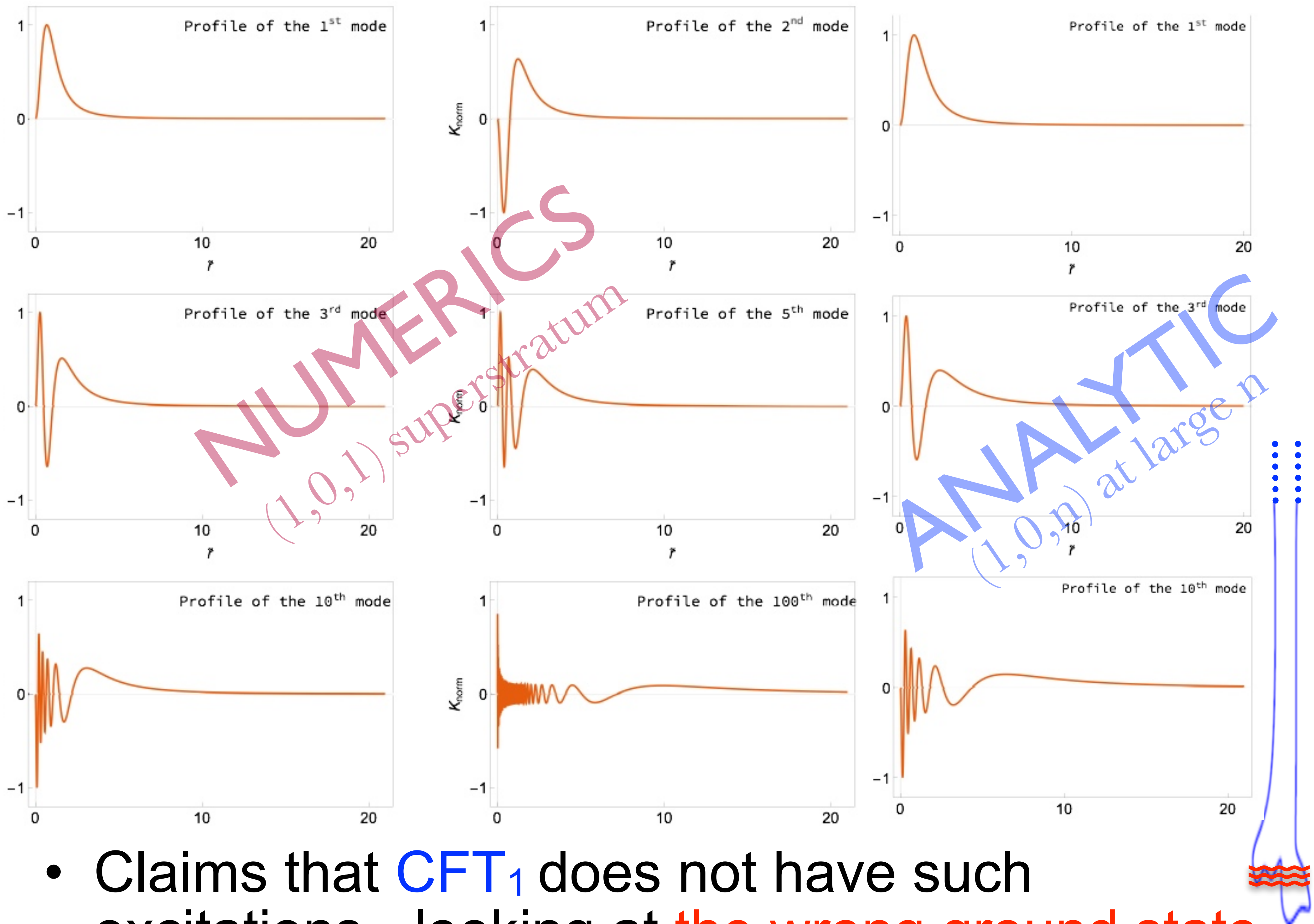
Quantum Gravity in AdS_2

Bena, Heidmann, Turton, to appear

- geometries with AdS_2 UV and IR cap
- BPS ground states of CFT_1 dual to AdS_2
- finite-energy time-dependent excitations →

  Paulos

- CFT_1 has no conf.-invariant ground state !!!
- Empty Poincaré AdS_2 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



