Black Holes

where Quantum Mechanics and General Relativity clash

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with

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erc

John Templeton Foundation

Agence Nationale de la Recherche ANR

DE LA RECHERCHE À L'INDUSTRIE cea SACLAY

Why Black Holes

- They exist in nature
  - Binary Systems

    M ~ 1- 30 $M_\odot$
  - Centers of galaxies

    M ~ 1 000 000 000 $M_\odot$

- They emit gravitational waves

Quantum Mechanics ⟷ General Relativity

Great Conflict

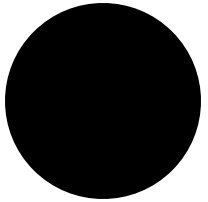
General relativity

- BH produced by gravitational collapse
- They have central singularity and a horizon
- Everything, including light that crosses the horizon cannot come out
- Black holes have no memory of the the objects that formed them

General Relativity

Information thrown into black hole is lost !!!

The only characteristics of black hole are:
- the mass
- the angular momentum
- the charge



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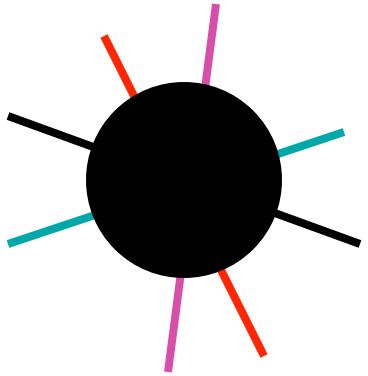

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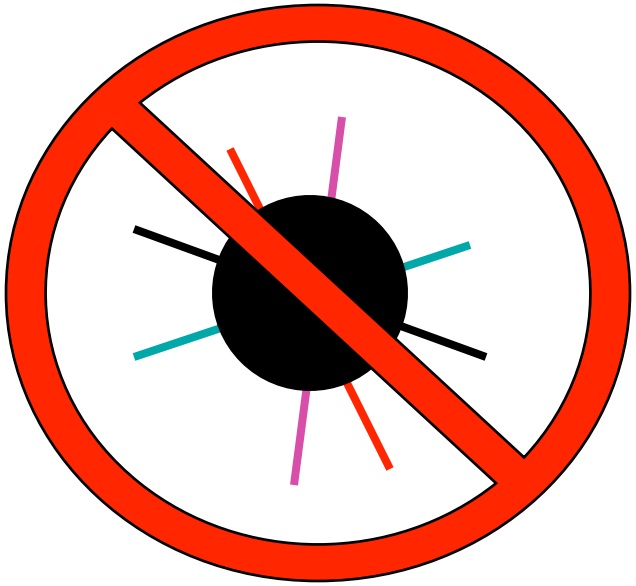
J.A. Wheeler:
Black holes have no hair
(găurile negre nu au păr ?)



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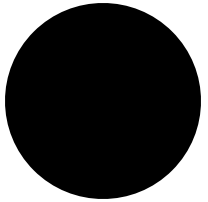
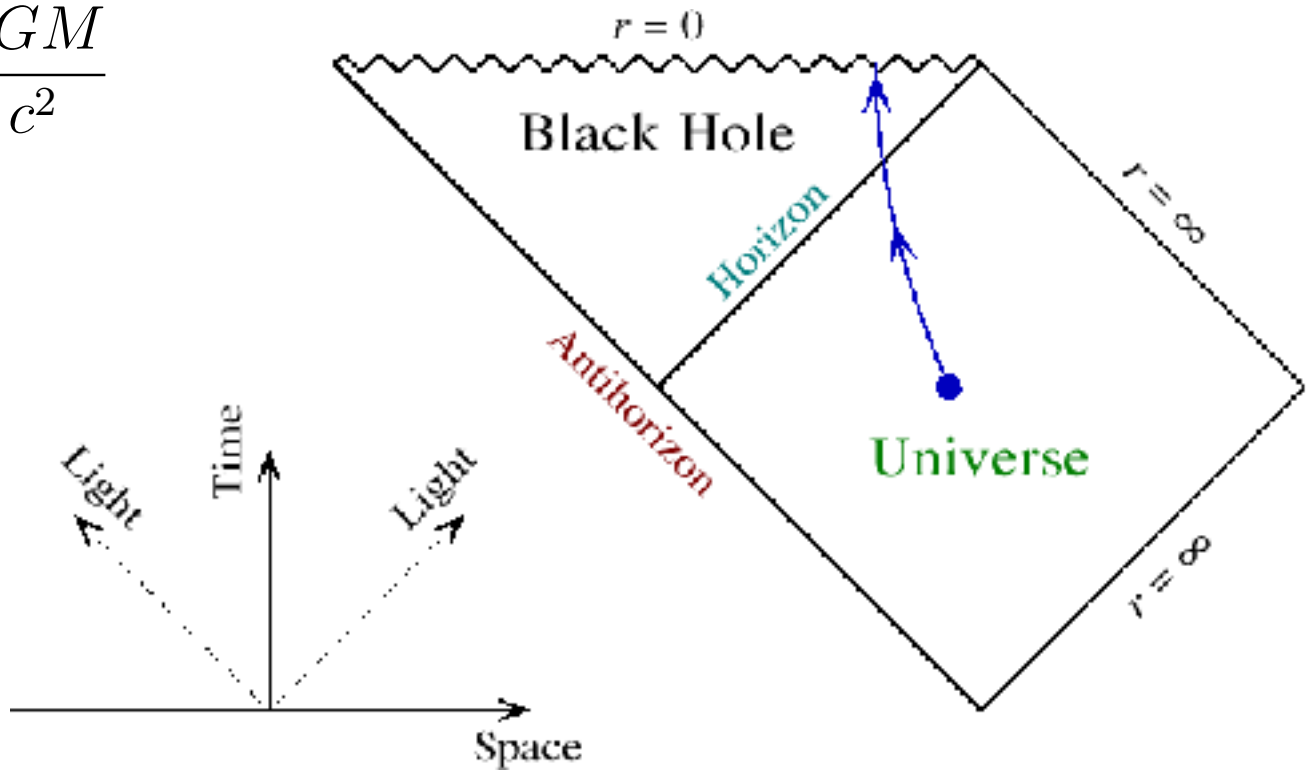


Impossible to distinguish between black holes formed by the collapse of
matter
antimattier
elephants
birocrați din birouri

The Schwarzschild Black Hole

$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \frac{dr^2}{1 - \frac{r_s}{r}} + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2$$

$$r_s = \frac{2GM}{c^2}$$



Quantum Mechanics:

Physics determined by wave function: Ψ

$$\Psi(t) = e^{-i\hat{H}t}\,\Psi(0)$$

$\hat{H}$ = **Hermitian** $\Rightarrow$

Evolution of Ψ is unitary:

Information is never lost !

Quantum Mechanics:

Bekenstein, Hawking:

We can associate to black hole an entropy and a temperature:

$$S_{BH} = \frac{A}{4l_P^2} \qquad l_P = \sqrt{G\hbar/c^3} = 1.6 \times 10^{-35}\ m$$

$$T_{BH} = 6.17 \times 10^{-8} \left(\frac{M_{sun}}{M_{BH}}\right) K$$

$S \sim 10^{77}$ $M_\odot$ black hole

$S \sim 10^{90}$ Center of Milky Way black hole

Black holes are thermodynamic objects !!!

