

Physics at the horizon

Mind the Gap !

Iosif Bena
IPhT



FQXi

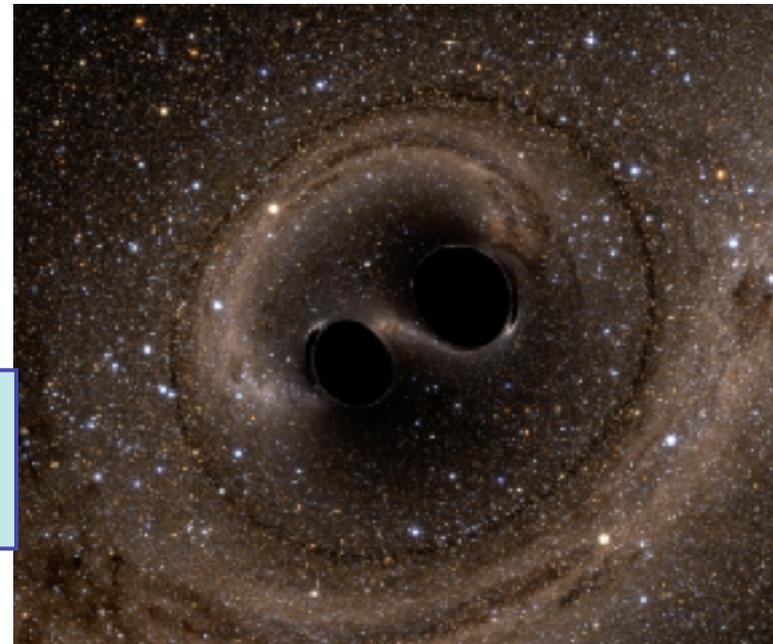
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ANR

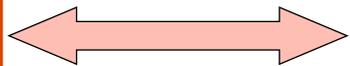
DE LA RECHERCHE À L'INDUSTRIE
cea
SACLAY

Why Black Holes

- They exist in nature
 - Binary Systems
 $M \sim 1 - 30 M_{\odot}$
 - Centers of galaxies
 $M \sim 1\,000\,000\,000 M_{\odot}$
- They emit gravitational waves



Quantum
Mechanics



General
Relativity

Great Conflict

General relativity

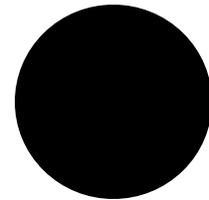
- BH produced by gravitational collapse
- They have **central singularity** and a **horizon**
- Everything, **including light** that crosses the horizon cannot come out
- Black holes have **no memory** of the the objects that formed them

General Relativity

Information thrown into black hole is lost !!!

The **only characteristics** of black hole are:

- the mass
- the angular momentum
- the charge

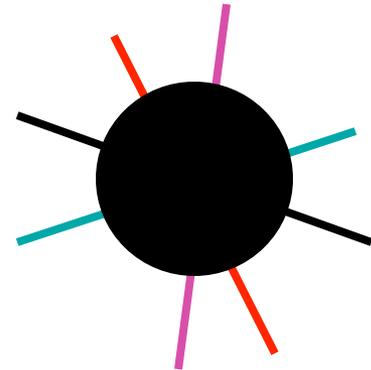


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General Relativity

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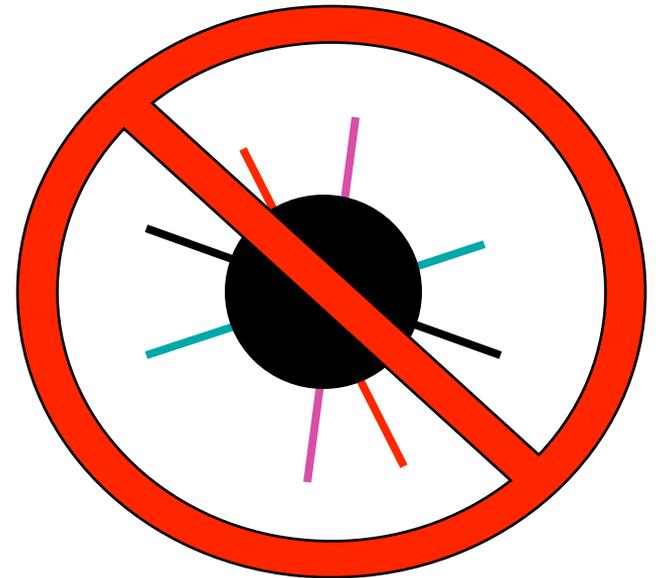
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J.A. Wheeler:

Black holes have no hair

(Les trous noirs n'ont pas de)



General Relativity

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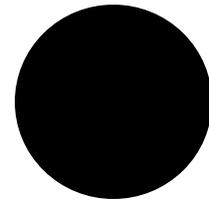
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Impossible to distinguish between black holes formed by the collapse of

