Black Holes
where Quantum Mechanics and General Relativity clash

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with

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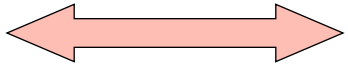
Why study Black Holes

- They exist in nature
  - Binary Systems

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

  M ~ 1 000 000 000 $M_\odot$

Quantum Mechanics



General Relativity

Great Conflict

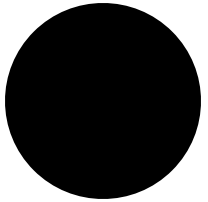
General relativity

- 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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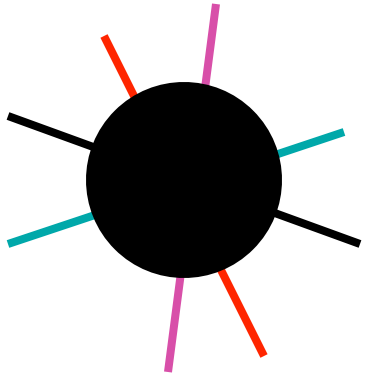

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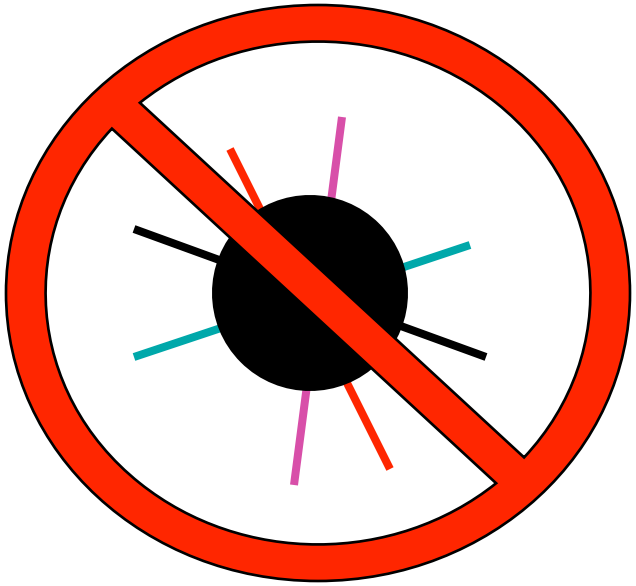
J.A. Wheeler:
Black holes have no hair
(Les trous noirs n'ont pas de ....)



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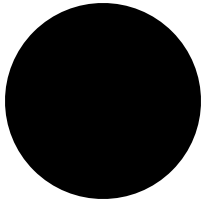
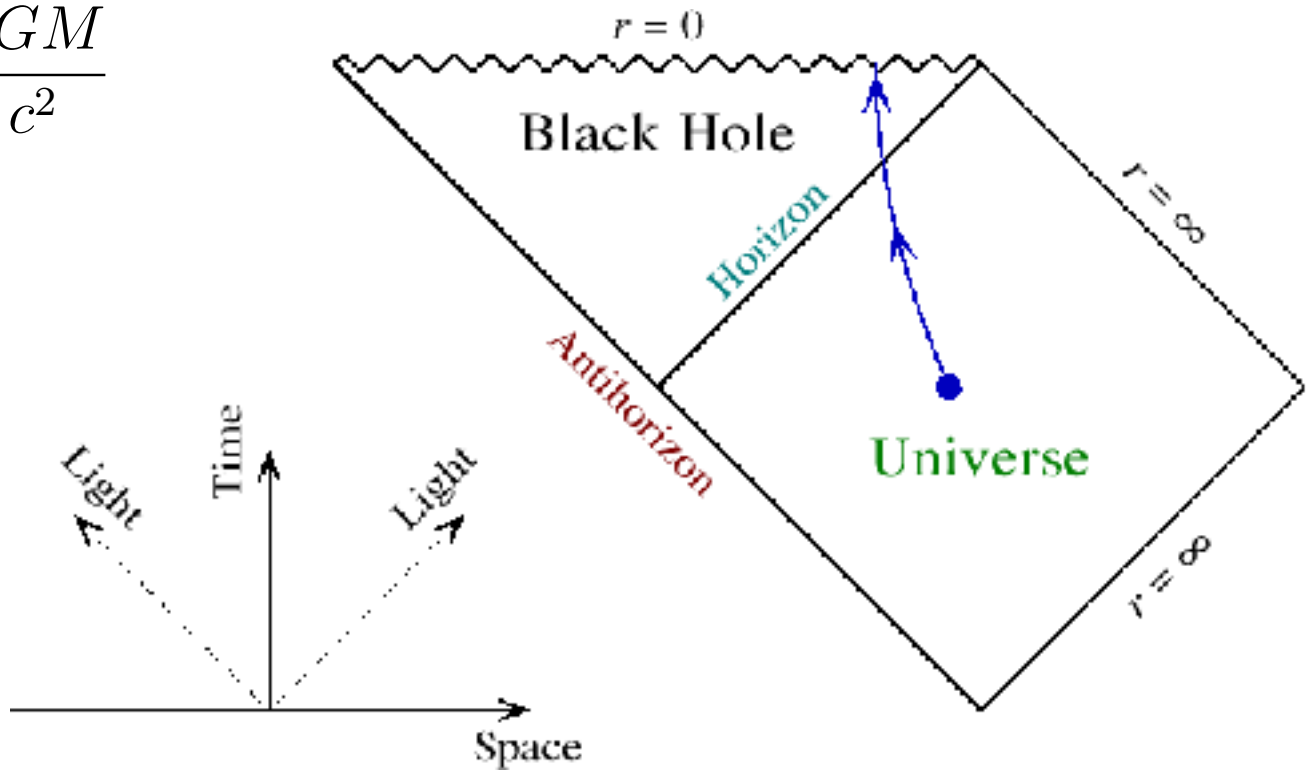


Impossible to distinguish between black holes formed by the collapse of
- matter
- antimattier
- elephants
- service du personnel bureaucrats

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

Largest discrepancy in all physics !