1) $dE = T\,dS + \Omega\,dJ + V\,dQ$
2) $\Delta S > 0$

The root of the information **paradox**

Schwarzschild black hole with $S \sim 10^{90}$

Quantum Mechanics: → $e^{10^{90}} = e^{10000000\ \ldots\ 00000}$ states

General Relativity →

→ 1 big fat state

Biggest unexplained number of physics

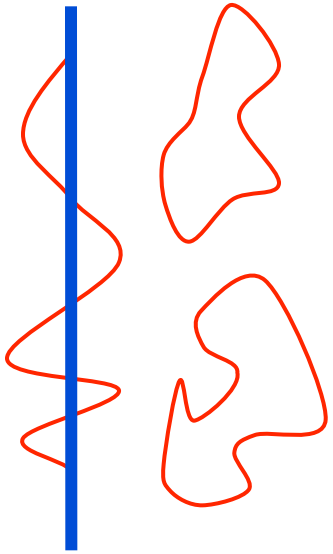
Black Holes

Quantum Mechanics: ⟷ General Relativity

QUESTIONS: Where is them black hole states ?
How do they look ?

Quantum Gravity / String Theory

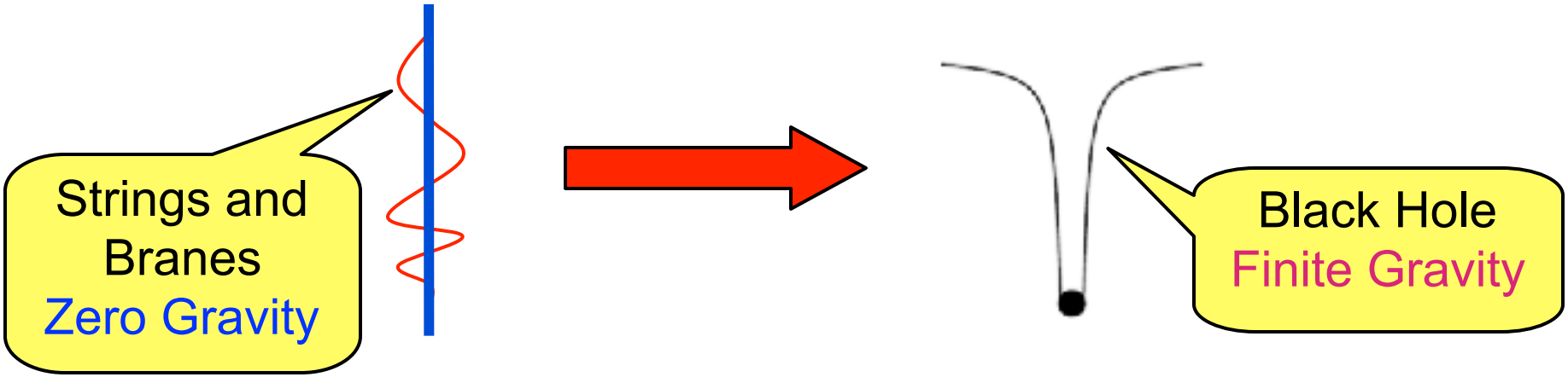
- 10 dimensions
- Strings, membranes (D-branes)
- Build *lots and lots* of black holes putting together D-branes



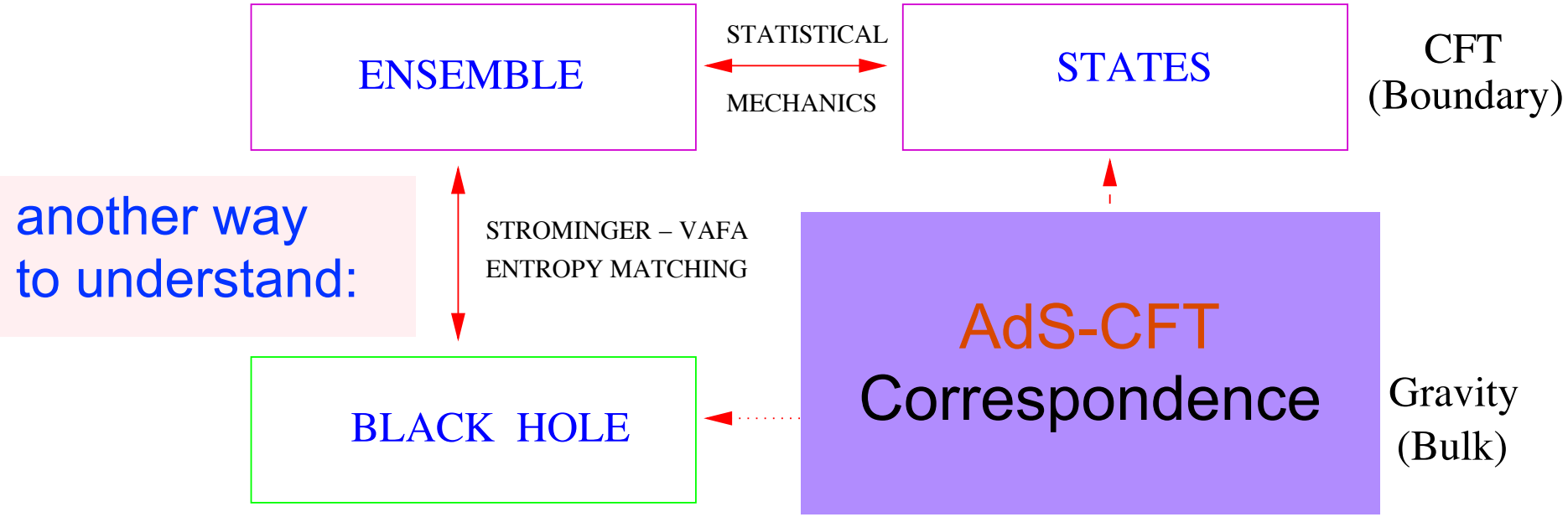
WHERE ARE THE STATES ?
HOW DO THEY LOOK ?

- Simpler question:
  - Count black hole states in any other way ?

Strominger and Vafa (1996)
+ 2000 other articles



- Count quantum states at zero gravity
- Entropy matches black hole classical horizon area !!!
- *2 absolutely different calculations*
  (Cardy Formula vs. classical area)
- Amazing success
  - Modular forms, hypergeometric, other beasts
  - Unmatched in other theories of gravity

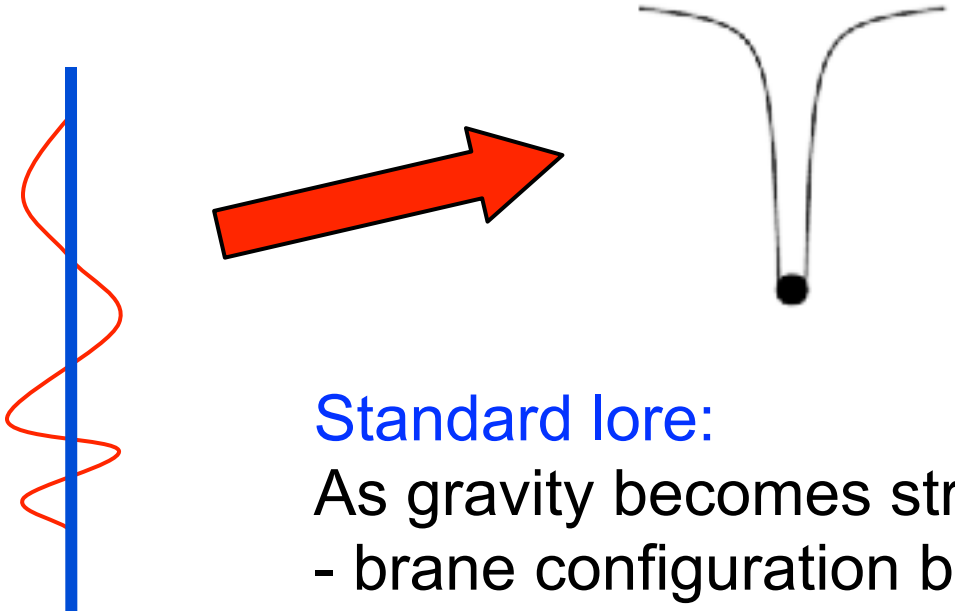


Strominger and Vafa (1996):