matter

antimatter

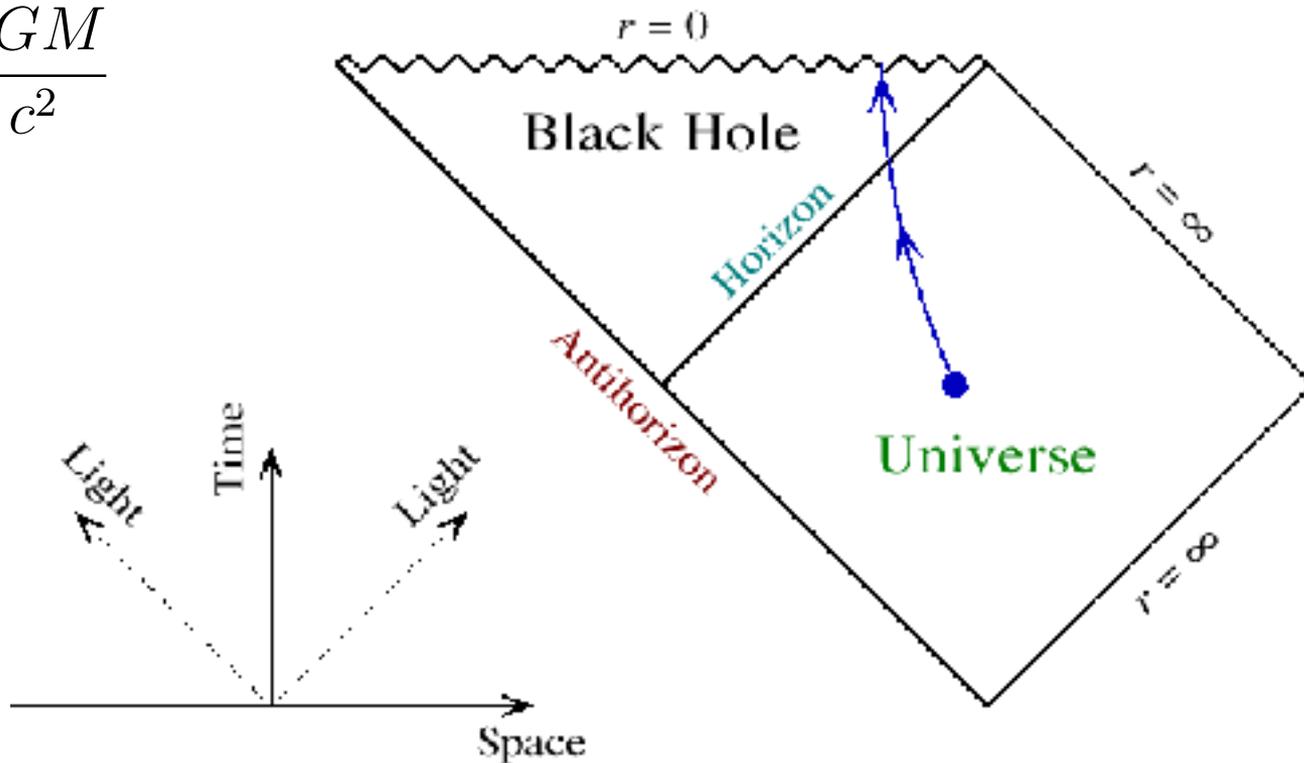
elephants

service du personnel bureaucrates

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

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

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

Evolution of Ψ is unitary:

Information is never lost !

Quantum Mechanics:

Bekenstein, Hawking:

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

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

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

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

$S \sim 10^{90}$ Center of Milky Way black hole (Sagittarius A*)

Black holes are thermodynamic objects !!!

1) $dE = T dS + \Omega dJ + V dQ$

2) $\Delta S > 0$

The root of the information paradox

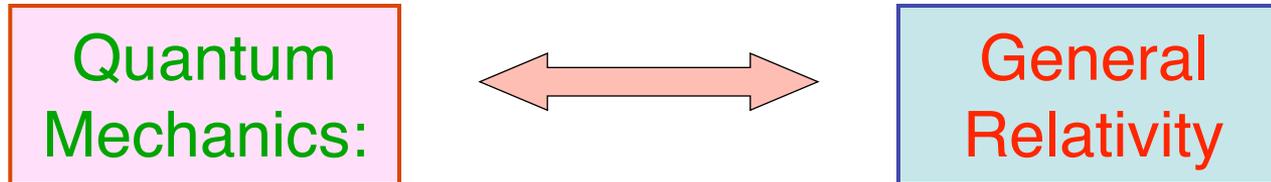
Schwarzschild black hole with $S \sim 10^{90}$

Quantum Mechanics: $\Rightarrow e^{10^{90}} = e^{100000000 \dots 00000}$ states

General Relativity ~~HAIR~~ \Rightarrow 1 big fat state

Biggest unexplained number of physics

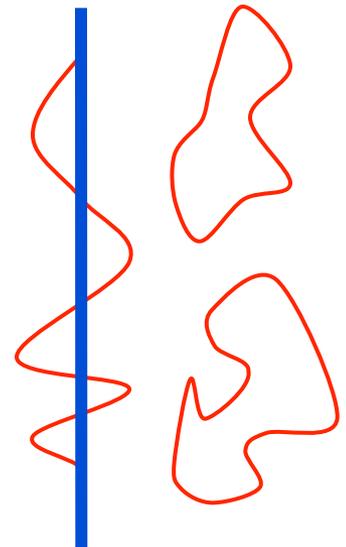
Black Holes



QUESTIONS: Where is their 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**

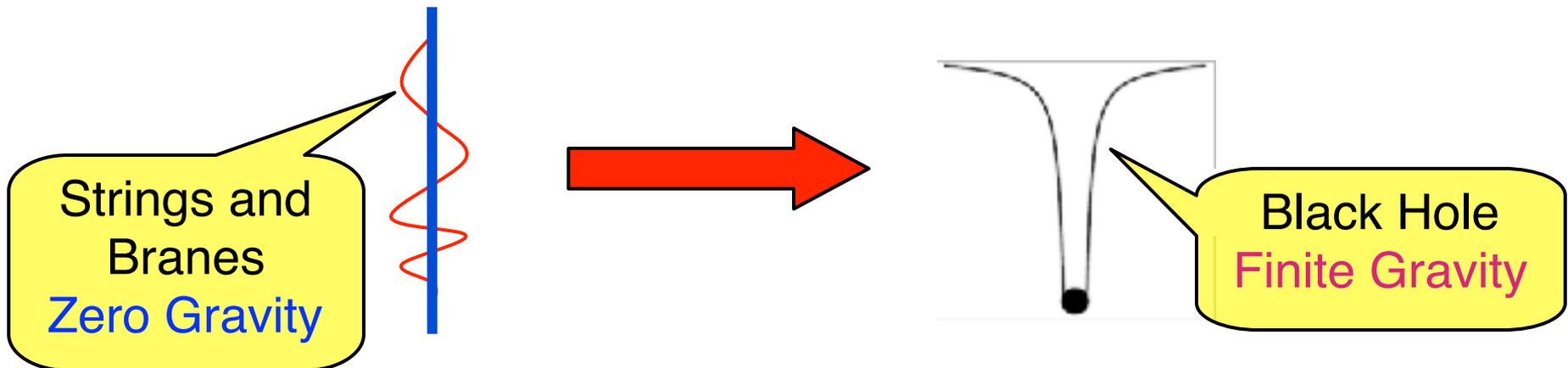


WHERE ARE THE STATES ? HOW DO THEY LOOK ?

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

Strominger and Vafa (1996)

+ 2500 other articles



Simplest Black Hole:

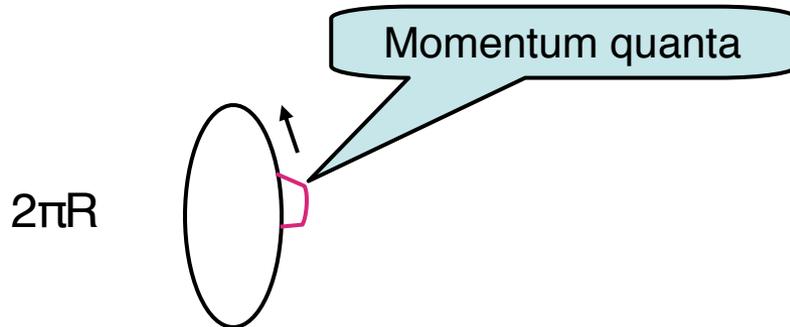
Strominger, Vafa

D1 branes (strings), D5 branes, momentum P

one D1 brane, $2\pi R$



Momentum quanta
 $\delta P = 1/R$



Simplest Black Hole:

Strominger, Vafa

D1 branes (strings), D5 branes, momentum P

one D1 brane, $2\pi R$

N_1 D1 branes, $2\pi R$

one D1 brane, $2\pi N_1 R$

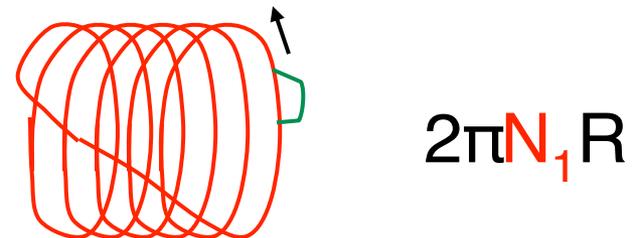
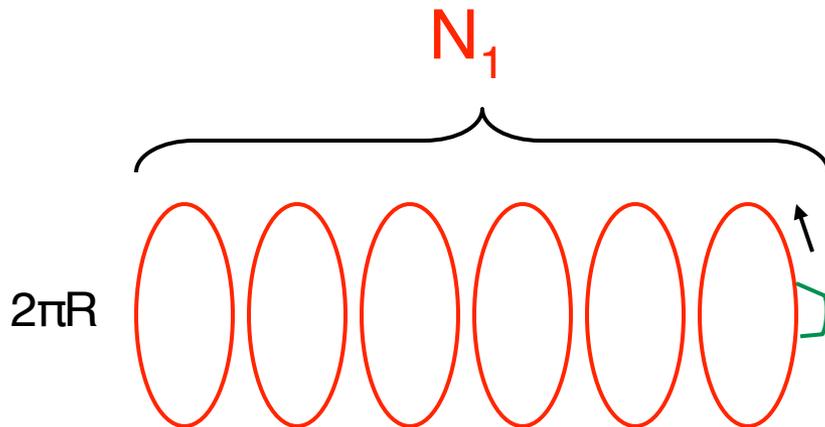


$$\delta P = 1/R$$



$$\delta P = 1/N_1 R$$

Momentum quanta



Simplest Black Hole:

Strominger, Vafa

D1 branes (strings), D5 branes, momentum P

one D1 brane, $2\pi R$

N_1 D1 branes, $2\pi R$

1 D1 brane, $2\pi N_1 R$

N_1 D1 + N_5 D5 branes

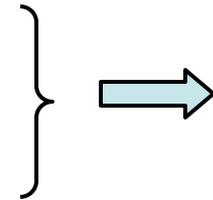
effective string, $2\pi N_1 N_5 R$



$$\delta P = 1/R$$

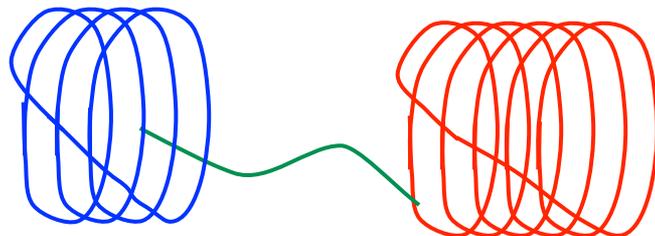


$$\delta P = 1/N_1 R$$



$$\delta P = 1/N_1 N_5 R$$

Momentum quanta



Microstate Counting

Strominger, Vafa

- Total momentum N_P / R carried by quanta of

$$1 / N_1 N_5 R$$

- Total = $N_1 N_5 N_P$ quanta

- Number of states \Leftrightarrow partitions of $N_1 N_5 N_P$

- How many states (partitions) ?

$$N_1 N_5 N_P = 2 : (1,1) (2)$$

$$N_1 N_5 N_P = 3 : (1,1,1) (2,1) (3)$$

$$N_1 N_5 N_P = 5 : (1,1,1,1,1) (1,1,1,2) (1,1,3) (1,4) (5) (1,2,2) (2,3)$$

$N_1 N_5 N_P$ quanta: e^S states,

$$S_{\text{MICRO}} = 2\pi(N_1 N_5 N_P)^{1/2}$$

Bekenstein-Hawking entropy

$$ds^2 = -(Z_1 Z_5 Z_P)^{-\frac{2}{3}} dt^2 + (Z_1 Z_5 Z_P)^{\frac{1}{3}} (dr^2 + r^2 d\Omega_3^2)$$

$$Z_1 = 1 + \frac{r_1^2}{r^2}, \quad Z_5 = 1 + \frac{r_5^2}{r^2}, \quad Z_P = 1 + \frac{r_P^2}{r^2}$$

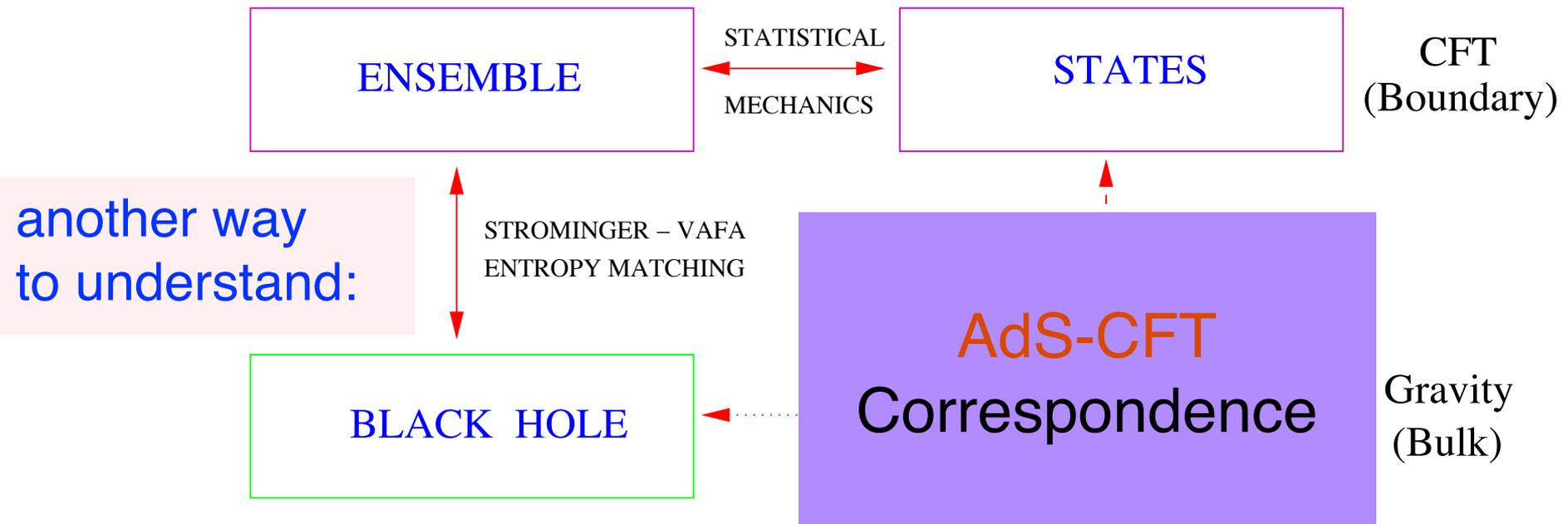
$$r_1^2 = \frac{g_s N_1 l_s^6}{V}, \quad r_5^2 = g_s N_5 l_s^2, \quad r_P^2 = \frac{g_s^2 N_P l_s^8}{R^2 V}$$

- Horizon at $r = 0$

$$S_{BH} = \frac{A}{4l_P^2} = 2\pi (N_1 N_5 N_P)^{1/2} = S_{\text{MICRO}} !!!$$

More complicated black holes \rightarrow hypergeometric functions ...