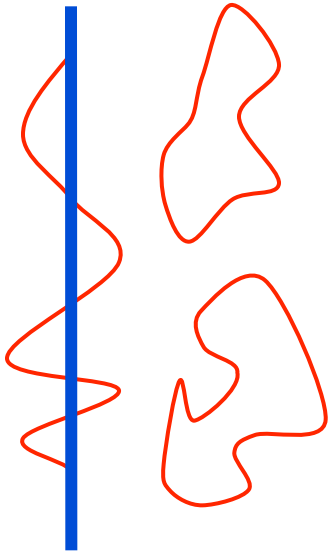
Black Holes

Quantum Mechanics: ⟷ General Relativity

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

Quantum Gravity / String Theory

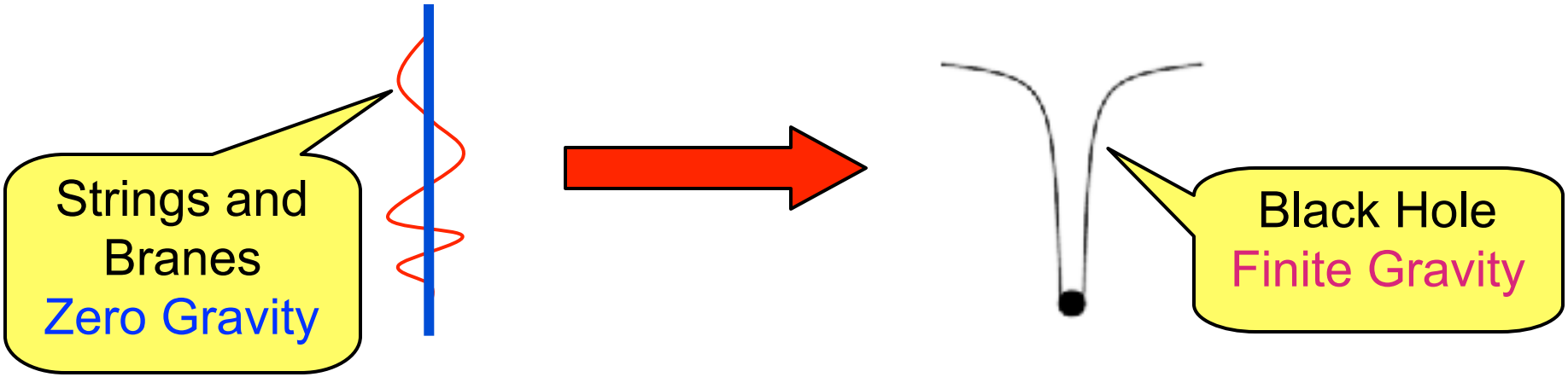
- 10 dimensions
- Strings, membranes (D-branes)
- Build *lots and lots* of black holes putting together D-branes



WHERE ARE THE STATES ?
HOW DO THEY LOOK ?

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

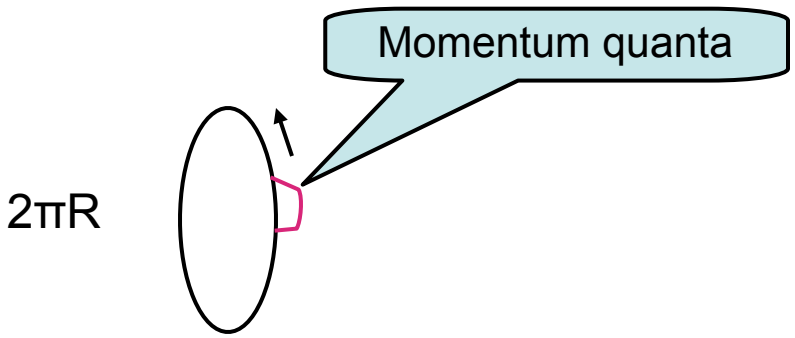
Strominger and Vafa (1996)
+ 2000 other articles



- Simplest Black Hole:
  D1 branes (strings), D5 branes, momentum P

Momentum quanta

one D1 brane, $2\pi R$ ⇒ $\delta P = 1/R$



- Simplest Black Hole:
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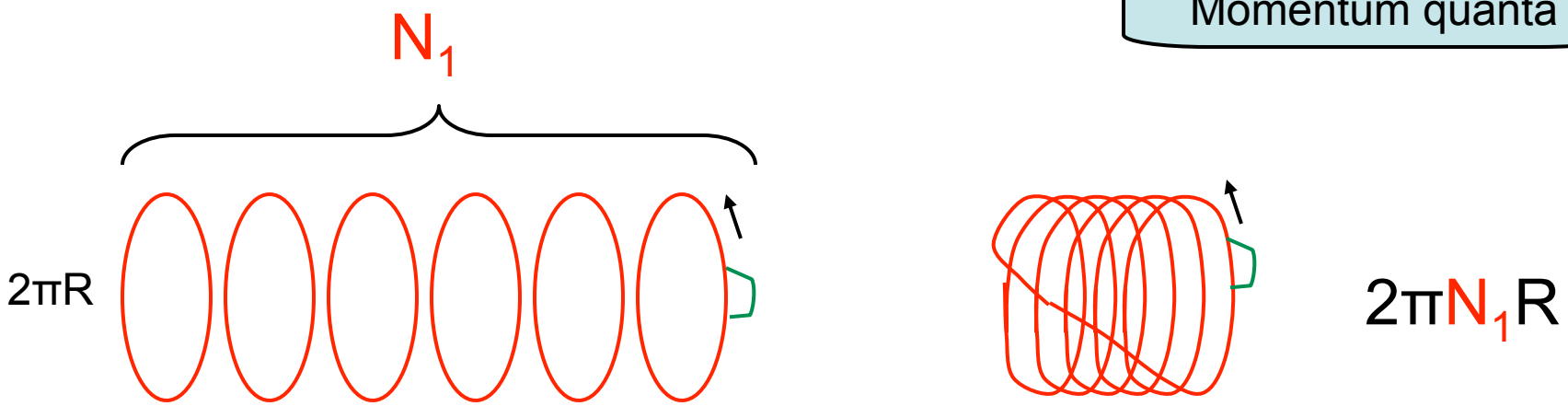
one D1 brane, $2\pi R$ ⇒ $\delta P = 1/R$