*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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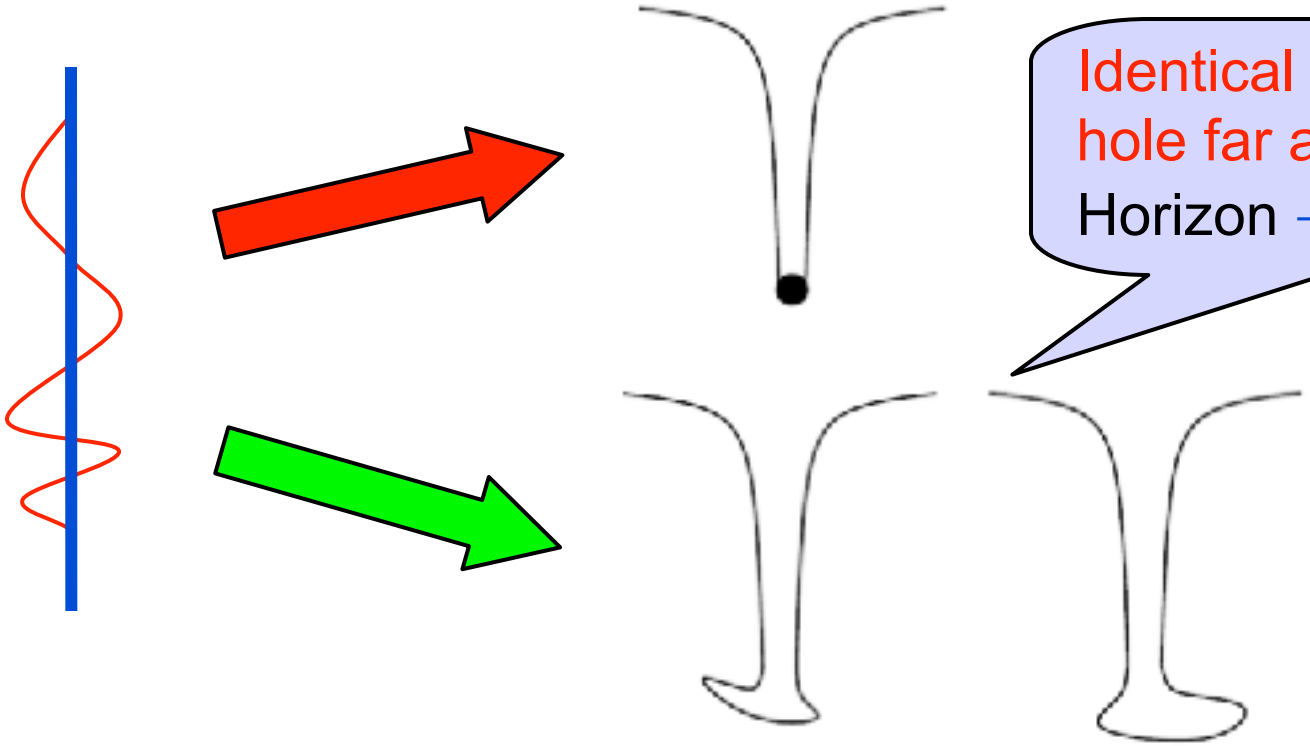


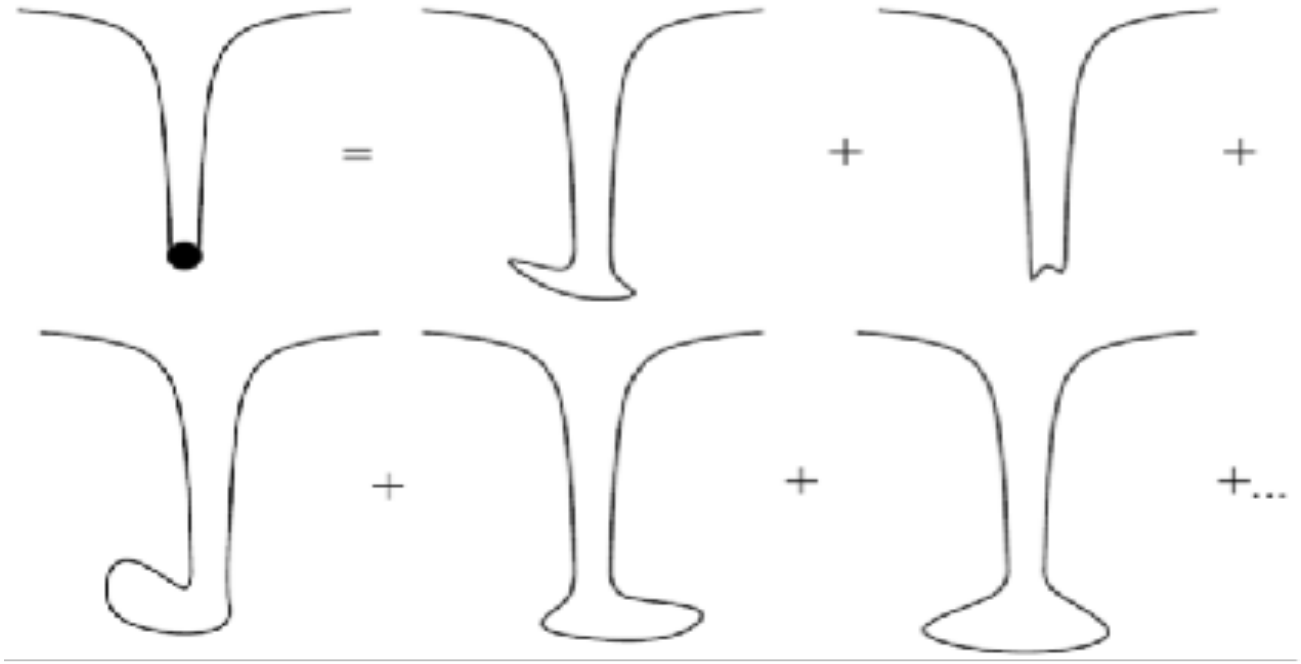
our work over the
past 12 years

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

?

Black hole = ensemble of horizonless microstates

Fuzzball Proposal
(Mathur & friends)

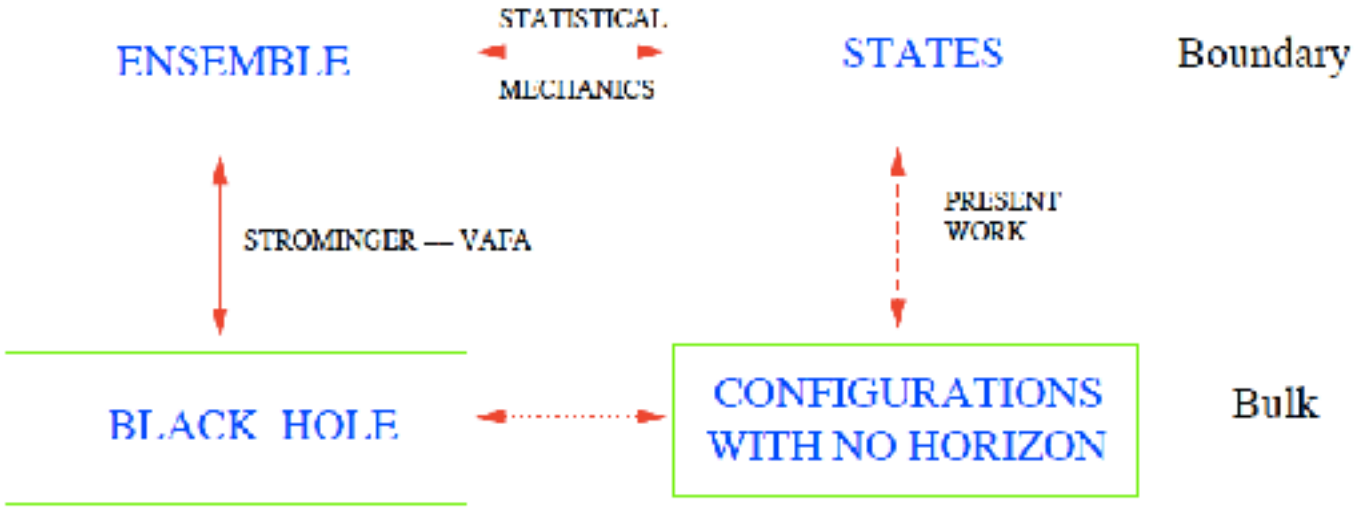


Other formulations:

e.g. Bena, Warner, 2007

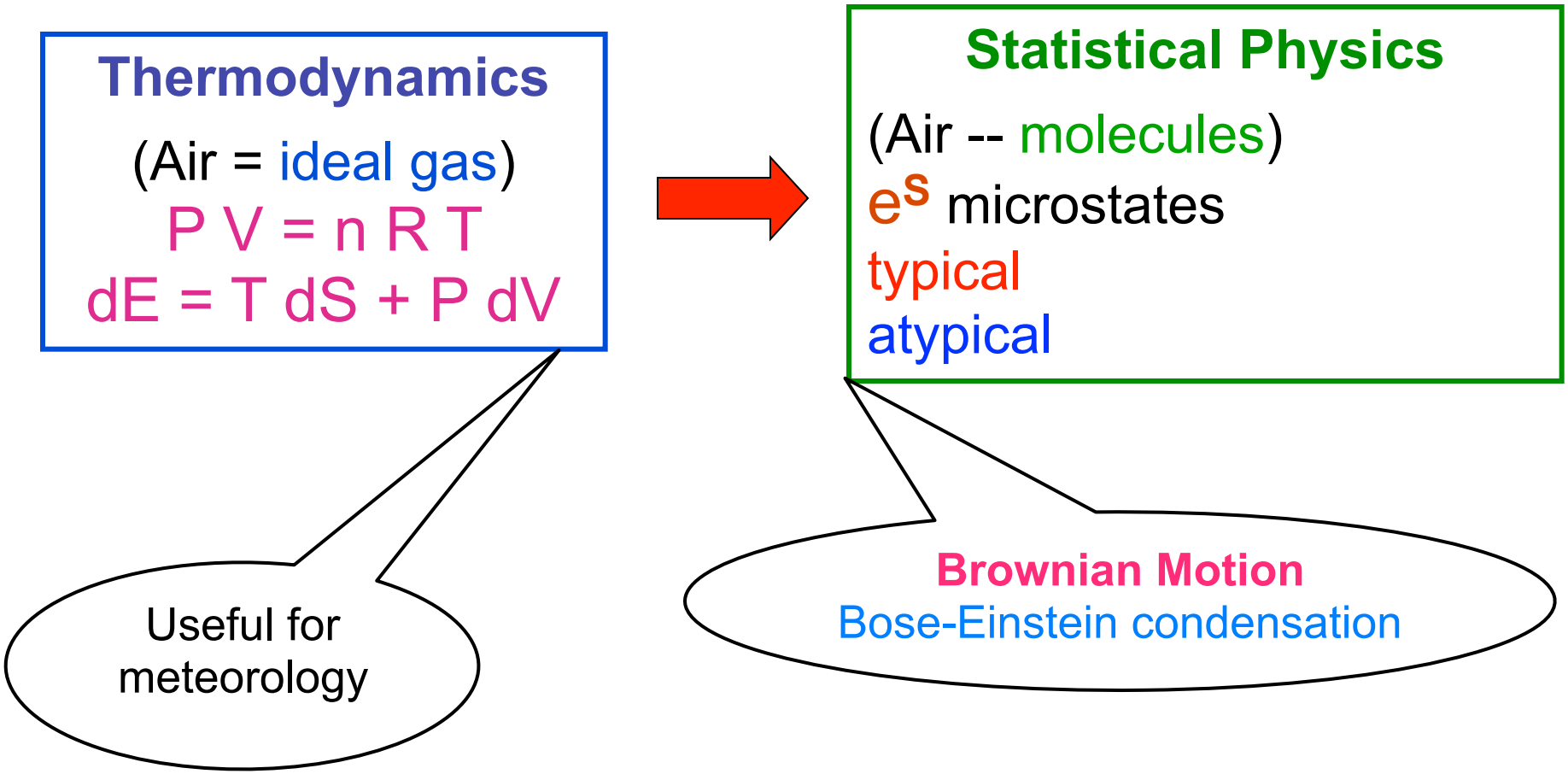
- Thermodynamics (EFT) breaks down at horizon. New low-mass d.o.f. kick in.

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



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

Analogy with ideal gas



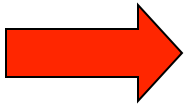
Analogy with ideal gas

Thermodynamics

(Air = ideal gas)

$P V = n R T$

$dE = T dS + P dV$



Statistical Physics

(Air -- molecules)

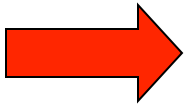
e^S microstates

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
  - Infinite density firewall hovering above horizon
  - Gas of wormholes
  - Bose-Einstein condensate of gravitons
  - LQG configuration
  - Quark-star, boson-star …

satisfy 3 very stringent tests:

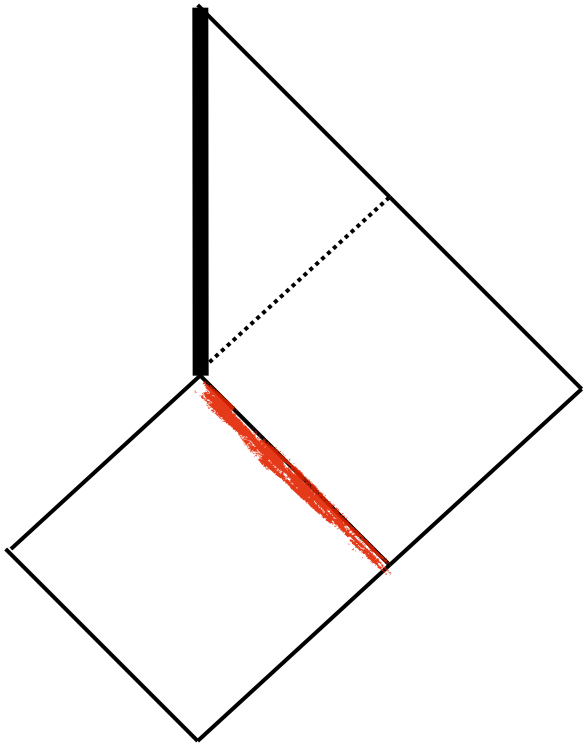
1. Same growth with $G_N = g_s^2$!!! Horowitz

- 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

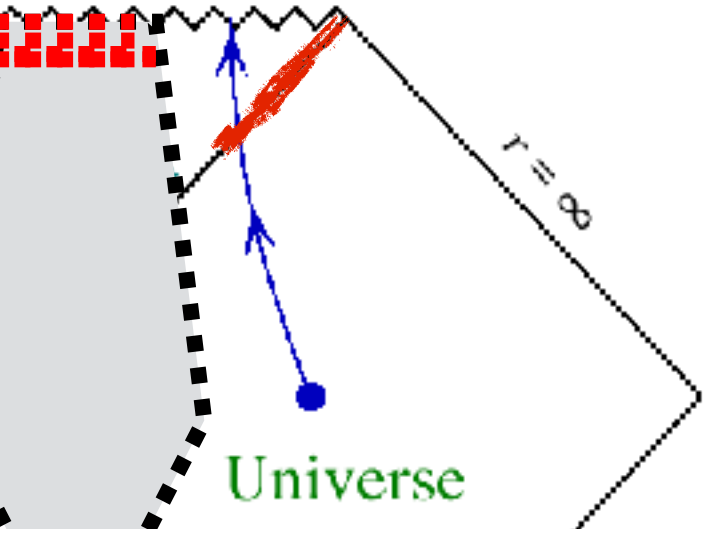
- Nothing can live there !
  (or carry degrees of freedom)
- No membrane, no spins
- No (fire)wall

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 !