- 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



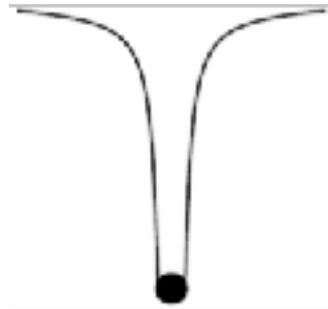
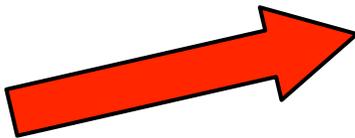
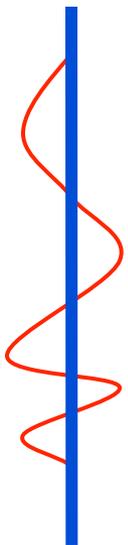
Strominger and Vafa (1996):

Count Black Hole Microstates (branes + strings)

Correctly match B.H. entropy !!!

Zero Gravity

Black hole regime of parameters:



Standard lore:

As gravity becomes stronger,

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

Susskind
Horowitz, Polchinski
Damour, Veneziano

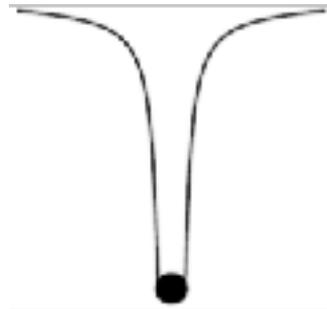
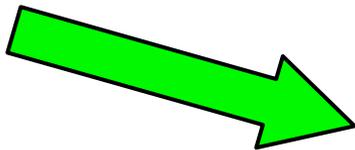
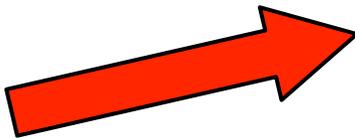
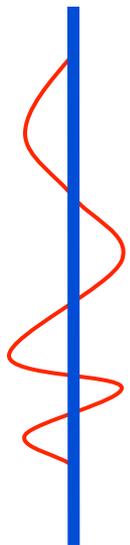
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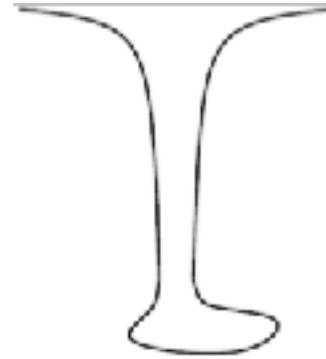
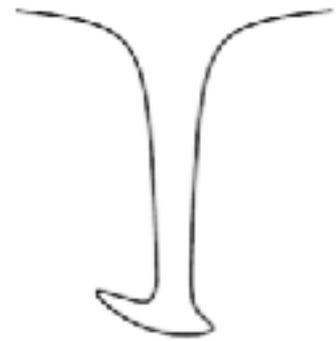
Zero Gravity

Black hole regime of parameters:



Identical to black hole far away.

Horizon → Smooth cap



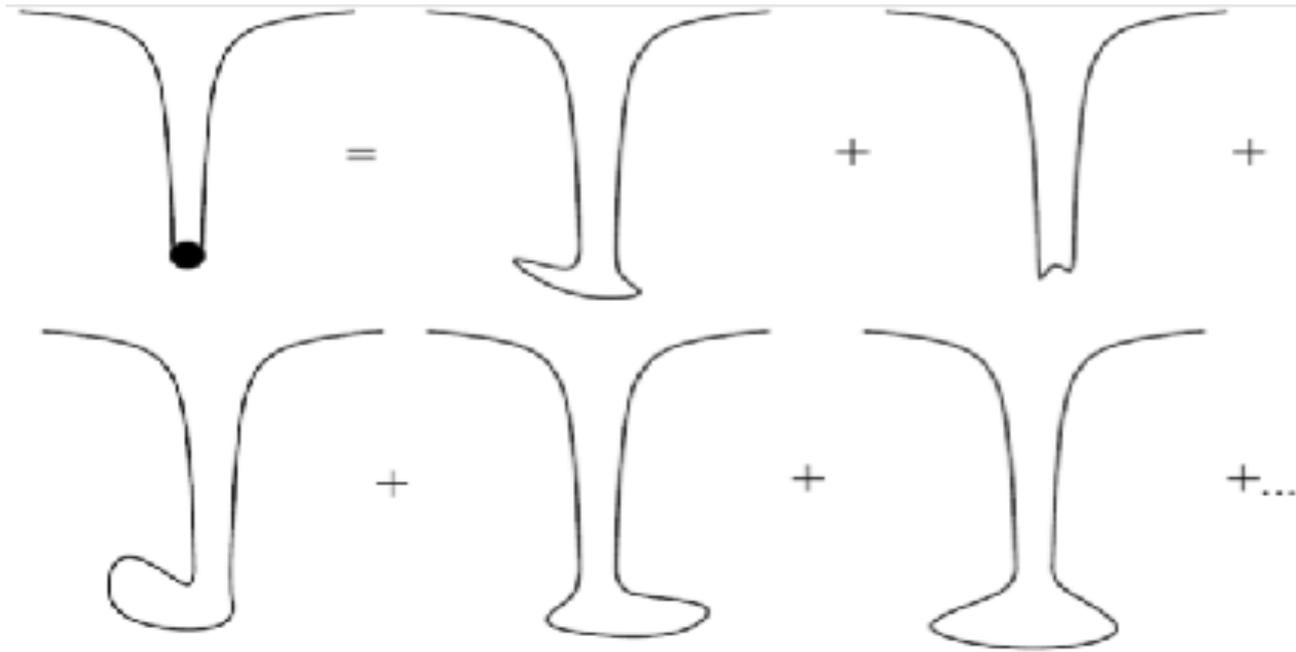
Giusto, Mathur, Saxena
Bena, Warner
Berglund, Gimon, Levi

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

?