N_1 D1 branes, $2\pi R$

one D1 brane, $2\pi N_1 R$ ⇒ $\delta P = 1/N_1 R$

Momentum quanta



- Simplest Black Hole:
  D1 branes (strings), D5 branes, momentum P

une D1 brane, $2\pi R$ ⇒ $\delta P = 1/R$

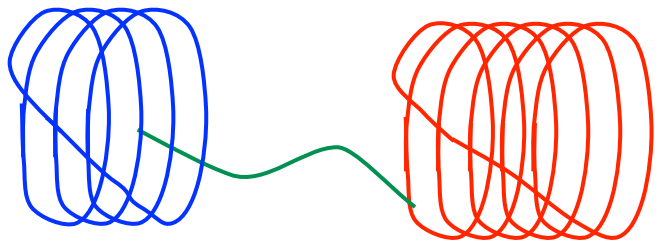
N_1 D1 branes, $2\pi R$

1 D1 brane, $2\pi N_1 R$ ⇒ $\delta P = 1/N_1 R$

N_1 D1 + N_5 D5 branes

effective string, $2\pi N_1 N_5 R$ ⇒ $\delta P = 1/N_1 N_5 R$

Momentum quanta



Microstate Counting

- 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

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

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

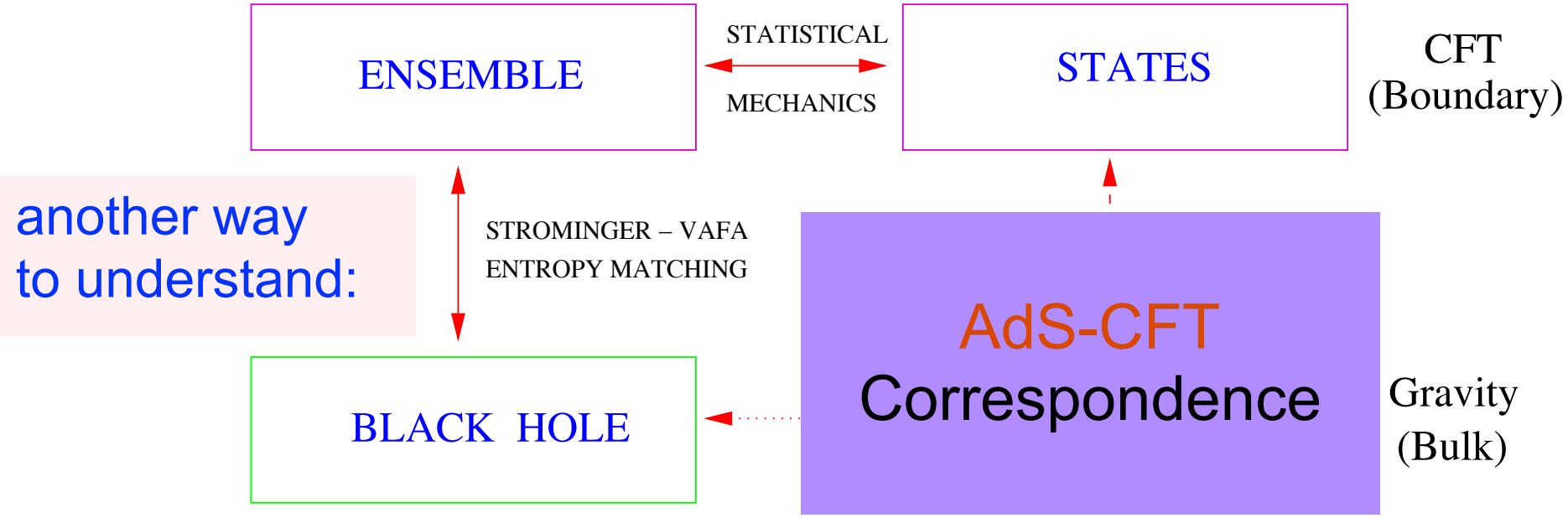
$$r_1^2 = \frac{g_s N_1 l_s^6}{V} , \qquad r_5^2 = g_s N_5 l_s^2 , \qquad r_P^2 = \frac{g_s^2 N_P l_s^8}{R^2 V}$$

- Horizon at $r = 0$

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

More complicated black holes → 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

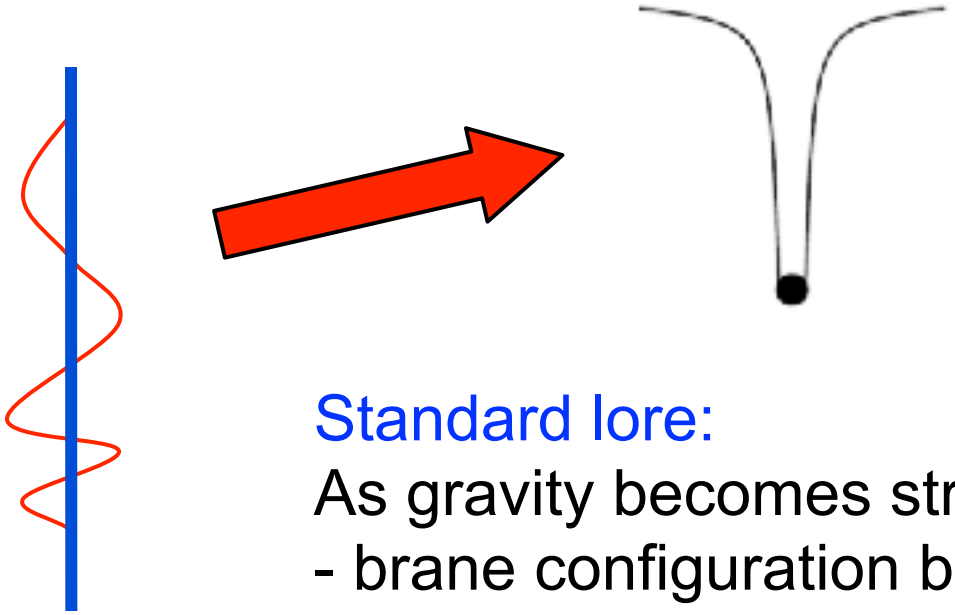


Strominger and Vafa (1996):