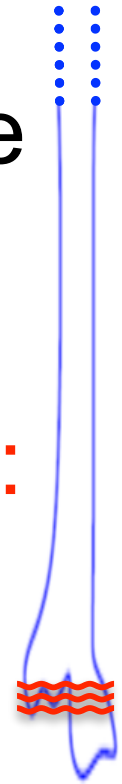
- Claims that CFT$_1$ does not have such excitations - looking at the wrong ground state

Quantum Gravity in AdS_2

Bena, Heidmann, Turton, to appear

- Non-BPS excitations do not destroy AdS_2 UV ! IR cap is crucial
- Microstates of AdS_2 non-extremal black hole

  Castro, Grumiller, Larsen, McNees
- Kosher holography - AdS_2 UV
- SYK, J-T, near-AdS & friends = non-Kosher: non-AdS UV, irrelevant ops, IR to UV flows
- Can one link the two approaches ?
  - see absence of conf. symmetry of ground states from SYK ?

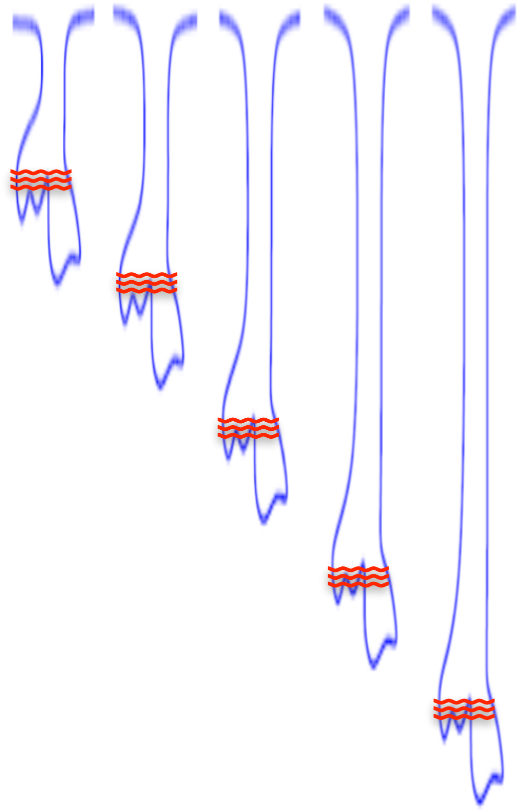


Gluing back to AdS_3

Bena, Heidmann, Turton, to appear

- AdS_2 microstates: $J=0$
- J comes from AdS_2-AdS_3 gluing
- Deep microstate geometries fit inside AdS_2 $\rightarrow$ genuine BH states

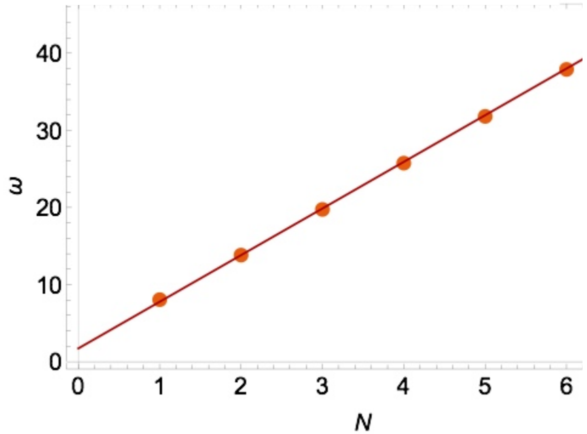
Sen



- AdS_3 mass gap depends on length
- Length of AdS_2 throat quantized

CFT dual, deBoer & al

- smallest gap = 2 x $1/N_1N_5$
  CFT_1 finite-energy excitations $\rightarrow$ CFT_2 excitations above gap