Black hole = ensemble of horizonless microstates

Fuzzball Proposal
(Mathur & friends)

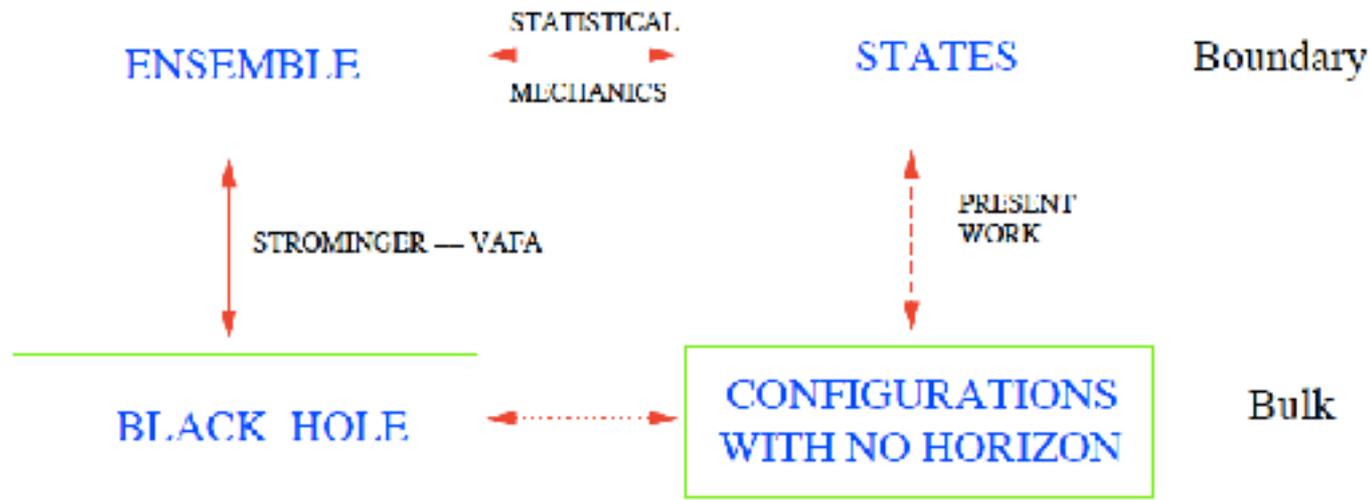


Other formulations:

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:

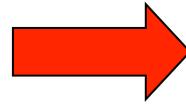
Thermodynamics

(Air = ideal fluid)

$$P V = n R T$$

$$dE = T dS + P dV$$

Useful for meteorology



Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Brownian Motion

Bose-Einstein condensation

Analogy with ideal gas:

Thermodynamics

(Air = ideal fluid)

$$P V = n R T$$

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Statistical Physics

(Air -- molecules)

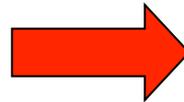
e^S microstates

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
 - LQG configuration
 - Quark-star, you name it ...
 - satisfy 3 very stringent tests:

1. Same growth with G_N !!!

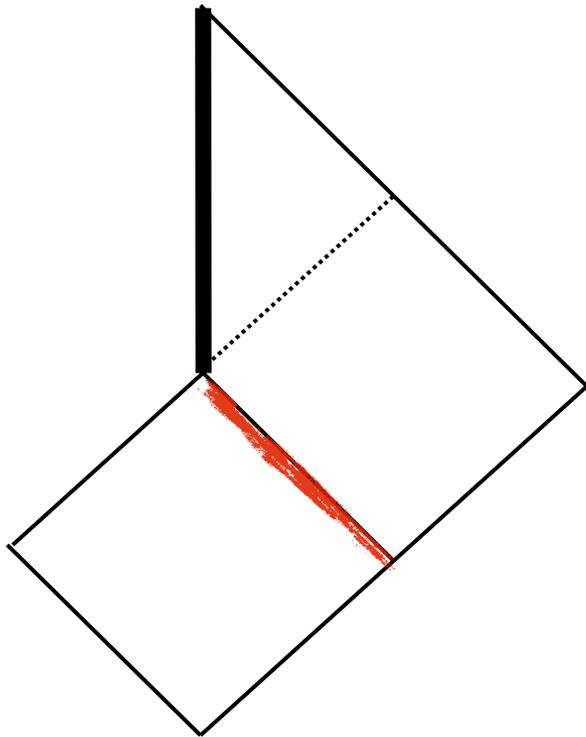
Horowitz

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

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

2. Mechanism not to fall into BH

Very difficult !!!



General Relativity Dogma:
Thou shalt not put anything
at the horizon !!!

- Horizon is null
- Must go at speed of light.
- If massive: ∞ boost \rightarrow ∞ energy
- If massless: dilutes with time
- Nothing can live there !
(or carry degrees of freedom)
- No membrane
- No (fire)wall

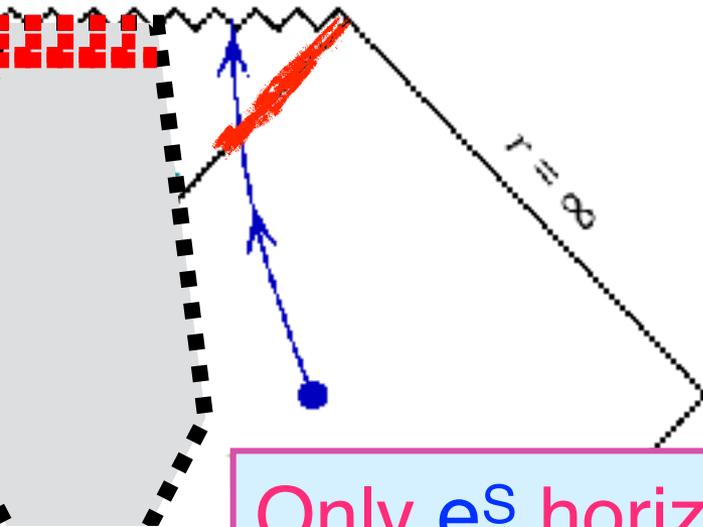
Otherwise b.s.

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 (60 hours for NGC 4889 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, Vercocke

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

Black hole entropy the structure must have



Microstates geometries

- Where is the BH charge ?

$$L = q A_0$$

magnetic

$$L = \dots + A_0 F_{12} F_{34} + \dots$$

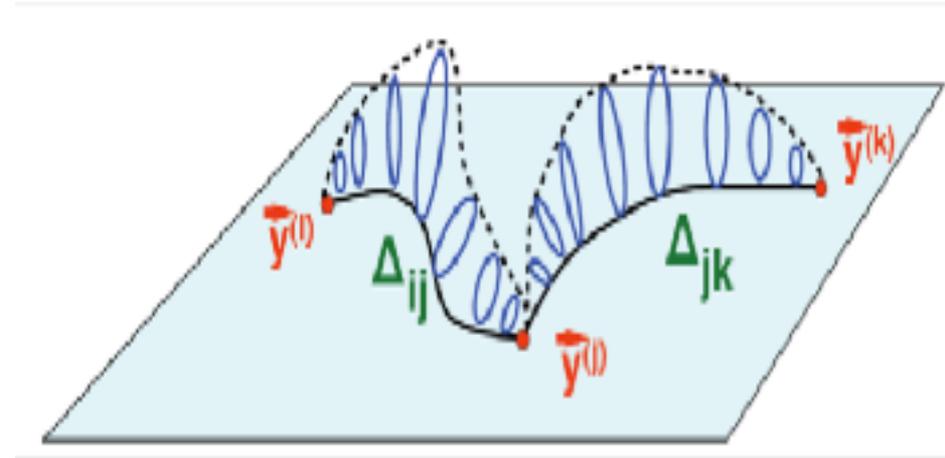
- Where is the BH mass ?