*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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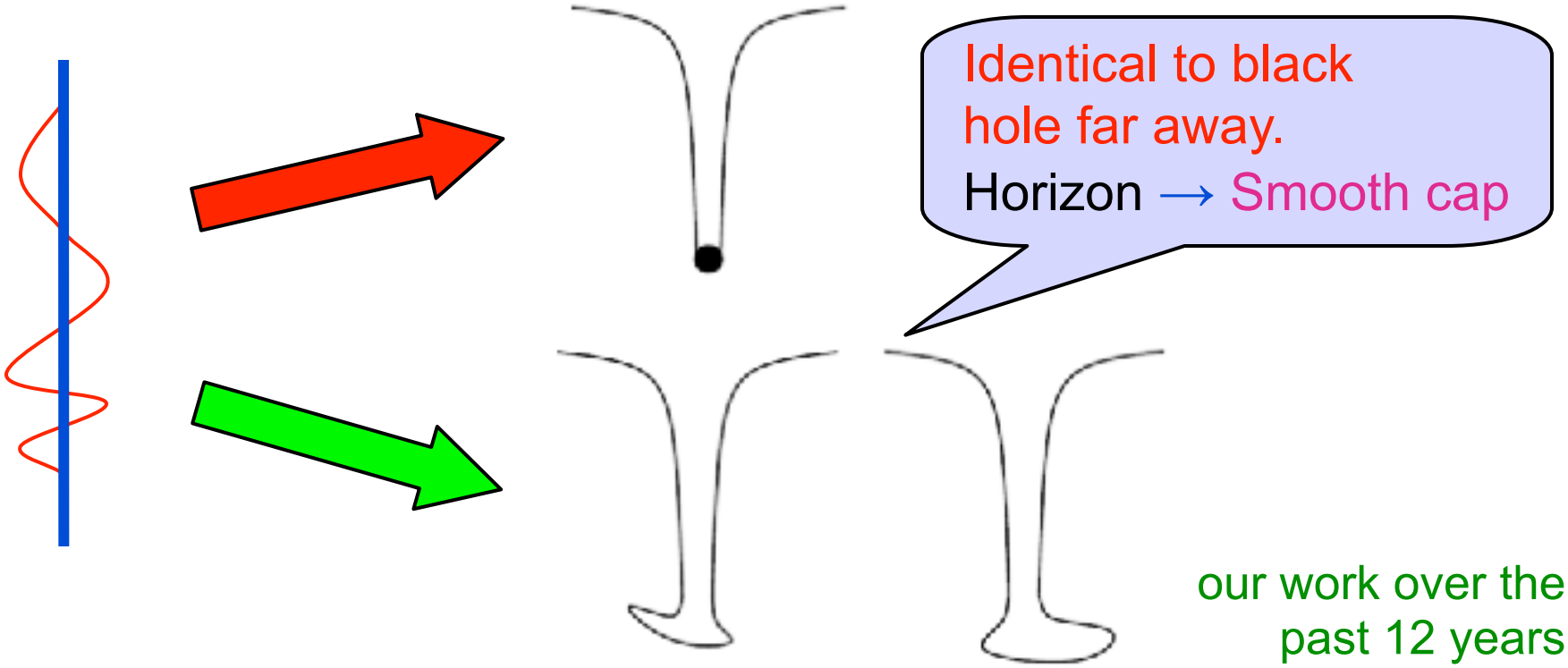


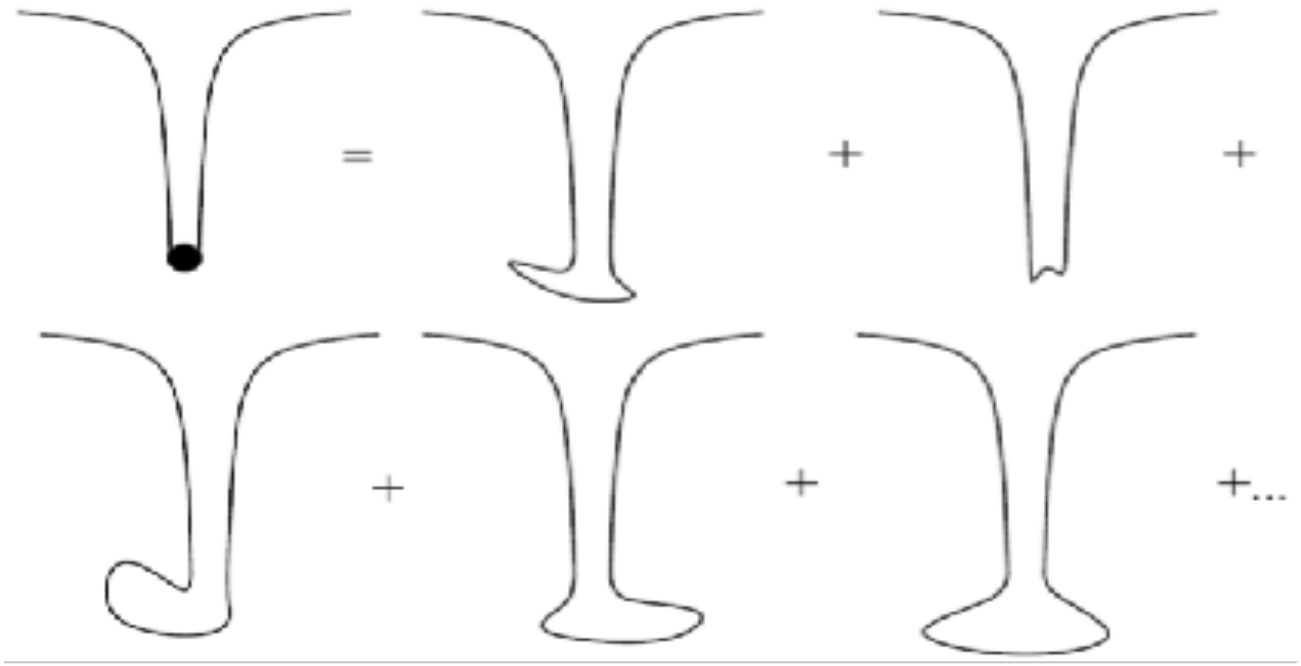
our work over the
past 12 years

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

?