Microstates geometries

- Where is the BH charge ?

$L = q\, A_0$ magnetic

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

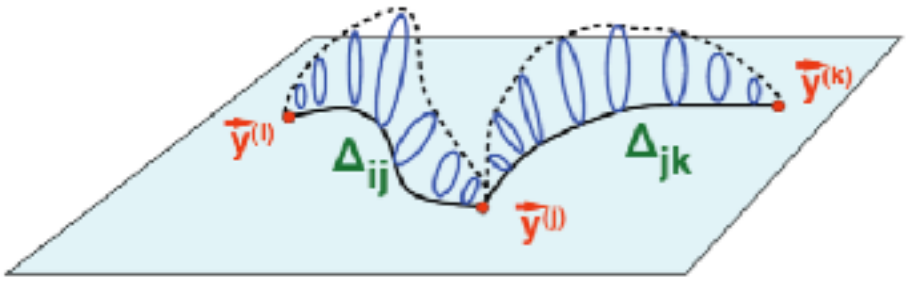
- Where is the BH mass ?

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

- 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

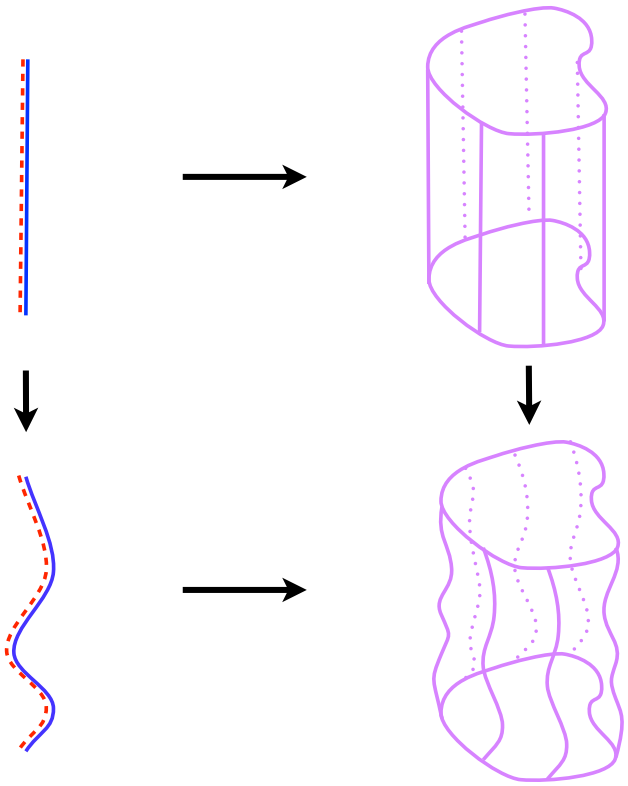
More general bubbling solutions

- 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 !!!

Largest family of solutions known to mankind

Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

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

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

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

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

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

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

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

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

$$\frac{Z_4}{\mathcal{P}}\mathcal{C}\wedge(du+\omega)\wedge(dv+\beta) ,$$

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

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

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

$$|\,(m_1 \quad 1)(m_1 \quad 2)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2 \quad 2)\Delta_{k_2+m_1-1,m_1+1}$$

$$- m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1^2(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big] ,$$

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

$$+ (m_1^2-2m_1+k_2-1)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}$$

$$+ m_1(k_2-m_1-1)\Delta_{k_2\,|\,m_1\;\;1,m_1\;\;1} + (k_2(m_1^2+m_1-1) - m_1(m_1+1))\Delta_{k}$$

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

$$- 2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1}$$

$$(m_1 \quad 1)(k_2 \quad 3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1 \quad 1)\Delta_{k_2+m_1+1,m_1-1}$$

$$(m_1 \quad 1)(m_1(k_2 \quad 1) + 1)\Delta_{k_2+m_1+1,m_1+1}\Big] .$$

String theory input crucial

Giusto, Russo, Turton

Habemus Superstratum !!!

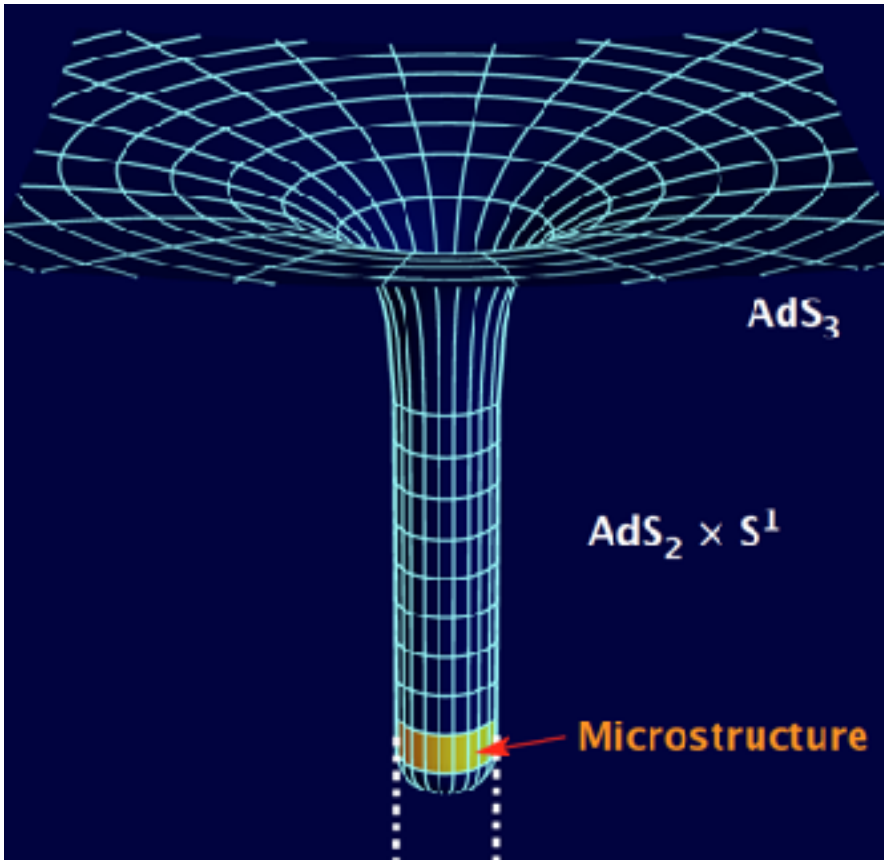
Deep superstrata

Entropy:

- D1-D5 supertube - dimension of moduli space
  - classically: dimension = ∞
  - quantize: $4N_1N_5$ = number of superstratum momentum carriers
- Counting (+ fermions) (à la MSW)

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

  Bena, Shigemori, Warner



- Build deep superstrata: black-hole-like throats

  Bena, Giusto, Martinec Russo, Shigemori, Turton, Warner (PRL editor's selection)
- First BTZ microstates