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

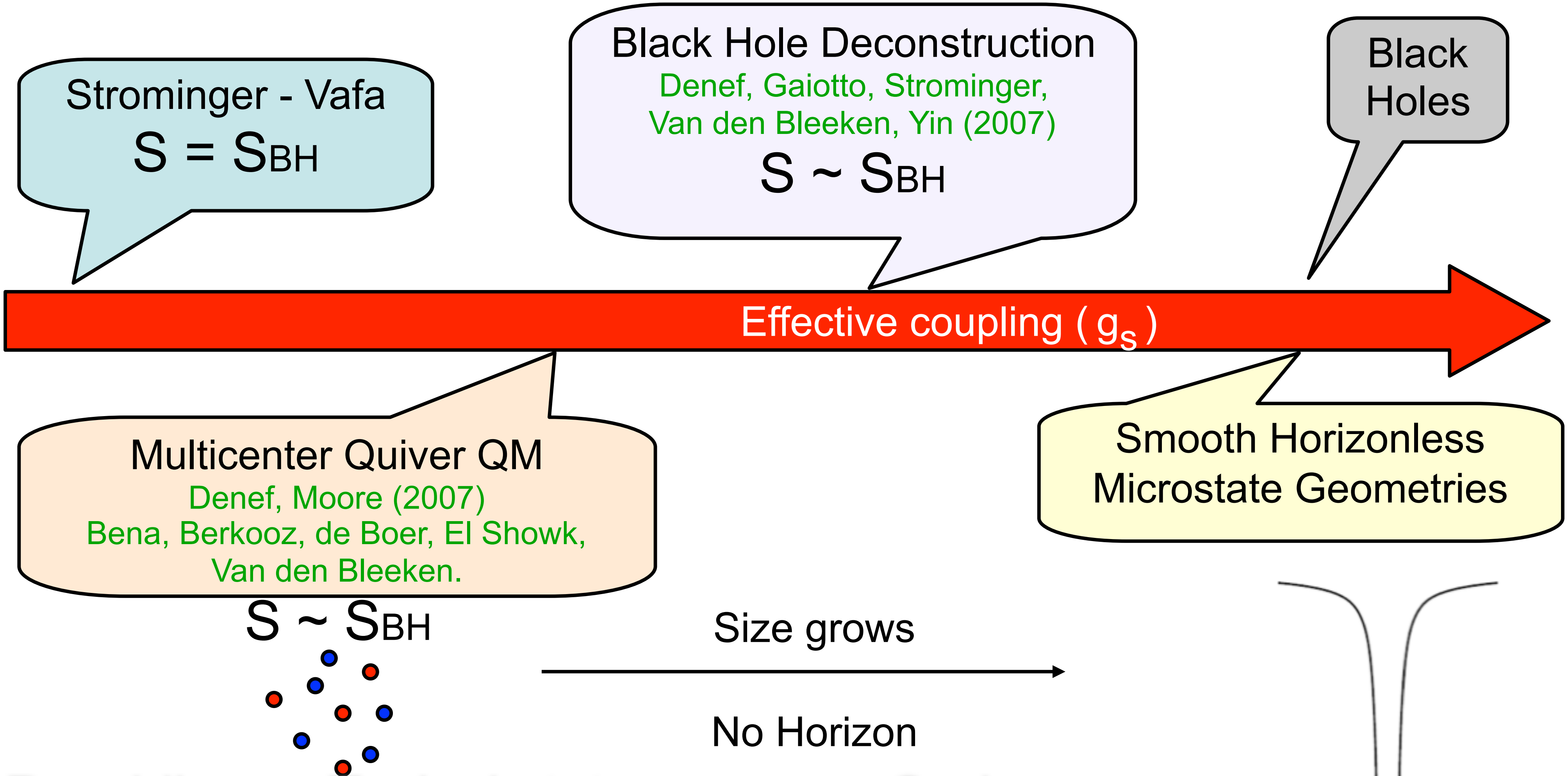
- Dual to CFT states in typical sector
  - This is where BH states live too ☺F
  - CFT_1 has no conformally-invariant ground state ! hence BH microstates have no horizon