Black hole = ensemble of horizonless microstates

Fuzzball Proposal
(Mathur & friends)

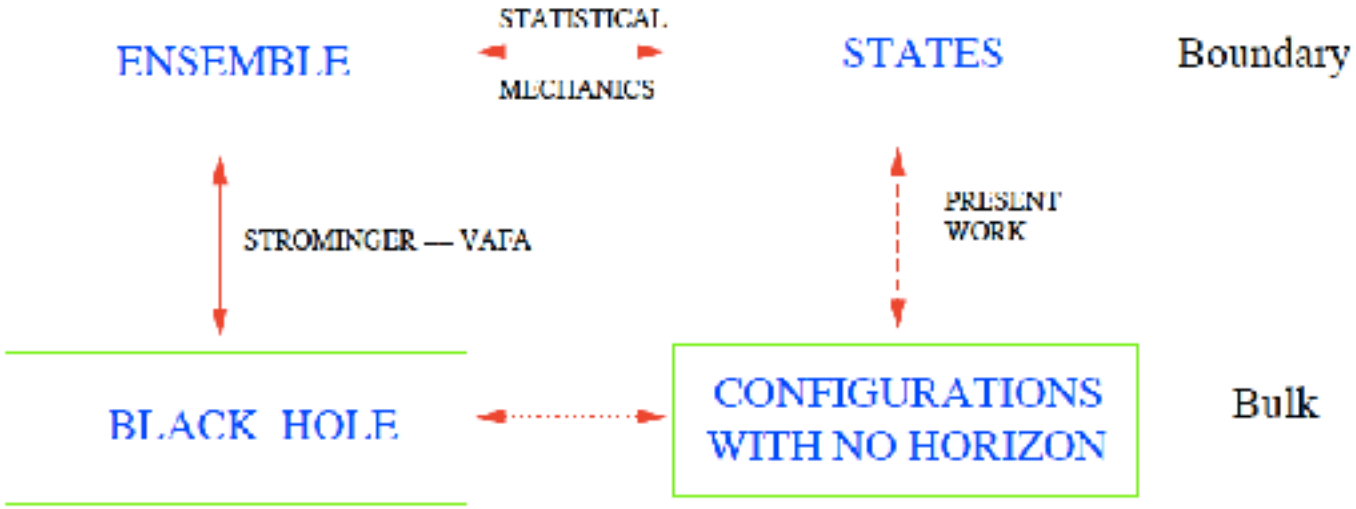


Other formulations:

e.g. Bena, Warner, 2007

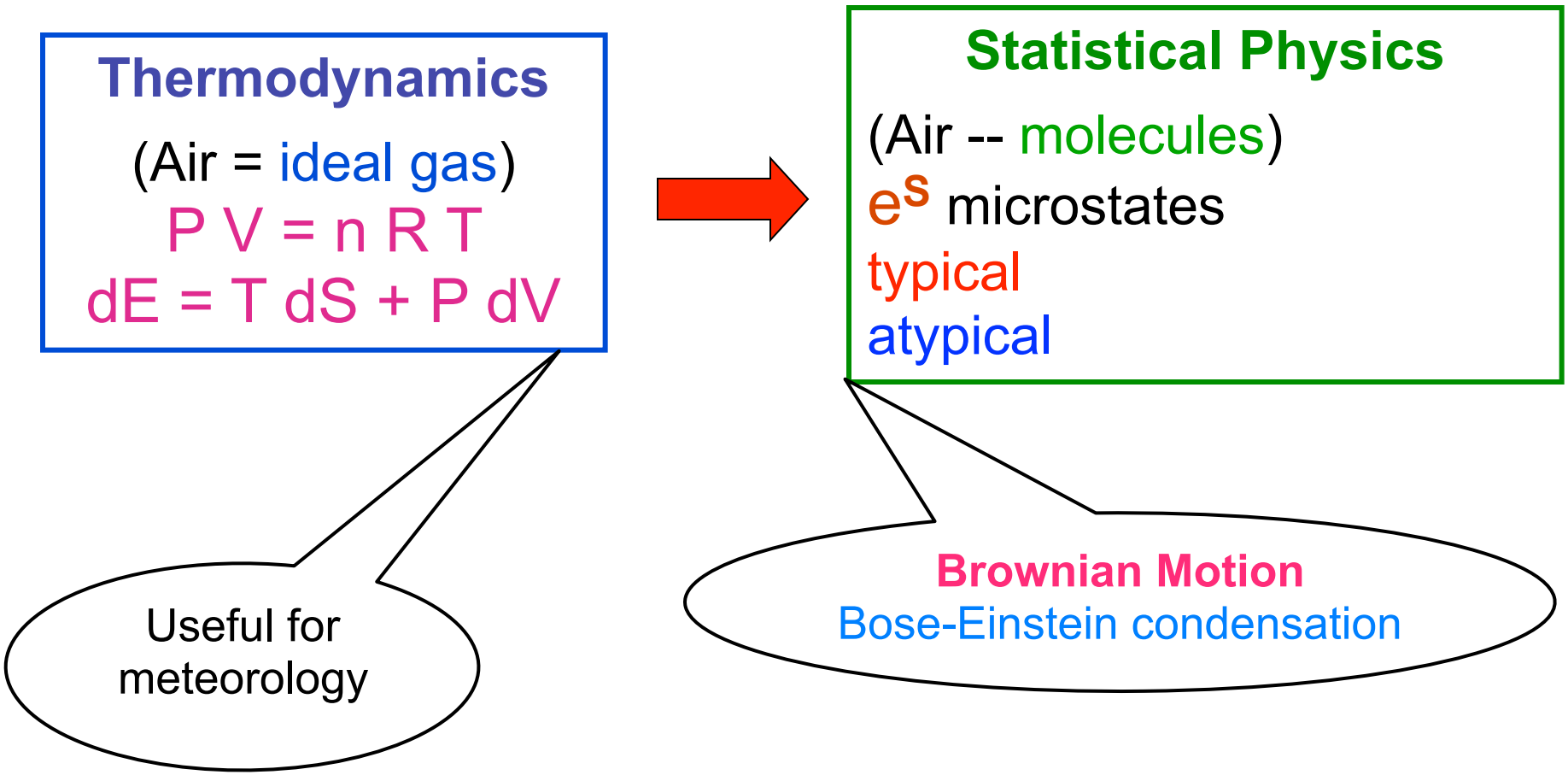
- Thermodynamics (EFT) breaks down at horizon. New low-mass d.o.f. kick in.