MSW Superstrata

Bena, Martinec, Turton, Warner

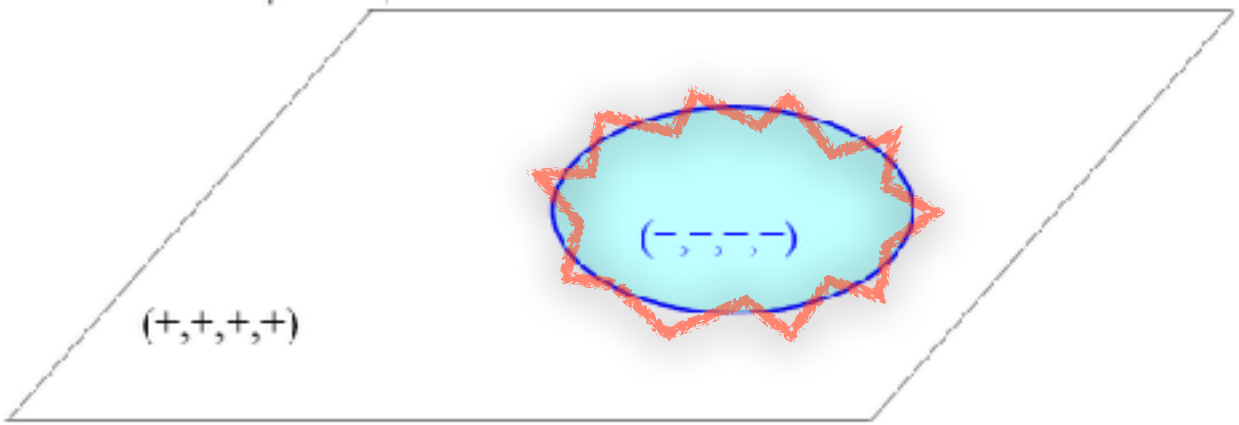
- D1-D5 solution: $AdS_3 \times S^3 \times T^4$
  - T-dualize on the Hopf fiber of S^3+ few more times
  - $AdS_3 \times S^2 \times T^6$: NS vacuum of the MSW CFT
- Central charges match
- subsector of MSW CFT $\Leftrightarrow$ subsector of D1-D5 CFT !!!
- One arbitrary function worth of smooth solutions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

MSW CFT

- D1-D5 superstratum built on $AdS_3 \times S^3 \times T^4$
  - 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

SUSY microstates – the story:

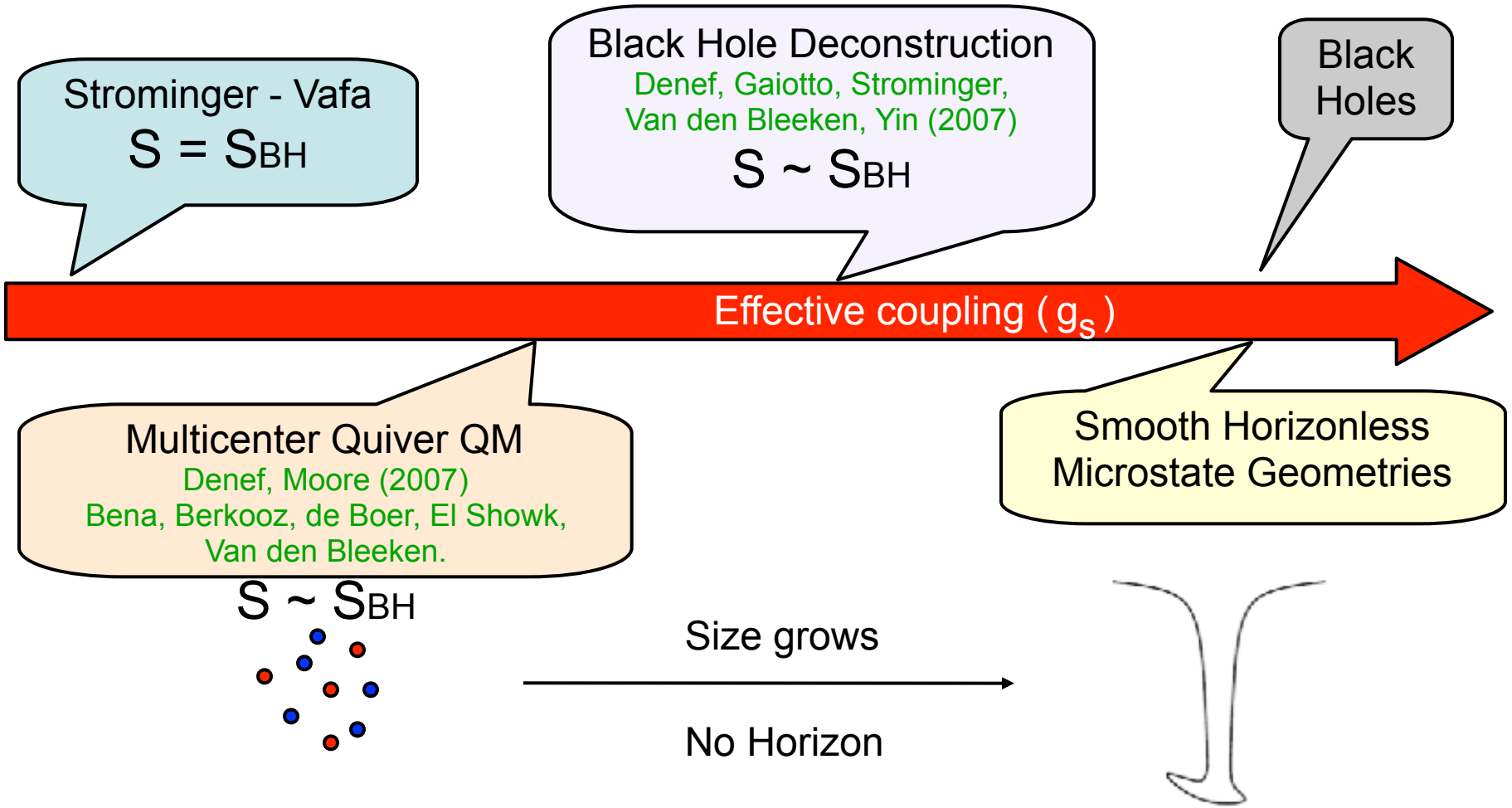
- We have a huge number of them
  - Arbitrary continuous functions of 2 variables
  - Superstrata reproduce black hole entropy ☺

