Signals from the structure@horizon

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Nick has hopefully convinced you that there must exist STRUCTURE @ horizon scale

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

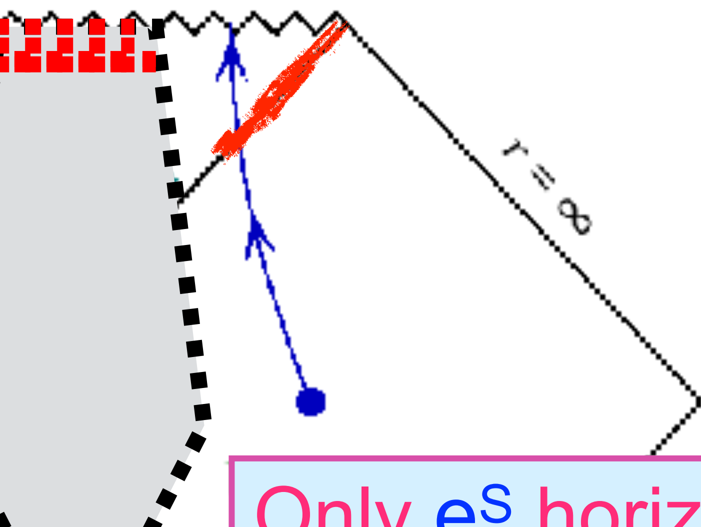
Microstate geometries

Long distance physics
Gravitational lensing

Physics at horizon
Information loss
Gravity waves ?

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}

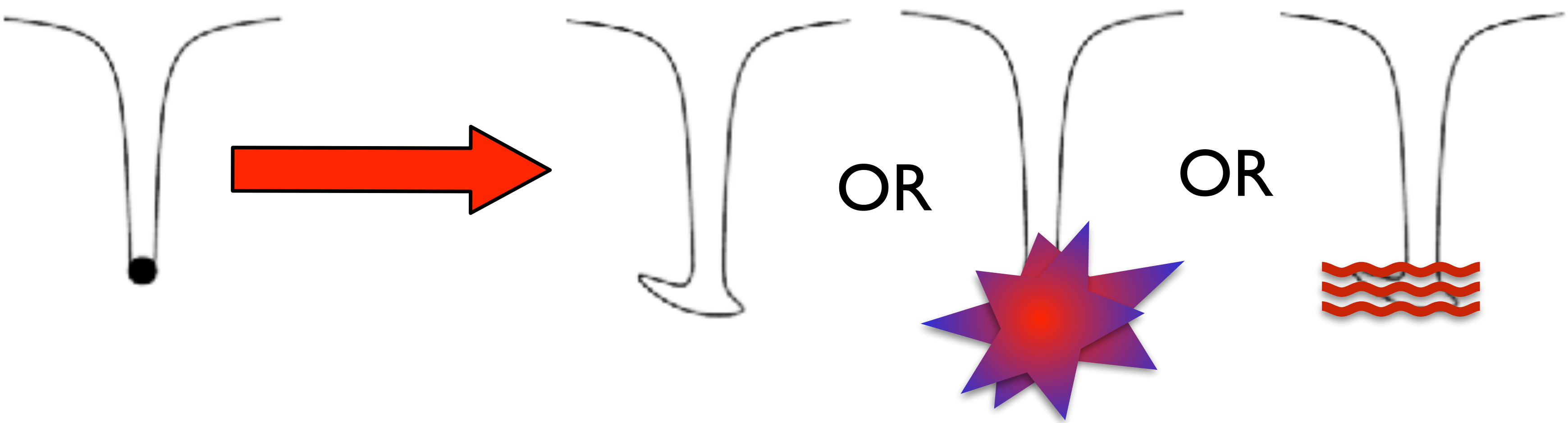
Will tunnel with probability **ONE** !!!

Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

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

Black hole entropy the structure must have

MICROSTATE GEOMETRIES
whose construction we can trust



HOW DO WE GET FROM
String Theory BH to Real World BH ?