- 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



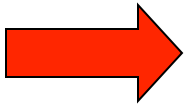
Analogy with ideal gas

Thermodynamics

(Air = ideal gas)

$P V = n R T$

$dE = T dS + P dV$



Statistical Physics

(Air -- molecules)

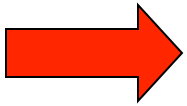
e^S microstates

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:

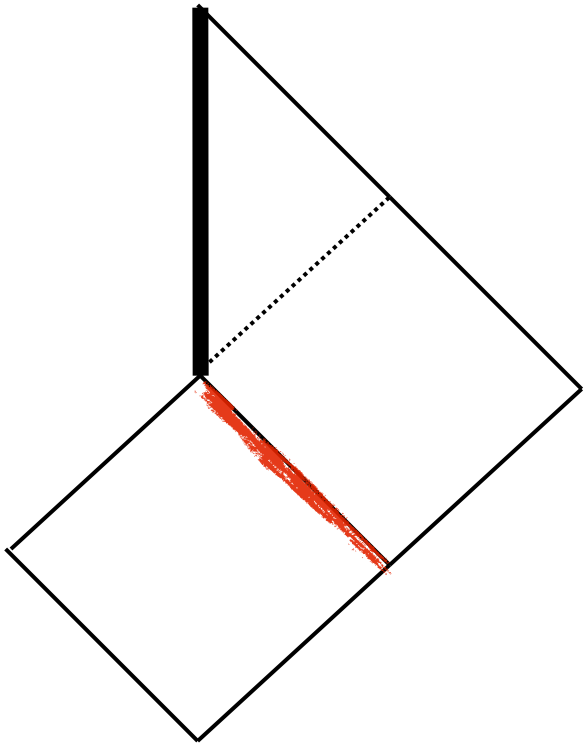
1. Same growth with $G_N = g_s^2$!!! Horowitz

- 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

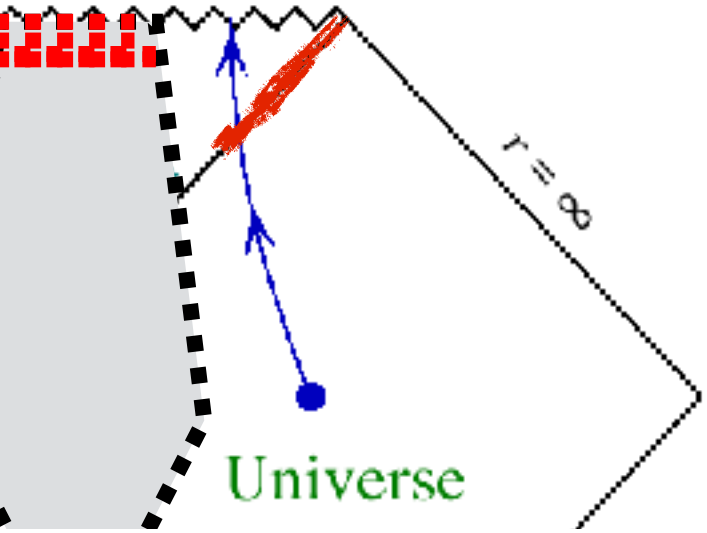
- Nothing can live there !
  (or carry degrees of freedom)
- No membrane, no spins
- No (fire)wall

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 !

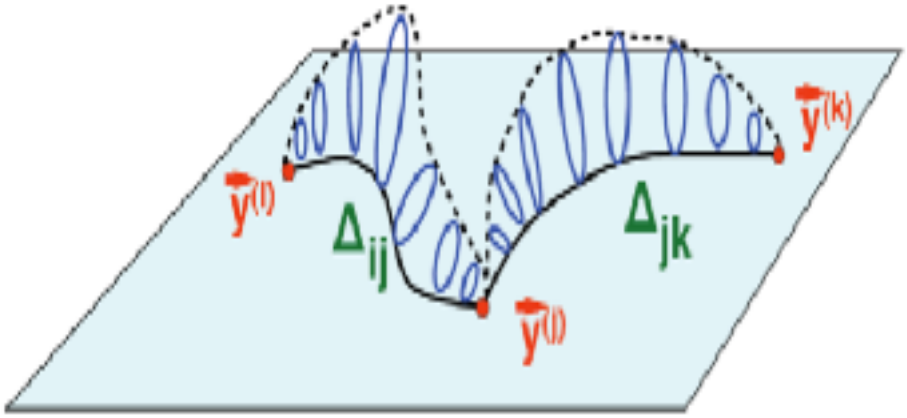
Microstates geometries

- Where is the BH charge ?

$L = q\, A_0$ magnetic

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

2-cycles + magnetic flux



- Where is the BH mass ?

