INFORMATION LOST & FOUND

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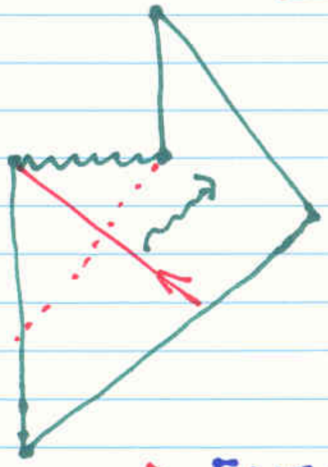
INFORMATION LOST?



- A PURE QUANTUM STATE CAN COLLAPSE SEMICLASSICALLY TO MAKE A BLACK HOLE
- HOW CAN THE ASYMPTOTIC OBSERVER TELL WHAT THE STATE OF THE BLACK HOLE IS?

⟹ EVEN GIVEN MANY POSSIBLE INTERNAL STATES, INFORMATION IS LOST IF ASYMPTOTIC OBSERVER CAN'T MEASURE THEM

2 PICTURES OF A BLACK HOLE

HORIZON SURROUDING AN INACCESSIBLE INTERNAL SPACE

VS.

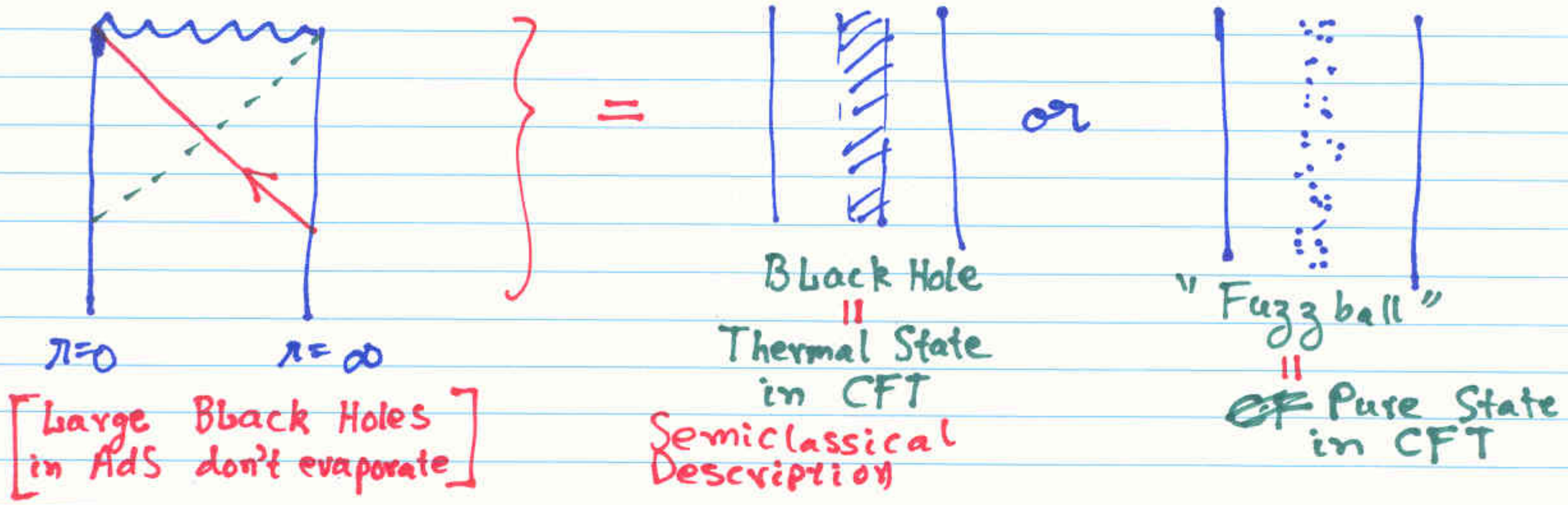
PURE STATE WITHOUT A HORIZON — COMPLICATED "FUZZBALL" (Mathur, Lunin....)

- IS THE SEMI-CLASSICAL PICTURE OF A HORIZON SIMPLY WRONG
- OR ARE THE TWO PICTURES EFFECTIVELY THE SAME FOR ALMOST ALL EXPERIMENTS?

INFORMATION FOUND?

PROPOSAL: BLACK HOLES ARE PURE STATES, POSSIBLY "FUZZBALLS" WITHOUT HORIZONS, BUT ALMOST NO PROBES CAN IDENTIFY THE STATE.