$$E = \dots + F_{12} F^{12} + \dots$$

- BH angular momentum

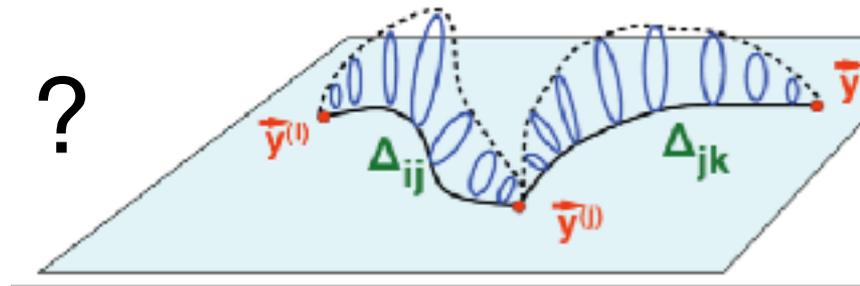
$$J = E \times B = \dots + F_{01} F_{12} + \dots$$

2-cycles + magnetic flux



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

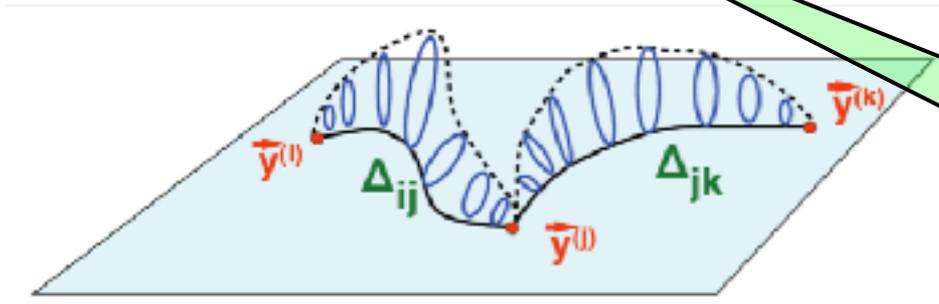
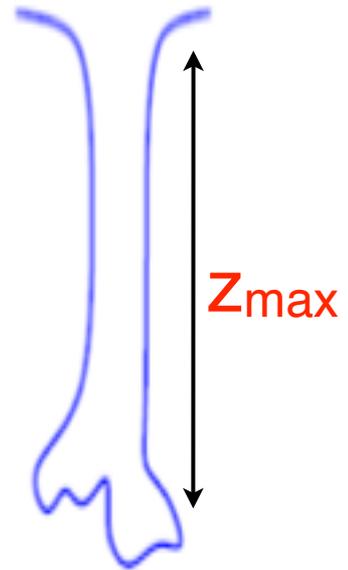
Why not collapsing ?



- 5(+6)d : smooth solutions + **quantized** magnetic flux on topologically-nontrivial **2-cycles**
 - cycles smaller \rightarrow 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 \rightarrow centers with **negative D6 charge** and **negative mass**
 - common in String Theory (e.g. orientifolds); **nowhere else**
 - **Highly unusual** matter from a 4d perspective

Four Scales

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



Can be traded for gap in

SUSY microstates – the story:

- We have a huge number of them
 - Arbitrary functions of 2 variables !
 - Habemus Superstratum !
 - Reproduce black hole entropy ☺
Bena, Giusto, Russo, 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
- 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



Strominger - Vafa

$$S = S_{\text{BH}}$$

Black Hole Deconstruction

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

$$S \sim S_{\text{BH}}$$

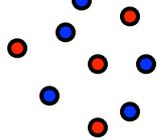
Black
Holes

Effective coupling (g_s)

Multicenter Quiver QM

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

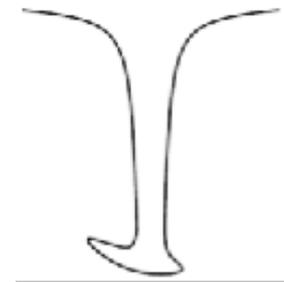
$$S \sim S_{\text{BH}}$$



Size grows

No Horizon

Smooth Horizonless
Microstate Geometries



Punchline: Typical states **grow** as G_N increases.

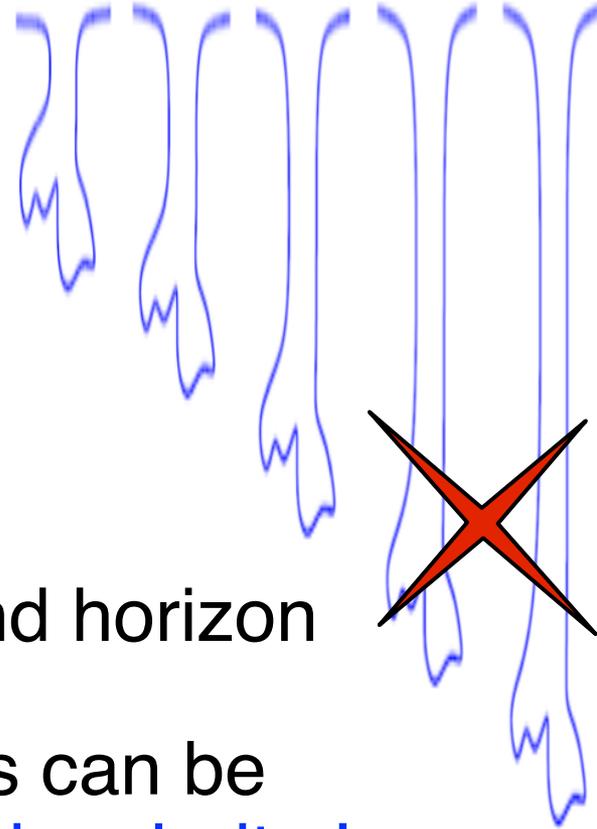
Horizon never forms.