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

- BH angular momentum

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

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

Largest family of solutions known to mankind

Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

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

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

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

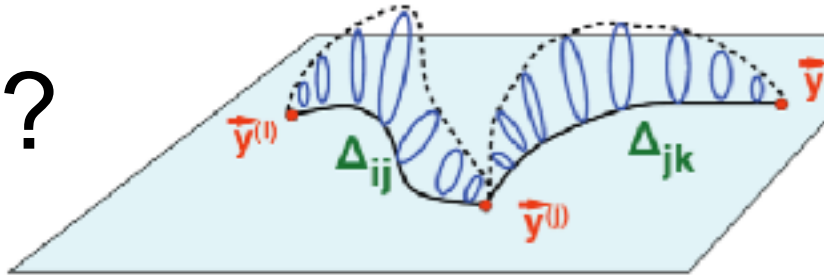
String theory input crucial

Giusto, Russo, Turton

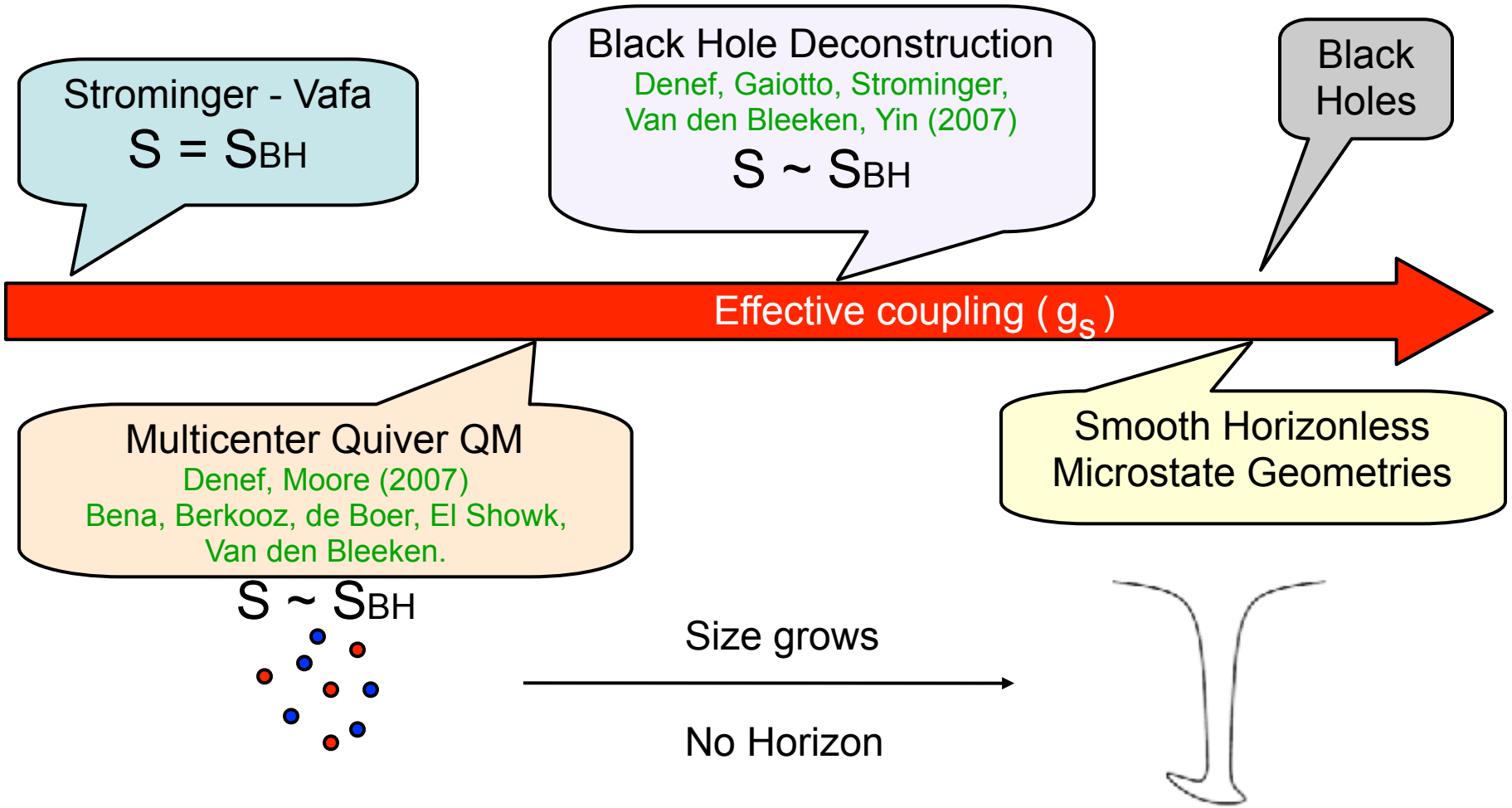
Bianchi, Morales, Pieri

Habemus Superstratum !!!

Why not collapsing ?



- 5d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller ⟶ increases energy: $S \sim F_{\theta\phi}^2 g^{\theta\theta} g^{\phi\phi} \sim r^{-4}$
  - 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 !
- 4d : multicenter solutions Denef
  - certain intersections of cycles ⟶ D6 brane centers with negative 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



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

Pure BH states have no horizon - 4 approaches:

(1) Quantum information-theory Mathur 2009, AMPS

- required by no-cloning
- secondary question: firewall ? burn or sail through ?

Agnostic about theory No mechanism for Hair !

(2) Generic AdS/CFT

- nontrivial vevs ⇒ no spherical symmetry ⇒ 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

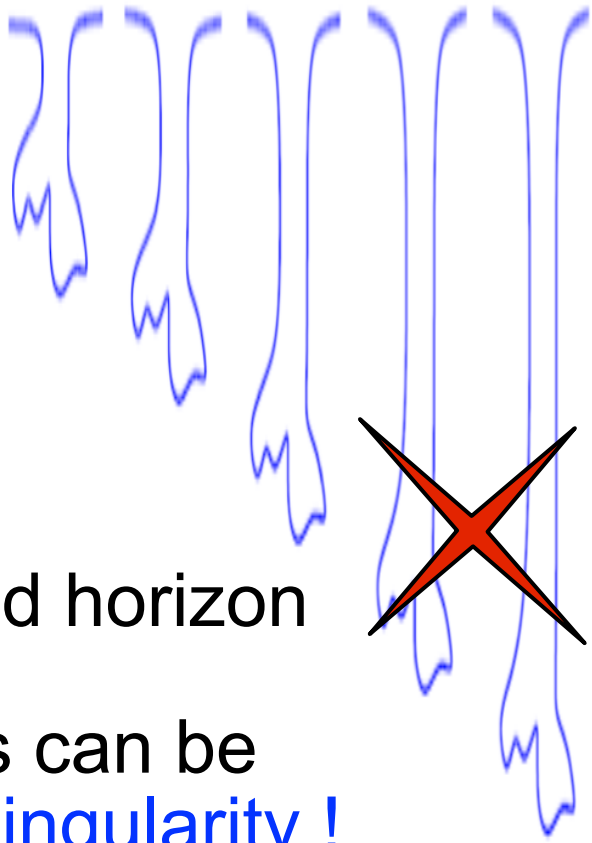
  Bena, Berkooz, de Boer, El Showk, Van den Bleeken; Lee, Wang, Yi,

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

- Mechanism: bubbles
- Can account for BH entropy

Why destroy horizon ? Low curvature !