  Bena, Wang, Warner; Bena, Heidmann, Turton

- 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



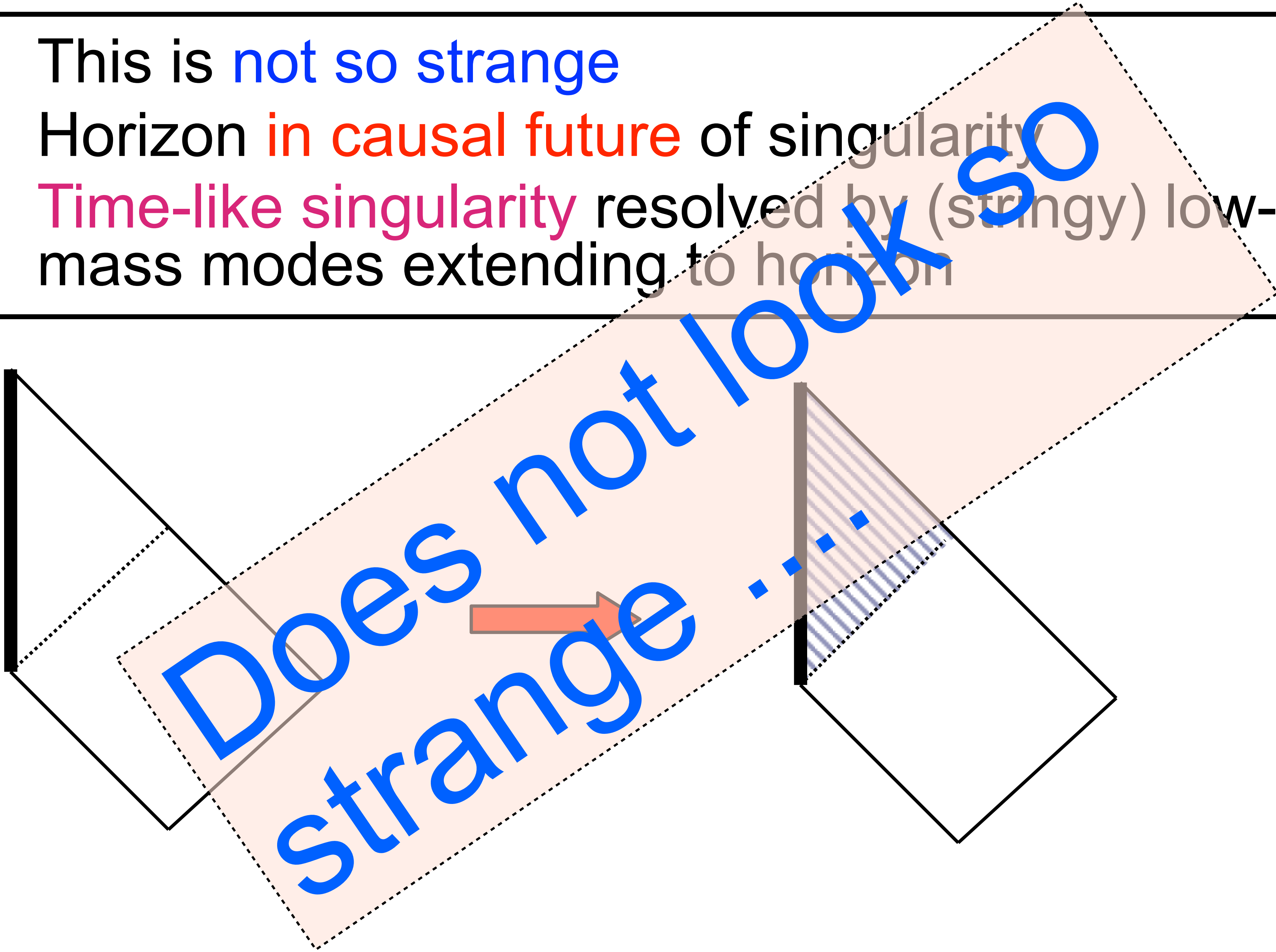
Punchline: Typical states grow as G_N increases
Horizon never forms
CFT_1 has no conformally-invariant ground state
Quantum effects from singularity extend to horizon