AdS/CFT FORMULATION



- WE'LL ARGUE THAT THE TYPICAL PURE STATE IN THE CFT IN THE BLACK HOLE RANGE OF PARAMETERS IS VERY DIFFICULT TO DISTINGUISH FROM THE THERMAL ENSEMBLE ⇒ SEMICLASSICAL DESCRIPTION IS ALMOST ALWAYS ADEQUATE
- ALSO, SHOW HOW THE STATE IS DETECTED ⇒ HOW INFORMATION IS RECOVERED

BLACK HOLES IN AdS_5 (SCHWARZSCHILD)

$$ds^2 = -\left(1+\frac{r^2}{\ell^2}-\frac{r_0^2}{r^2}\right)dt^2 + (\quad)^{-1}dr^2 + r^2 d\Omega^2$$

$+\ S^5$ ← RADIUS ℓ

HORIZON: $r_h = \frac{\ell}{2}\sqrt{-1+\sqrt{1+\frac{4r_0^2}{\ell^2}}}$

MASS: $M \sim \frac{r_0^2}{G_5}$ $\qquad G_5 \sim \frac{G_{10}}{\ell^5} \sim \frac{g_s^2 \ell_s^8}{\ell^5}$

- RECALL THE DICTIONARY RELATING $AdS_5 \times S^5$ AND THE DUAL CFT

$\ell^4 \sim g_s \ell_s^4 N$ ($SU(N)$) ; $M\ell = \Delta$ (CONFORMAL DIMENSION)

$g_{YM}^2 \sim g_s$; $g_s N \sim \lambda =$ 't Hooft Coupling

- LARGE BLACK HOLES

$$r_h \sim \ell \implies r_0 \sim \ell$$

[$r_0 \ll \ell \Rightarrow r_h \sim r_0 \ll \ell$ ← SMALL BLACK HOLES ARE UNSTABLE]

FOR LARGE BLACK HOLES THE MASS TRANSLATES AS:

$$\Delta = M\ell \sim \frac{\ell^3}{G_5} \sim \frac{\ell^8}{g_s^2 \ell_s^8} \sim \frac{g_s^2 \ell_s^8 N^2}{g_s^2 \ell_s^8} \sim N^2$$

N.B. INDEPENDENT OF COUPLING

E!

SO IF THE BLACK HOLE IS (SHOULD BE) A PURE STATE

$$|\text{BLACK HOLE}\rangle = \mathcal{O}|0\rangle \; ; \quad \Delta(\mathcal{O}) \sim N^2$$

SOME SCALES FOR COMPARISON

- SUGRA STATES $\quad \Delta \sim \mathcal{O}(1) \quad \left(\Delta \sim \frac{d}{2} + \frac{\sqrt{d^2+4m^2}}{2}\right)$
- SMALL STRING $\quad E \sim 1/\ell_s \Rightarrow \Delta \sim \frac{\ell}{\ell_s} \sim (g_s N)^{1/4} \sim \lambda^{1/4}$
- SMALL BLACK HOLE [UNSTABLE TO LOCALIZATION ON S^5] $\quad M \sim \frac{\ell^5 r_0^2}{g_s^2 \ell_s^8} \Rightarrow \Delta \sim \frac{r_0^2 N^2}{\sqrt{\lambda}\, \ell_s^4}$
- GIANT GRAVITONS (det X) $\quad \Delta \sim N$
- ~~[illegible]~~

SO THESE ARE VERY HEAVY STATES, CONTAINING AS MUCH MASS AS N GIANT GRAVITONS.

- WHAT IS THE ENTROPY?

$$S \sim \frac{r_h^3}{G_5} \sim \frac{\ell^3}{G_5} \sim \frac{\ell^8}{G_{10}} \sim N^2 \sim \Delta$$

SO IF THE BLACK HOLE IS A PURE STATE, THERE SHOULD BE e^{N^2} ~~STAT~~ OPERATORS WITH THE SAME CHARGES.

WHAT DO THESE OPERATORS LOOK LIKE?

- THE FIELDS OF $\mathcal{N}=4$ SYM ARE:

$$A_\mu, \quad X, Y, Z, \quad \psi \ldots$$

GAUGE FIELDS — 3 COMPLEX ADJOINT SCALARS — FERMIONS

- A BASIS OF GAUGE INVARIANT OPERATORS IS; THE SET OF LONG POLYNOMIALS IN X, Y, Z, $F_{\mu\nu}$, ψ, WITH LORENTZ ~~AND~~ INDICES CONTRACTED & TRACES WRAPPED AROUND TERMS. DERIVATIVES CAN ALSO BE ADDED.

$$\text{e.g. } \mathcal{O} = \mathrm{Tr}\, XXYYZ \; \mathrm{Tr}\, YYZYZX \; \mathrm{Tr}\, XX \; \mathrm{Tr} \cdots$$