    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

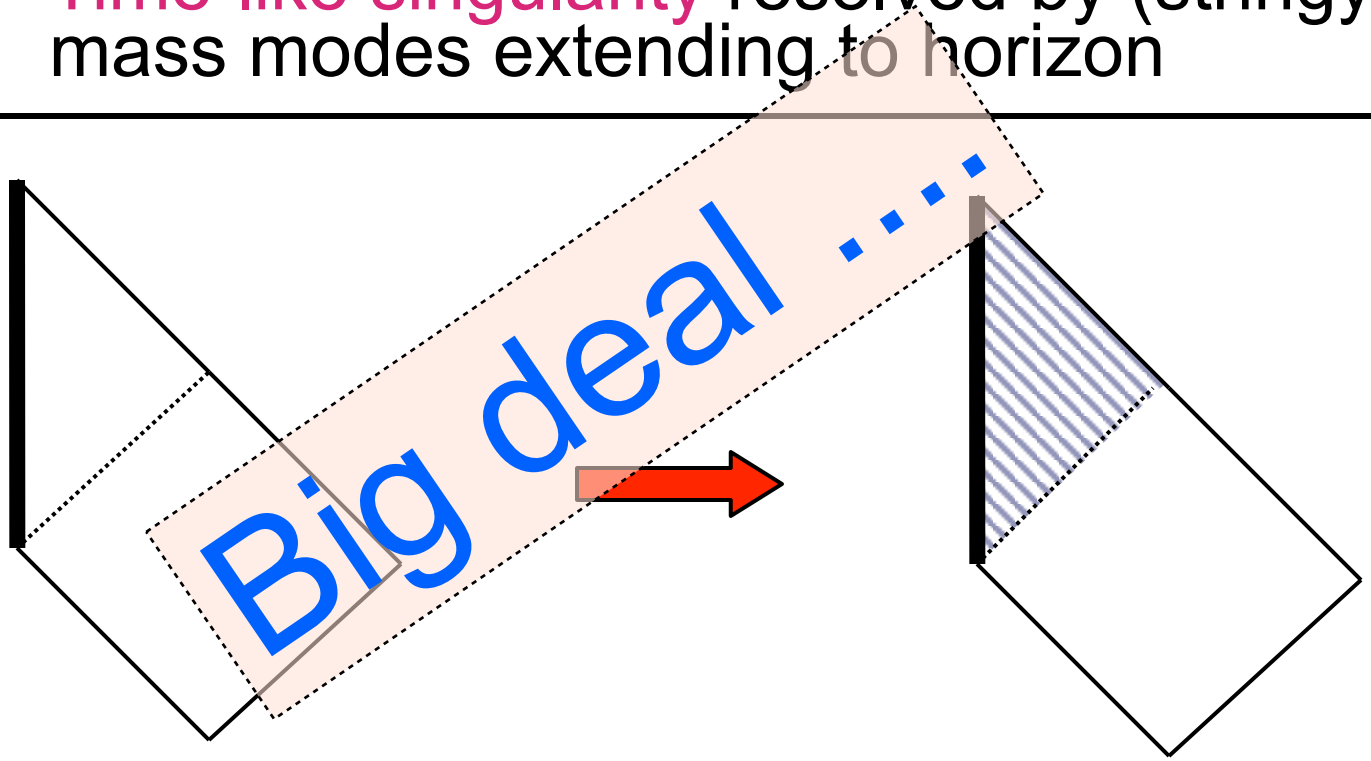


Punchline: Typical states grow as G_N increases.
Horizon never forms
Pure black hole states have no horizon

Similar story for non-SUSY extremal black holes

BPS Black Hole = Extremal

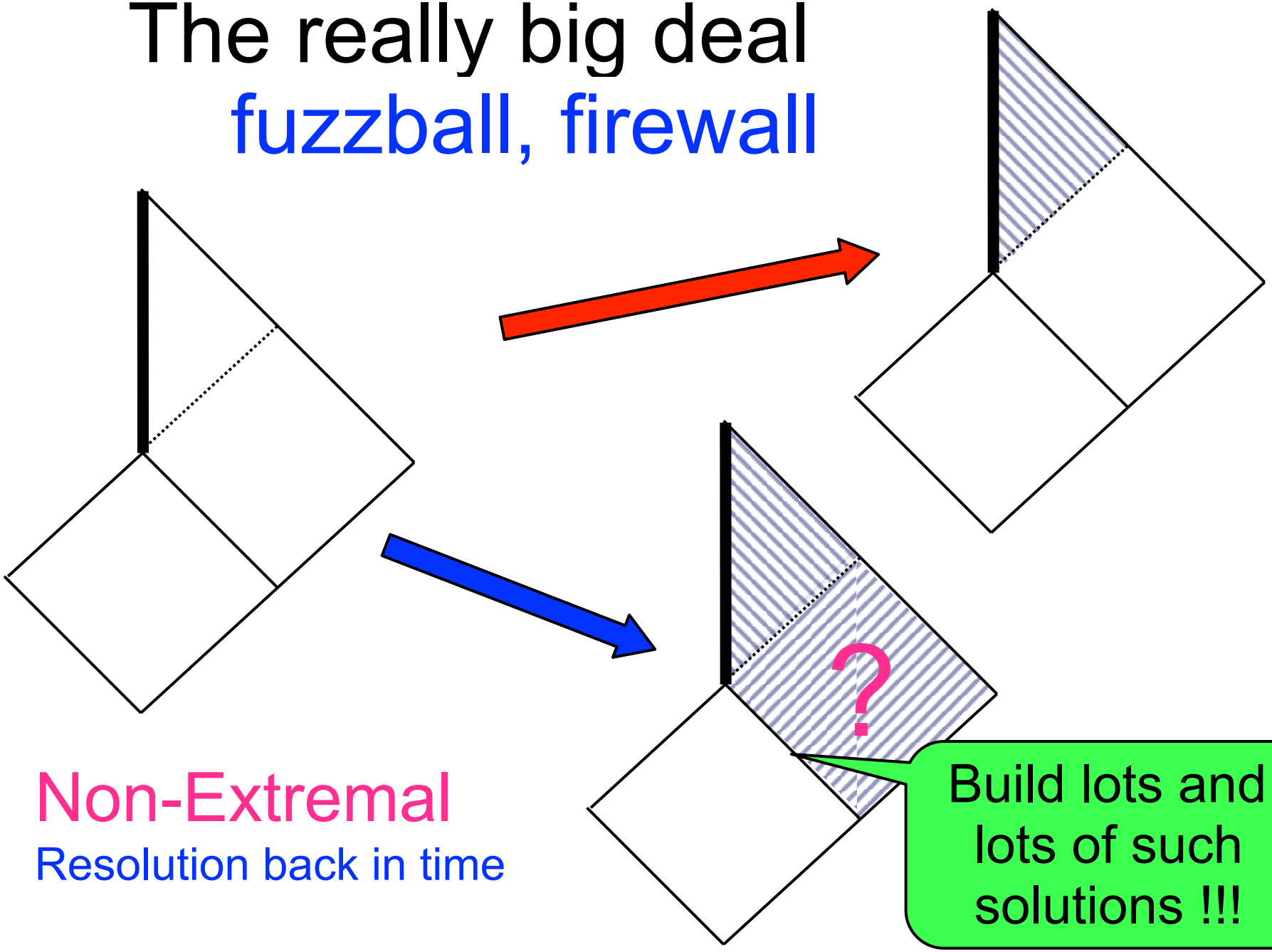
- This is not so strange
- Horizon in causal future of singularity
- Time-like singularity resolved by (stringy) low-mass modes extending to horizon



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

Să nu te rogi la sfântul care nu te ajută

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

proverb vechi Românesc

- 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

La pasărea oarbă îi face Dumnezeu cuib

God makes the nest of the blind bird!