Quantum effects from singularity **extend to horizon**

Similar story for non-SUSY extremal black holes

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



New small-mass degrees of freedom

N_1 D1 branes

$$\delta m \sim 1 / N_1$$

N_1 D1 branes +

N_5 D5 branes

$$\delta m \sim 1 / N_1 N_5$$

N_1 D1 branes +

N_5 D5 branes +

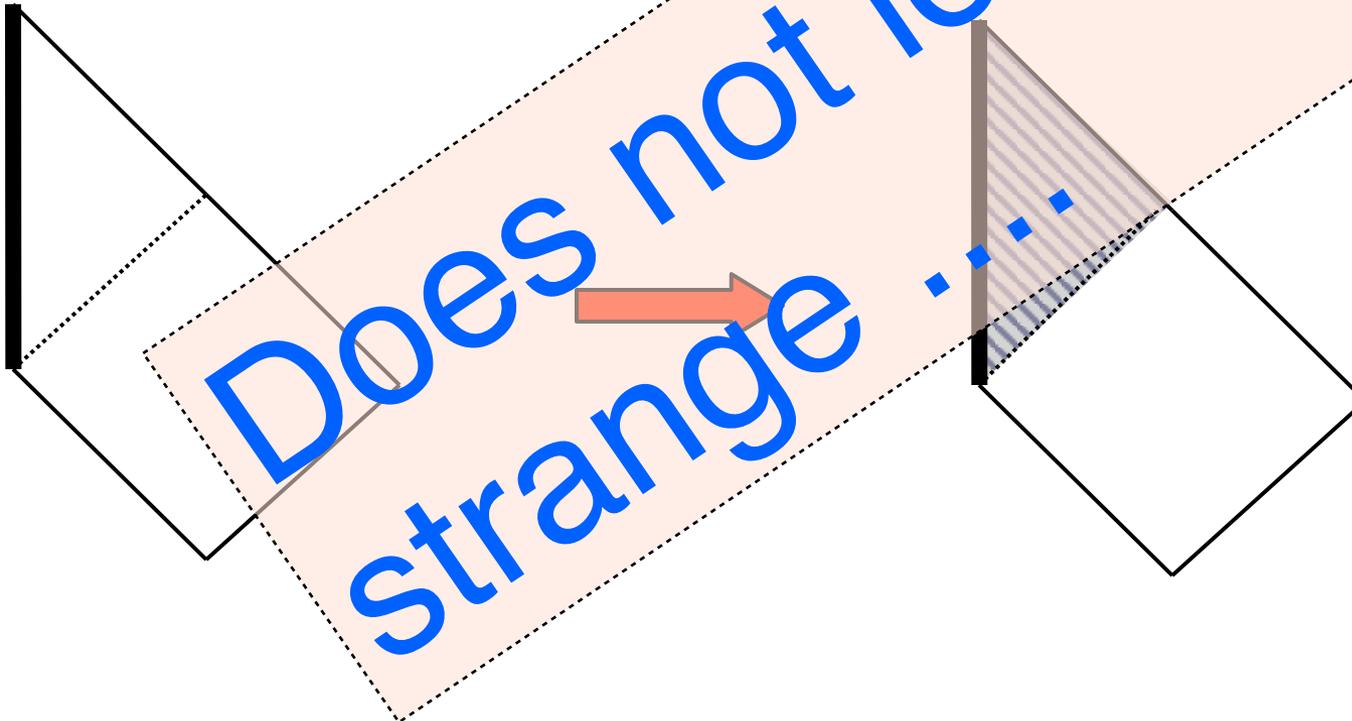
N_P momentum quanta

$$\delta m \sim 1 / N_1 N_5 N_P$$

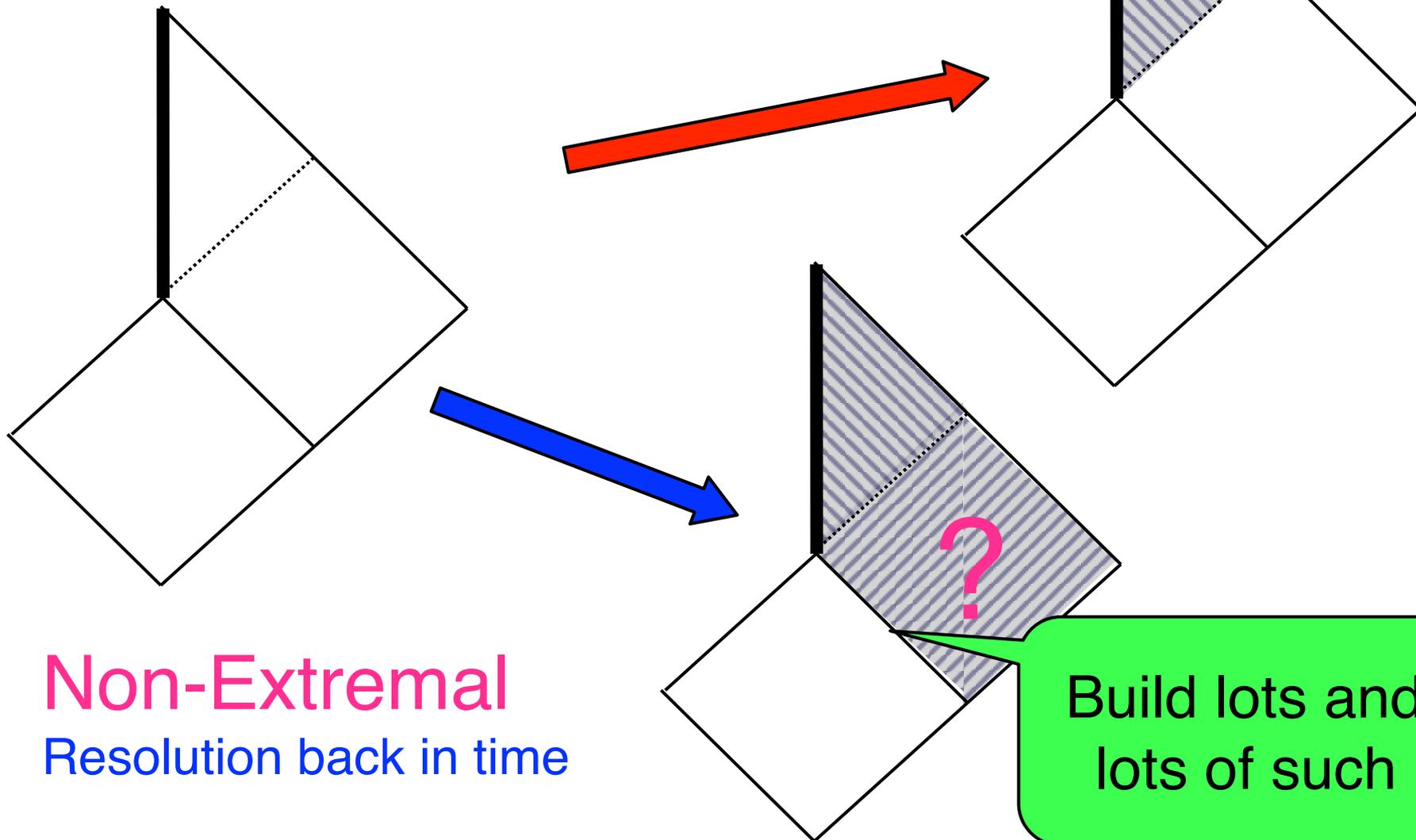
$$\delta R \sim 1 / \delta m \sim N_1 N_5 N_P \quad \text{horizon scale}$$

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 2nd 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, Vernocke
- Decay to susy minima:
brane-flux annihilation - Hawking radiation
- Microstates of **near-extremal BH**

Very few known. JMaRT. Extremely hard to build...