HOW DOES STRUCTURE AFFECT
HORIZON PHYSICS ?

Important feature

- Have the same size as the BH for any mass $\leftrightarrow$ size grows with G_{Newton}
- Boson stars need different scalar fields of different masses to replace various BH's: One field for $M_{\odot}$, another for 30 $M_{\odot}$, etc
- String theory automatically produces fields whose mass decreases for larger BH
  - Non-perturbative physics
- They are the reason why microstate geometries have BH size for ANY BH mass

Simplest Black Hole:

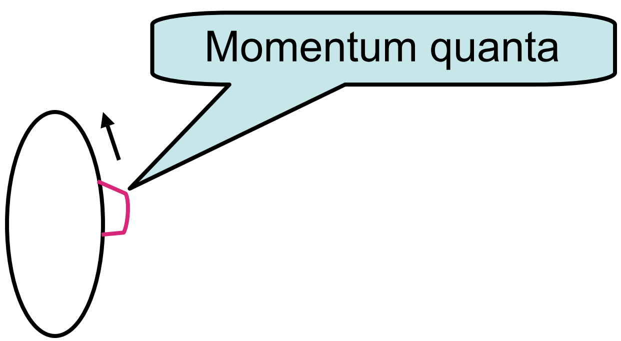
Strominger, Vafa

D1 branes (strings), D5 branes, momentum P

Momentum quanta

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

2πR



Simplest Black Hole:

Strominger, Vafa

D1 branes (strings), D5 branes, momentum P

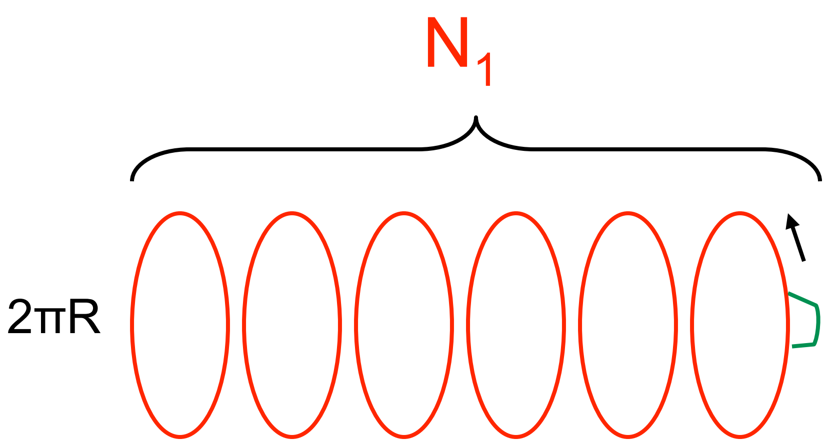
one D1 brane, $2\pi R$ ⇨ $\delta P = 1/R$

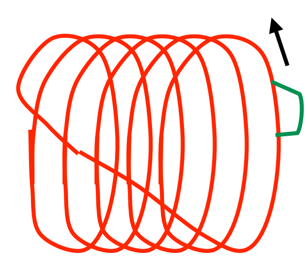
N_1 D1 branes, $2\pi R$

one D1 brane, $2\pi N_1 R$

} ⇨ $\delta P = 1/N_1 R$

Momentum quanta





$2\pi N_1 R$

Simplest Black Hole:

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N_1 D1 branes, $2\pi R$

1 D1 brane, $2\pi N_1 R$

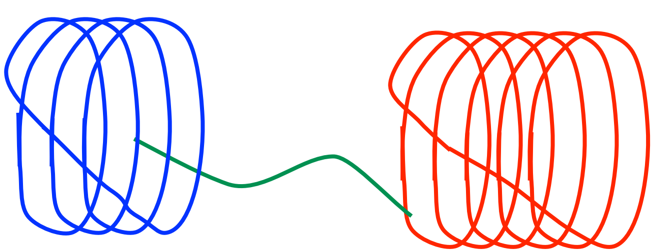
} ⇒ $\delta P = 1/N_1 R$

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

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,

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

Low-mass degrees of freedom

Given total energy budget:
most entropy obtained by making
brane-antibrane pairs:

$$S=2\pi\,(N_1^{1/2}+\underline{N}_1^{1/2})(N_2^{1/2}+\underline{N}_2^{1/2})(N_3^{1/2}+\underline{N}_3^{1/2})$$