Similar story for non-SUSY extremal black holes

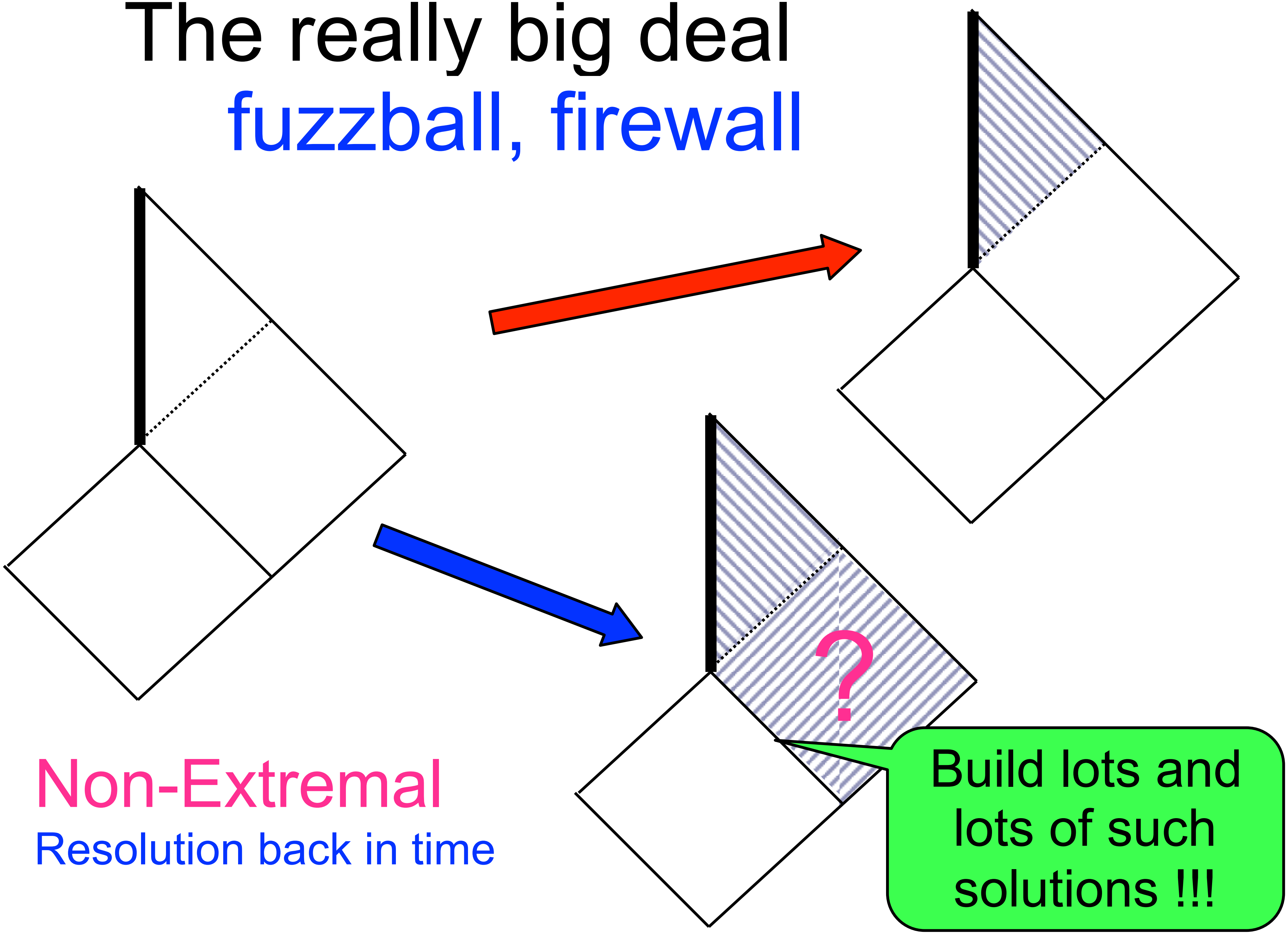
All based on almost-BPS ansatz   Goldstein, Katmadas

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 really big deal
fuzzball, firewall



Very few known. JMaRT. 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. JMaRT. 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

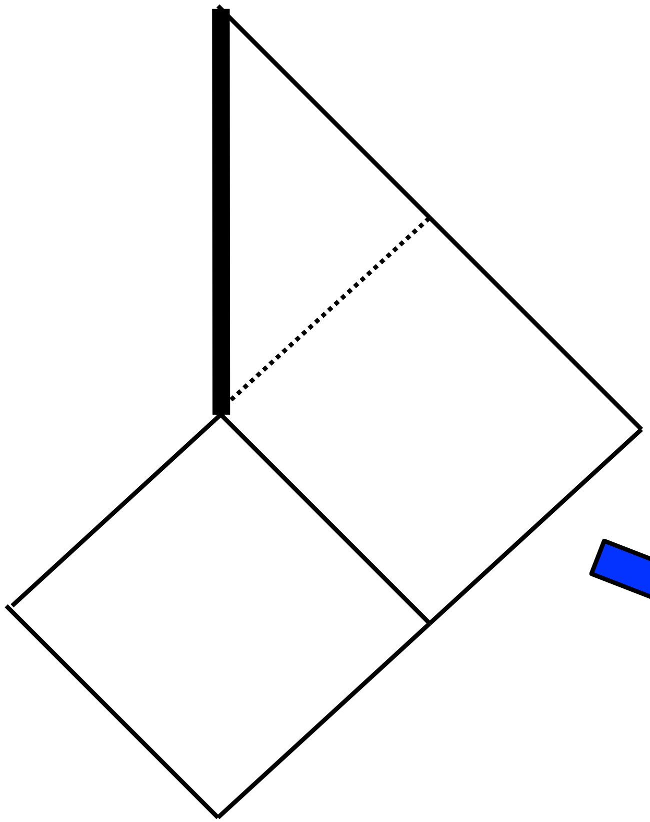
- For some solutions the 2‘nd order PDE's do factorize !!! Bossard, Katmadas
- We can build analytically certain classes of non-extremal solutions Bena, Bossard, Katmadas, Turton
- Add extra cycles to JMART
- Method can get us far from extremality.
- How far ? How generic ? Antibranes ?