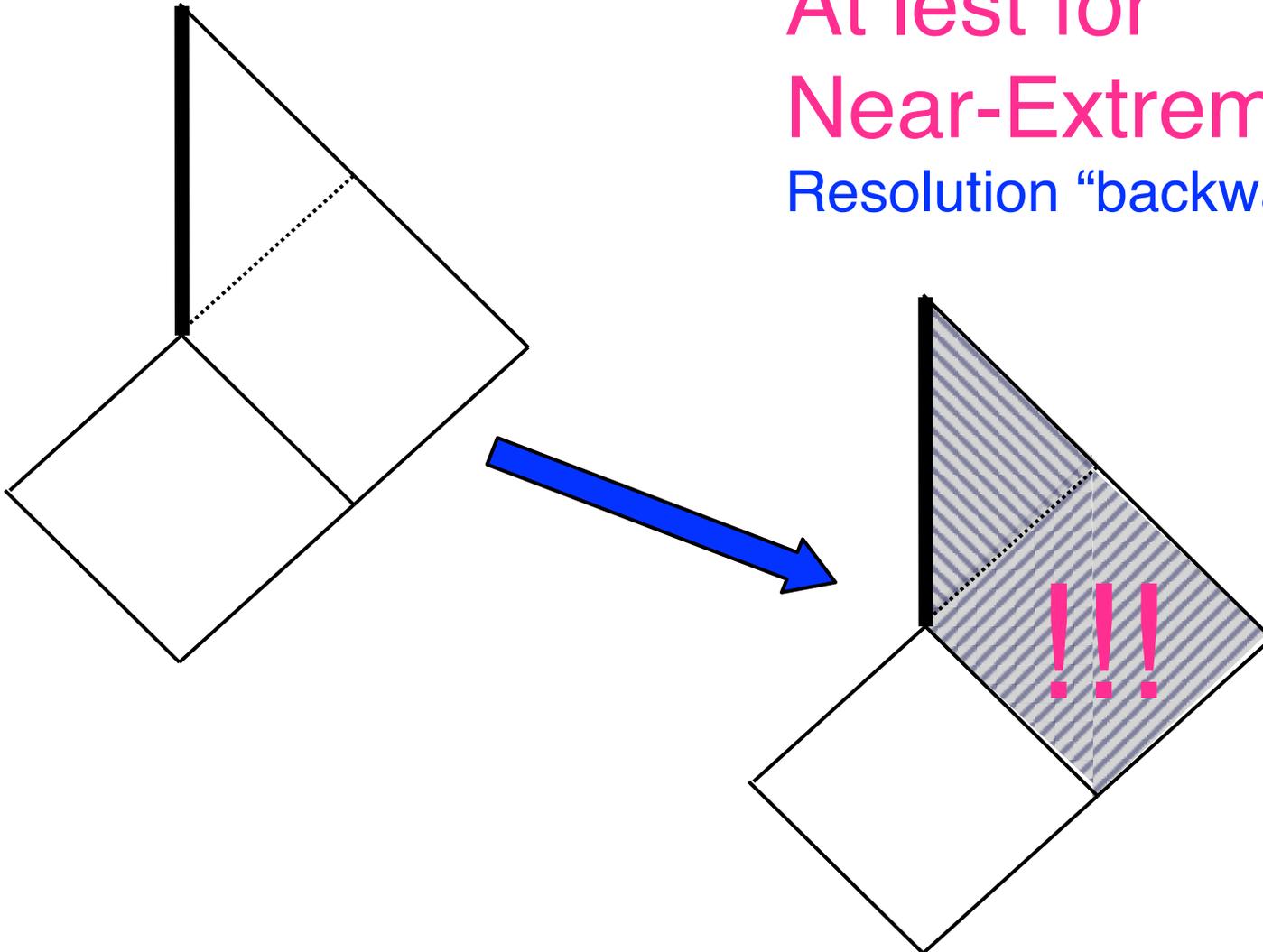
– Coupled nonlinear 2nd order PDE's do not factorize

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

- For some solutions the 2nd 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 least 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 still through ?

(2) Generic AdS-CFT

- nontrivial \rightarrow no spherical symmetry \Rightarrow no horizon

(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) Build lots of BH microstate geometries = Hair !!!

- Mechanism: bubbles

- Universal lesson: 2 new scales, E_{gap} , λ_T

Agnostic about theory
No mechanism for Hair !

A few questions

- **Would all microstates be classical ?**
 - No, but classical solutions are the only things we can construct
 - **Hovering mechanism extrapolates** \Rightarrow brane polarization, non-Abelian
 - Typical states: many small bubbles ($\lambda_T \sim \ell_P$), or just a few ($\lambda_T > \ell_P$)
 - Larger bubbles have more entropy Denef, Moore; Bena, Shigemori, Warner

- **What about cosmological singularities ?**
 - Resolved backwards in time ! How ?
 - Approaching space-like singularity - one encounters e^S new states.
 - Small tunneling probability: e^{-S}
 - Will tunnel with probability ONE !!!
 - How do these states look like ?

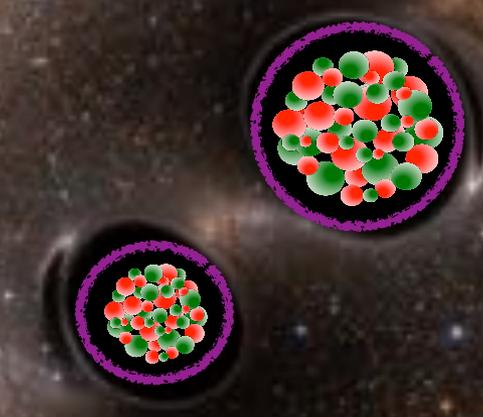
A few questions

- 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:

YugeTM amount of new degrees of freedom @ horizon



Horizon viscosity

Microstate mountains

Distortion of the Kerr multipoles / Love number

- Kerr microstate geometries **Heidmann**

Summary and Future Directions

- String theory has configurations that **hover above horizon**. Highly nontrivial **mechanism**
- **Supersymmetric black hole microstates** = horizonless solitons
 - **low-mass modes** affect **large (horizon) scales**
 - Convergence of many research directions
 - **Habemus Superstratum** - 2 variables - **Entropy !**
- Likely extends to extremal non-susy black holes
- Does it extend to **non-extremal** black holes ?
 - It should (firewall, fuzzball, information-theory arguments)
 - **Near**-extremal OK
 - **Far** from extremality hard
 - Maybe start thinking about **experimental** consequences ?