Horowitz, Maldacena, Strominger

Mass gap = $1/N_1N_2N_3$

Larger BH → lower mass-gap → larger size

Essentially same result as boson star whose scalar mass decreases with increasing BH size !

Easy (relatively…)	**Hard**
Supersymmetric	Non-supersymmetric
Extremal	Non-extremal
Classical	Quantum
Stationary	Time-dependent

Universal features:

Yuge™ amount of new degrees of freedom @ horizon

Two new scales: size of bubbles

distance from the horizon - E_{GAP}

Horizon viscosity

Microstate mountains

Distortion of Love numbers / Kerr multipoles

Horizon viscosity

Lots of low-mass-gap degrees of freedom: $e^{10^{90}}$
(entropy of BH @ center of galaxy = 10^90)

- can cause dissipative effects (like for electron moving parallel to a conducting plate)

- any distortion of structure@horizon immediately dissipated by these degrees of freedom

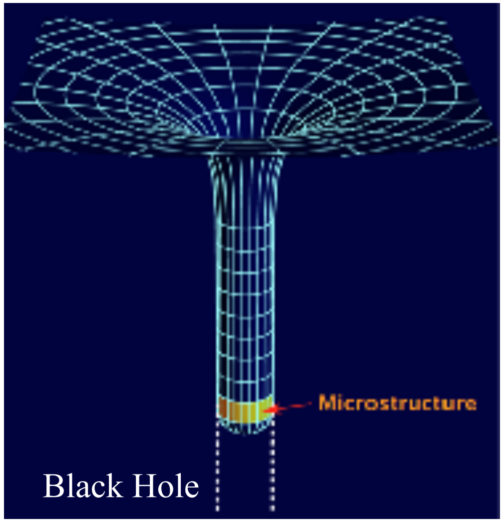
- hard to get any reflection - unless one can convince these degrees of freedom not to get excited

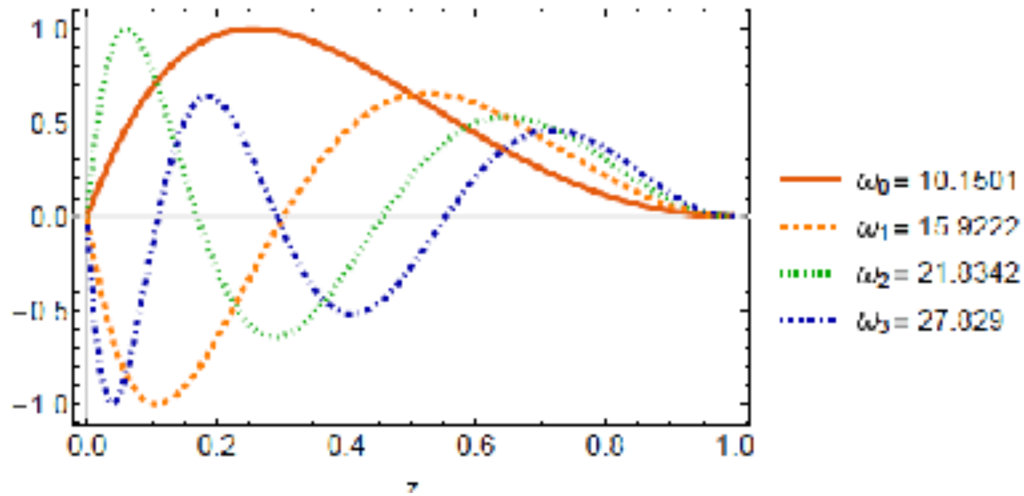
😈 Already taken into account by **perfectly-absorbing boundary conditions** of GR BH ?