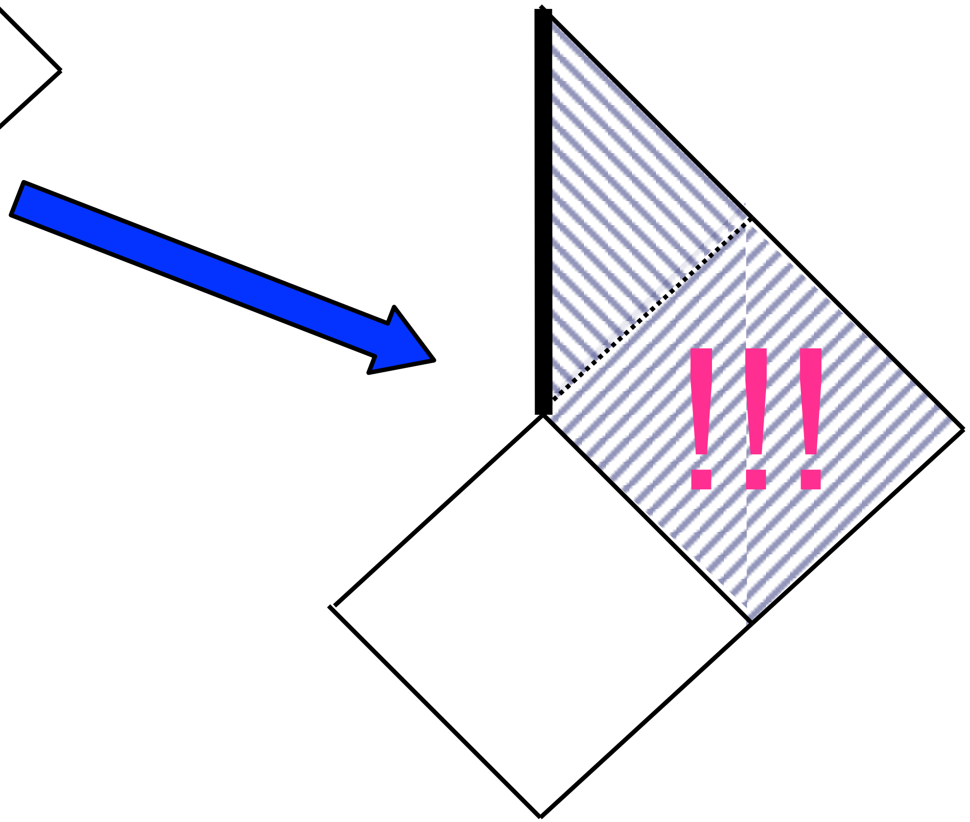
Bossard, Katmadas, Turton

The really big deal

At lest for
Near-Extremal

Resolution “backwards in time!”





Pure BH states have no horizon - 4 approaches:

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

- secondary question: firewall ? burn or sail through ?

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

- nontrivial vevs ⇒ no spherical symmetry ⇒ no horizon
- CFT_1 no conf-invariant ground state Bena Heidmann, Turton

(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

A few questions

- Would all microstates be classical ?
  - Only constructions that include gravity and one can trust.
  - Hovering mechanism extrapolates ⇒ brane polarization, non-Abelian
  - Typical states: many small bubbles (size ~ ℓ_P), or few big bubbles ?
  - 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
  - D1-D5: BPS left-movers + right movers Mathur
- What about non-linear instabilities ? Eperon, Santos, Reall
  - 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

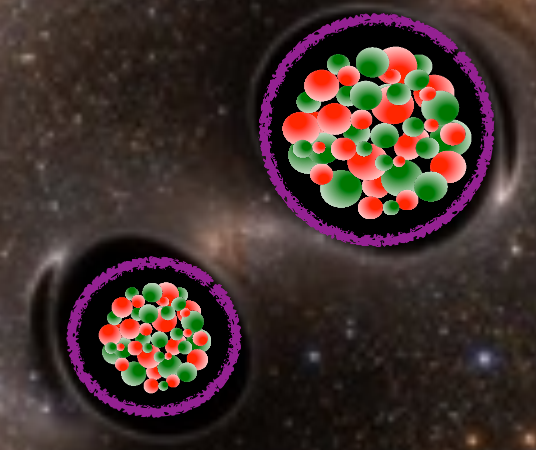
A few questions

- 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.