- SCHWARZSCHILD IS NOT BPS. THUS $\mathrm{Tr}(X\bar{X})$ ETC. ARE INCLUDED

- SINCE SUSY IS BROKEN, CONFORMAL DIMENSION WILL BE RENORMALIZED

  THUS, TO GET $\Delta = N^2$, THE CLASSICAL DIMENSION NEED NOT BE N^2

- TO GET ORIENTED LET'S LOOK AT THE CLASSICAL DIMENSION. ⇒ WORK FOR NOW IN FREE FIELD THEORY

  Then we want $\Delta = N^2$ and we fix the charges of the operator to match the spacetime charges of the black hole

NOTE: OPERATORS OF SUCH HIGH DIMENSION MIX STRONGLY EVEN IN THE FREE THEORY. WE ARE NOT SEEKING AN ORTHONORMAL BASIS

- THERE ARE LOTS OF OPERATORS LIKE THIS

e.g. JUST CONSIDER $\mathcal{O} = \sum_i (\mathrm{Tr}\, X)^{n_1}\, \mathrm{Tr}(X^2)^{n_2} \ldots$

(I SHOULD ONLY HAVE EVEN POWERS FOR SU(N))

n_i = # OF TERMS $\mathrm{Tr}\, X^i$

$\Rightarrow \sum_{i=1}^{\Delta} n_i i = \Delta$

$\Rightarrow$ FOR LARGE DELTA, # OF OPS. IS $\sim e^{\sqrt{\frac{\Delta}{6}}}$

- NOTE: $\Delta = N^2$ & $S = N^2$ FOR BLACK HOLES

$\Longrightarrow$ NEED e^{N^2} OPS.

ALSO THEY MUST HAVE THE RIGHT GLOBAL CHARGES, e.g. EQUAL NUMBERS OF X & $\bar{X}$

- IT'S DIFFICULT TO GET SO MANY STATES

e.g. USING LETTERS $X_1 \cdots X_k$ AND TRACES.

$(\quad * \quad \uparrow_{\mathrm{Tr}} X_1 X_1 \quad X_5 \uparrow_{\mathrm{Tr}} X_3 \quad X_1 \uparrow_{\mathrm{Tr}} X_4 X_4 X_4 \quad \ldots$

OF OPS. $\leq k^{\Delta} \sum_{i=1}^{\Delta} \Delta^i \leq k^{\Delta}\, \Delta\, \Delta^{\Delta}$

$\Rightarrow$ # OF OPS $\ll e^{\Delta \ln \Delta}$

WHERE ARE ALL THE OPERATORS?

$\hookrightarrow$ CAN INCLUDE UP TO Δ DERIVATIVES ~~OPER.~~

- THE RENORM. OF CONFORMAL DIMENSION MUST BE INCLUDED.

- REGARDLESS, OF THE ~~ANOM~~ CORRECTIONS TO DIMENSION, IT IS REASONABLE TO ASSUME THAT THE BLACK HOLE IS DESCRIBED BY LONG OPERATORS

- ~~SO IGNORING RENORM, MIXING FOR NOW, AND ALSO FORGETTING ABOU~~

- IGNORE RENORM., MIXING.
  FOR SIMPLICITY NEGLECT DERIVATIVES AND CONSIDER A SINGLE TRACE

$$\mathcal{O} \sim \mathrm{Tr}[\, X X \, Y \, \bar{Y} \, Z Z \, \bar{X} \cdots \,]$$

$\sim$ LONG POLYNOMIAL

(Traces & Derivs can be sprinkled in freely)

CLAIM: CONSIDER A PROBE OPERATOR $\mathcal{O}_p$ AND ITS CORRELATION FUNCTIONS IN $|\mathcal{O}\rangle = \mathcal{O}_p|0\rangle$

→ $\langle \mathcal{O}| \, \mathcal{O}_p \cdots \mathcal{O}_p \, |\mathcal{O}\rangle$ DEPENDS ONLY ON Δ AND THE GLOBAL CHARGES OF $(\mathcal{O}, \mathcal{O}_p)$, UP TO TINY (EXPONENTIAL?) CORRECTIONS, FOR ALMOST ALL $\mathcal{O}_p$.

WHY IS THIS CLAIM PLAUSIBLE?

$$\langle 0 | \underbrace{Tr(XYZXXYYX)^{+}}_{\mathcal{O}^{+}} \overbrace{Tr(XX)^{+}}^{\mathcal{O}_P^{+}} \overbrace{Tr(XX)}^{\mathcal{O}_P} \underbrace{Tr(XYZXXYYX)}_{\mathcal{O}} | 0 \rangle$$

- IN FREE FIELD THEORY WICK CONTRACTIONS ARE DOMINATED BY "PATTERN MATCHING"
  - (a) LEADING TERMS = OCCURRENCES OF PROBE $\mathcal{O}_P$ WITHIN LONG OPERATOR $\mathcal{O}$
  - (b) SPLITTING LETTERS OF PROBE WHILE DOING CONTRACTIONS $\Rightarrow$ $1/N$ SUPPRESSIONS

- THE LEADING PIECES IN THIS CORRELATOR WILL BE UNIVERSAL BECAUSE THE TYPICAL LONG OPERATOR IS A RANDOM STRING.