Why do people get reflection / echoes ?

Ashfordi & friends

Solve wave equation in one particular microstate geometry





Beautiful gapped spectrum.
Infalling wave reflected ➙ echoes

Ignoring huge number of low-energy excitations that move this geometry to the other geometries

Microstate mountains

- microstate geometries break spherical symmetry
  - similar to molecules breaking translational symmetry of fluid approx.
  - visible at the scale of the **mean free path** (shot noise)
- analogous to mountains on neutron stars
  - create jitters on infalling stuff

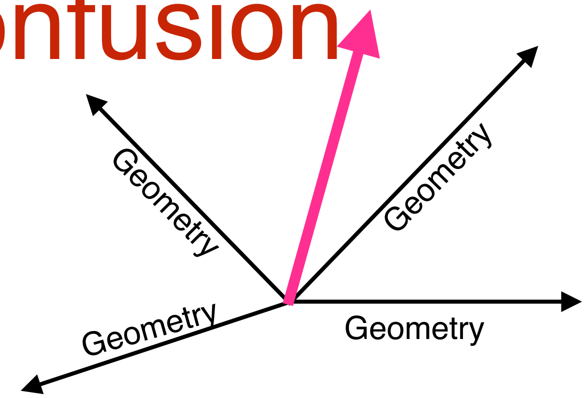
Questions:

- What is the scale where spherical symmetry is broken ? (width of microstate mountains ?)
- By how much ? (height of mountains ?)
- Can people who do signals from neutron stars implement them in their calculations ?

😈 Typical microstates may be **very spherical** ?

Planck-size bumps ?

Quantum - Classical confusion



- Quantum Tunneling important
- Hilbert space dimension = $e^{10\wedge 90}$
- Microstate geometries = coherent states
  - basis for Hilbert space (overcomplete) Glauber ‘63
- Typical state in Hilbert space will be quantum superposition of geometries → expectation values ~ $e^{-S/2}$???
- Decoherence → one will get result from typical microstate Don Page, private communication

Multipole moments

- spinning ball of dust, liquid, solid shell, boson star
- Kerr BH with vacuum at horizon
- spinning STRUCTURE@horizon scale

Gravity waves from EMRI with non-aligned spins:
Need 3 moments to rule out Kerr BH, 4 to rule out spinning boson star
(Ryan '95)

What we **need**: Kerr microstate geometries

What we **have**: NHEK microstates (Heidmann '18)

Next steps: Glue NHEK to Kerr
go non-extremal

Multipole moments

Love numbers : response to tidal stress

zero for BH Damour, Nagar '09

finite for other objects

log dependence on scale above horizon

Cardoso, Franzin, Maselli, Pani, Raposo '17

Computable once we have Kerr microstates

😈 Fuzzball complementarity: unusual matter forming STRUCTURE @ horizon gives "classical horizon experience" to infalling observer. **Same as vacuum.**

Mathur, Turton

What if String Theory does not describe real world ?

- *Tant pis pour le monde réel* 😞
- More seriously: structure@horizon must be there in any QG theory
- Must have **unusual** properties:
  - lighter-mass effective fields for increasing BH size
  - non-perturbative degrees of freedom
  - nontrivial 4D matter to stay@horizon (no Pixie dust)
  - huge entropy: quantum tunneling
- “top-down predictions” ignoring this physics = b.s.
- Universal features - like low QGP viscosity predicted by AdS-CFT, measured at RHIC

What would help

- Solve second-order PDE’s with >10 functions of 2 variables
  - (rod structure → pentagon and more)
  - other spectral methods
- Essential for constructing systematically non-extremal BH microstates
- Signals for microstate mountains (same code as for neutron stars)
- Extra d.o.f. modify viscosity - can one take that into account ?