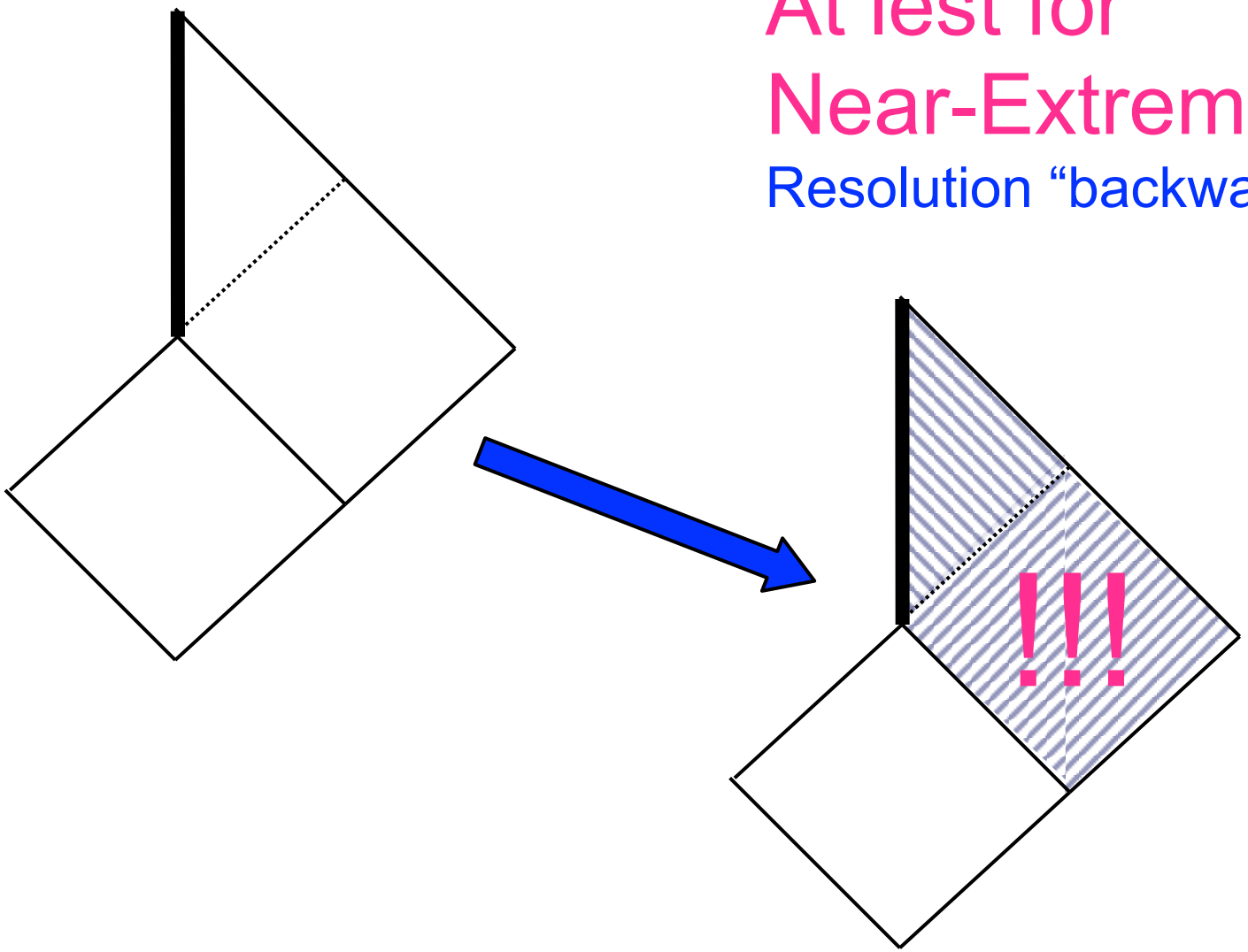
încă un proverb vechi Românesc

- 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 ?

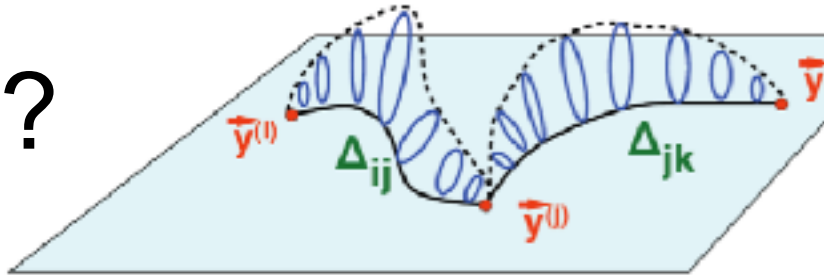
The really big deal

At lest for
Near-Extremal

Resolution “backwards in time!”

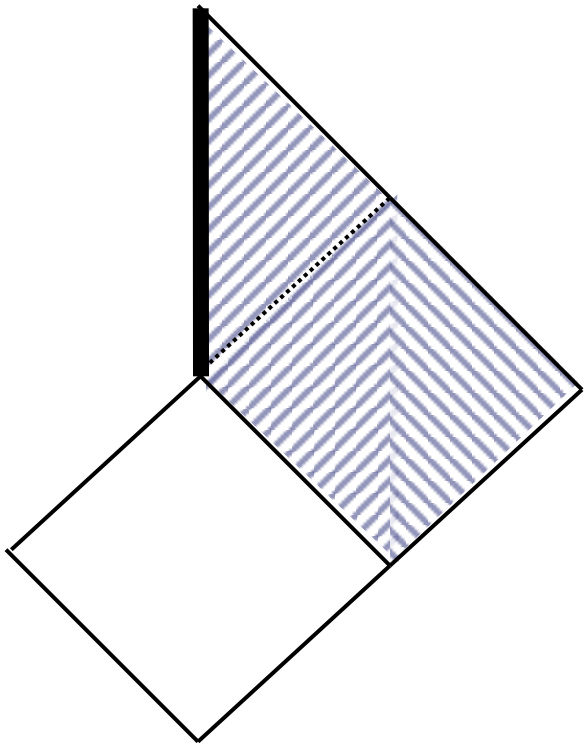


Why not collapsing ?



- 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); nowhere else
  - **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 sail 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 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
  - Typical states: many small bubbles or just a few ?
  - 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
- Can you fall through horizon drinking your coffee ? (as GR textbooks say) … Or do you go splat ?

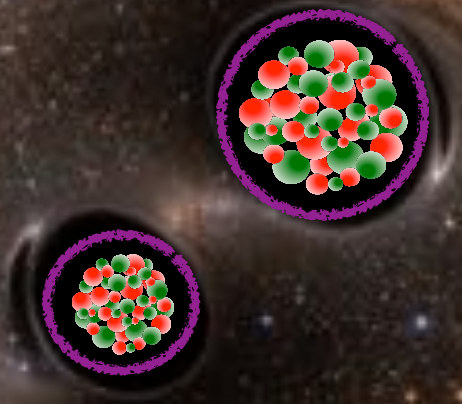
3 options

- 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 dissipation - different gavitational waves

Distortion of the Kerr multipole moments

Summary and Future Directions

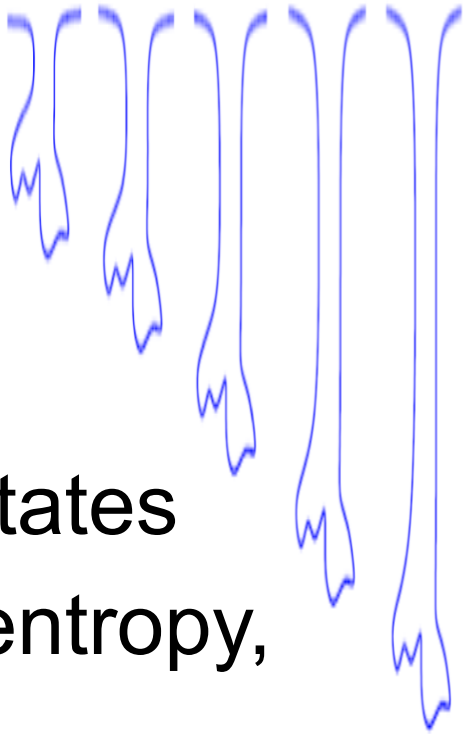
- String theory configurations that hover above horizon.
  Topology + fluxes ⇔ brane polarization ⇔ nonabelian d.o.f.
- BPS black hole microstates = horizonless solitons
  - low-mass modes affect large (horizon) scales
  - Convergence of many research directions
  - BPS superstrata - 2 variables - **Black Hole Entropy !**
- 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

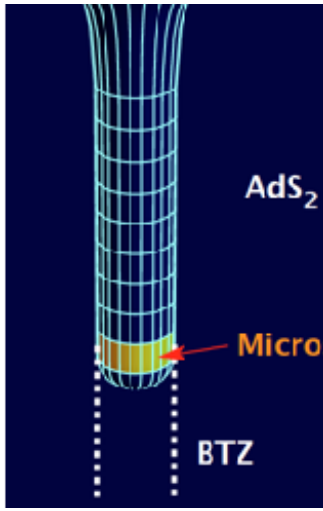
Quantum Gravity in AdS_2

- Everybody & their brother & SYK
  Sachdev, Ye, Kitaev
- AdS_2 - no finite-energy excitations
  Maldacena, Strominger
- backreaction of particle in AdS_2 either
  - destroys UV
  - singularity in IR
    (? ↔ 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





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 x N_2 x 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.