LIGO, eLISA:

Extra dissipation - different gavitational waves

Distortion of the Kerr multipole moments

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 !**
- Kosher AdS_2 holography. CFT_1 no conf. ground state !
- 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

Connection with T-branes

Bena, Blåbäck, Savelli, Zoccarato

$$F^{(0,2)} = 0\,,$$
$$\bar{\partial}_{\bar{A}}\Phi = 0\,,$$
$$\omega \wedge F_2 = [\Phi, \Phi^\dagger]$$

$$A_x = \frac{1}{2}(\Phi_1 + i\Phi_2)$$
$$A_y = \frac{1}{2}(\Phi_3 + i\Phi_4)$$
$$\Phi = \frac{1}{2}(\Phi_5 - i\Phi_6)$$

Constant worldvolume fields T-dualize

$$F^{(0,2)} = -i[A_x, A_y] = 0 \iff \begin{cases} [\Phi_1, \Phi_3] = [\Phi_2, \Phi_4] \\ [\Phi_1, \Phi_4] = [\Phi_3, \Phi_2] \end{cases}$$

$$\bar{\partial}_{\bar{A}_{\bar{x}}}\Phi = 0 = -i[A_{\bar{x}}, \Phi] = 0 \iff \begin{cases} [\Phi_1, \Phi_5] = [\Phi_2, \Phi_6] \\ [\Phi_1, \Phi_6] = [\Phi_5, \Phi_2] \end{cases}$$

$$\bar{\partial}_{\bar{A}_{\bar{y}}}\Phi = 0 = -i[A_{\bar{y}}, \Phi] = 0 \iff \begin{cases} [\Phi_3, \Phi_5] = [\Phi_4, \Phi_6] \\ [\Phi_3, \Phi_6] = [\Phi_5, \Phi_4] \end{cases}$$

$$\omega \wedge F_2 - [\Phi, \Phi^\dagger] = [A_x, A_{\bar{x}}] + [A_y, A_{\bar{y}}] - [\Phi, \Phi^\dagger] \iff [\Phi_1, \Phi_2] + [\Phi_3, \Phi_4] + [\Phi_5, \Phi_6]$$

Connection with T-branes

Bena, Johan Blåbäck, Savelli, Zoccarato

Solutions with infinite matrices:

$$D_i = \bigotimes_{j=1}^{6} \left((1-\delta_{ij})\mathbb{I}_M + \delta_{ij} D\right) \;, X_i = \bigotimes_{j=1}^{6} \left((1-\delta_{ij})\mathbb{I}_M + \delta_{ij} X\right) \qquad [D, X] = i\mathbb{I}_M$$

$$\Phi_1 = D_1 - \frac{1}{2}\sqrt{\alpha_1} X_1 X_3$$

$$\Phi_2 = D_2 - \frac{1}{2}\sqrt{\alpha_1} X_1 X_4 - \frac{1}{2}\sqrt{\alpha_2} X_1 X_2$$

$$\Phi_3 = D_3 - \frac{1}{2}\sqrt{\alpha_3} X_3 X_5$$

$$\Phi_4 = D_4 - \frac{1}{2}\sqrt{\alpha_3} X_3 X_6 + \frac{1}{2}\sqrt{\alpha_2} X_3 X_4$$

$$\Phi_5 = D_5 + \frac{1}{2}\sqrt{\alpha_2} X_1 X_5$$

$$\Phi_6 = D_6 + \frac{1}{2}\sqrt{\alpha_2} X_2 X_5 + \frac{1}{2}\sqrt{\alpha_3} X_5 X_6$$

D0	–	–	–	–	–	–
D4	×	×	×	×	–	–
D4	×	×	–	–	×	×
D4	–	–	×	×	×	×

D0 description of 4D susy BH

AdS_2

New microscopic counting !