$\Downarrow$

- ~~OPER~~ ORDERED OPS. LIKE $Tr(XXXXX)$ ARE RARE
- ALMOST ALL OPS. ~~HAVE~~ ARE STATISTICALLY RANDOM SEQUENCES OF LETTERS

(Theorem ~~informat~~ from Information Theory about "typical sets" of long ~~letter~~ messages built from a finite alphabet.)

$\Longrightarrow$ UP TO CORRECTIONS THAT ARE (EXPONENTIALLY?) SMALL IN LENGTH OF $\mathcal{O}$

$$\langle \mathcal{O} | \mathcal{O}_P^{+} \mathcal{O}_P | \mathcal{O} \rangle$$

WILL BE UNIVERSAL

$\downarrow$ STATISTICAL DEVIATIONS FROM TYPICALITY ARE EXPONENTIALLY SUPPRESSED.

WHAT SORTS OF PROBES CAN DETECT THE BLACK HOLE STATE?

- RECALL $\Delta(\text{BLACK HOLE}) \sim N^2$
- SEMICLASSICAL SUPERGRAVITY PROBES $(\Delta \sim \mathcal{O}(1))$ WILL BE TOTALLY INEFFECTIVE
- STRINGY PROBES $(\Delta \sim (g_s N)^{1/4})$ WILL BE PRETTY USELESS ALSO
- BRANE PROBES $(\Delta \sim N)$ WILL BE BETTER, BUT AT LARGE N, NOT PARTICULARLY SO
- BASICALLY, TO DETECT THE STATE ONE NEEDS $\Delta \sim N^2 \Rightarrow$ ANOTHER BLACK HOLE
  - ↳ IF THE PROBE $\mathcal{O}_p \approx \mathcal{O}(\text{BLACK HOLE})$ IN SOME SUITABLE SENSE, ONE WILL GET A LARGE RESPONSE.
  - OTHERWISE THE RESPONSE WILL BE SMALL & UNIVERSAL

ALMOST ALL PROBES GIVE NO INFORMATION

- GIVEN A BLACK HOLE $\mathcal{O}$ & ITS CHARGES, THE EXTERNAL OBSERVER HAS TO GUESS A PROBE $\mathcal{O}_p$

BUT: FOR MOST $\mathcal{O}$, $\mathcal{O}_p$ GIVES A UNIVERSAL ANSWER

$\Rightarrow$ TO IDENTIFY $\mathcal{O}$, NEED $e^S \sim e^{N^2}$ PROBES.

IT EASIER TO SAY WHAT $\mathcal{O}$ ISN'T, RATHER THAN WHAT $\mathcal{O}$ IS

WHAT IS AN ASKABLE QUESTION?

STATISTICAL QUESTIONS LIKE "HOW MANY PROBES DO YOU NEED, AND HOW SHOULD THEY BE ~~STATISTIC~~ STATISTICALLY DESIGNED TO SEPARATE THE BLACK HOLES OF MASS M INTO k CLASSES"

WHY IS ALL THIS DIFFERENT FROM THE STORY FOR A THERMAL GAS?

↳ IT ISN'T!

BOLTZMANN WOULD APPROVE.

- SO WHAT MAKES A BLACK HOLE DIFFERENT FROM A NEUTRON STAR?

↳ - FOR BOTH CASES INFORMATION RECOVERY & STATE IDENTIFICATION IS HARD

- AT LEAST WITHIN THE CFT SIDE OF AdS/CFT THIS IS NOT THE SIGNATURE OF A BLACK HOLE

- N.B. $G_N \uparrow \Longrightarrow$ NEUTRON STAR CAN COLLAPSE TO A BLACK HOLE

PHASE TRANSITION? ~~SYM~~ SU(N) SYM HAS PHASE TRANSITIONS AS A FUNCTION OF COUPLING

→ THE KEY ISSUE MAY SIMPLY BE GETTING e^{Δ} STATES OF DIM. Δ

INFORMATION REGAINED?

- WHAT IS THE BEST PLACE TO WORK OUT ALL DETAILS?
- $\frac{1}{2}$BPS BLACK HOLES OF FINITE AREA WOULD BE BEST FOR CONTROL OVER RENORMALIZATION ISSUES IN THE CFT
  - (a) ANY IN AdS_5?
  - (b) BTZ BLACK HOLES & D1-D5 CFT
- FOLLOWING RECENT WORKS ~~OF~~ ON EXACT SOLUTIONS FOR $\frac{1}{2}$ BPS STATES, IS DETECTING THE STATE EQUIVALENT TO MEASURING ALL MULTIPOLE MOMENTS?