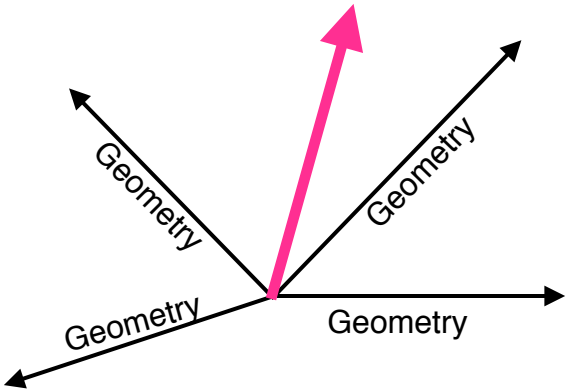
- Answer: space-time has singularity:
  - low-mass degrees of freedom
  - change physics on long distances
- Very common in string theory !!!
  - Polchinski-Strassler
  - Klebanov-Strassler
  - Giant Gravitons + LLM
  - D1-D5 system



- 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

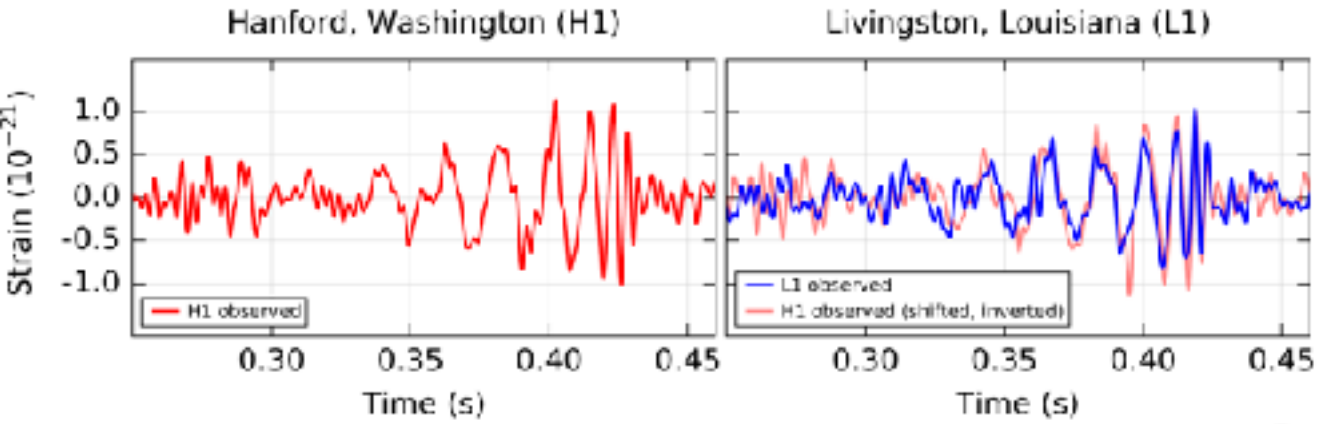
A few questions for people who know Quantum Mechanics better than me

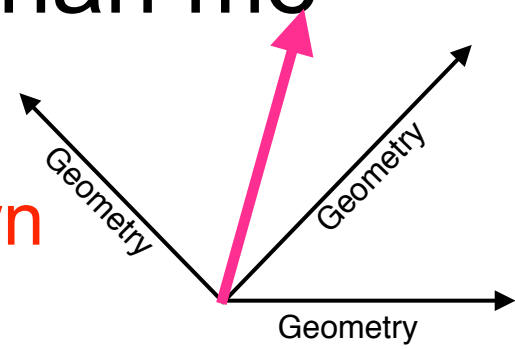
- Exp(10^{90}) classical geometries
  = coherent states forming basis
  for BH Hilbert space
- How do you interact with this mess ?
- Throw in a photon. Expect not to come out
  - Coherent state ? non-geometric: goes through all geometries, destructive interference (multi-slit exp.)
  - Decoherence ? just explores one geometry
    spends a lot of time? absorbed? exciting the geometry?
- Throw in a heavier probe
  - Experience flat space ? Complementarity? Tunneling ?
  - Plow through BH ? - get out on the other side ?

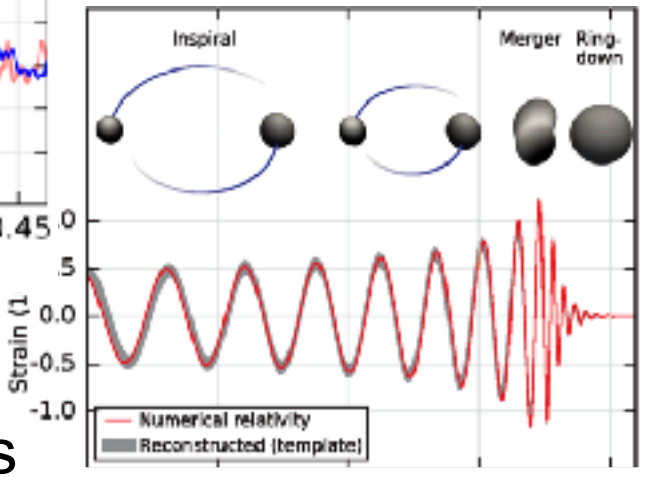


A few questions for people who know Quantum Mechanics better than me

- Throw in another black hole. LIGO.
- 3 phases: Inspiral, Merger, Ring-down





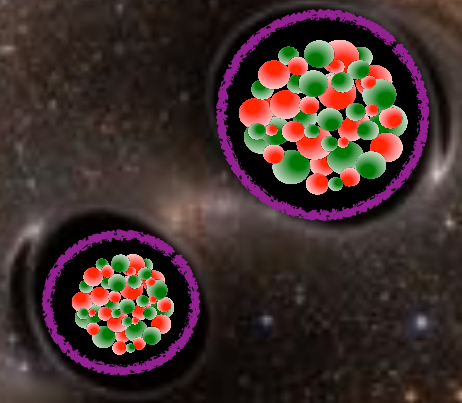


- Non-geometric: dipole moments ~ $e^{-S/2}$
- Geometric: larger dipole = inspiral bumps
- Mergers of non-aligned BH (5 days ago)
  - Non-geometric: essentially Kerr solution
  - Geometric: different solution

How can we observe this ?

Universal feature:

- **Low-mass degrees of freedom at horizon.**



LIGO, eLISA:

Bumps ?

Extra dissipation - different gavitational waves

Distortion of the Kerr multipole moments

Summary and Future Directions

- Black Hole pure states have no horizon !
  - Many different approaches
  - Only way to reconcile GR and Quantum Mechanics
- Can build them in String Theory
  - Largest family of solutions known to mankind
  - Highly-nontrivial matter
  - Mechanism not to collapse
- Very Unusual Quantum Systems.
  - e^{-S} tunneling probability into e^{S} horizonless microstates
  - How do they interact ?
  - Decoherence ? Geometric or non-geometric ?
- Gravity wave experiments. Consequences ?