WHAT DOES AdS/CFT

TEACH US ABOUT

THE WAVEFUNCTION OF

THE UNIVERSE?

JUAN MALDACENA

- QUANTUM THEORY OF GRAVITY
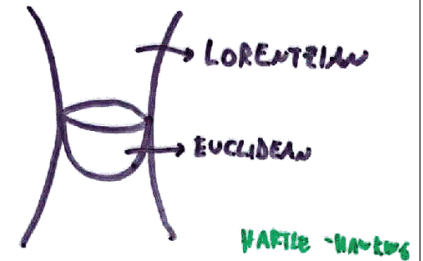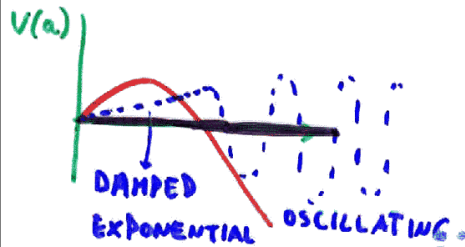
  WAVEFUNCTION $\longrightarrow$ GEOMETRIES

- SIMPLEST IDEA:

$$\Psi[\, g^{(3)}\,]$$

  $\hookrightarrow$ 3-geometries

- MINISUPERSPACE

$$ds_3^2 = a^2 \, ds_{\hat{3}}^2 \qquad \rightarrow \Psi[a]$$

e.g. $\hat{3} \rightarrow S^3$, $\Lambda > 0$ PURE GRAVITY

$V(a)$

DAMPED EXPONENTIAL   OSCILLATING

LORENTZIAN

EUCLIDEAN

HARTLE-HAWKING

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OBSERVATIONS

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- GIVEN BOUNDARY COND. → CFT → DETERMINED
  ⇒ UNIQUE ANSWER FOR ITS PARTITION FUNCTION

- IF A NON SINGULAR EUCLIDEAN GEOMETRY
  EXISTS → GIVES THE "RIGHT" ANSWER
  (SUM OVER ALL POSSIBLE GEOMETRIES)

- CFT IS THE NON PERTURBATIVE WAY
  TO DEFINE THE WAVEFUNCTION
  _ BUT IT ONLY GIVES US A SPECIAL LIMIT

- THE INTERIOR GEOMETRY CAN BE SINGULAR
  IF STRING THEORY ALLOWS SUCH SINGULARI-
  TIES.

→ IF WE FIND A UNIQUE WAVE FUNCTION IN THE
  EUCLIDEAN REGION ——→ SUGGESTS A UNIQUE
  WAVE FUNCTION IN THE LORENTZIAN REGIONS.

QUESTIONS

- HOW DO WE DEFINE PERTURBATION THEORY?

- NORM?

- HOW DO WE PICK A SOLUTION OF
  THE WHEELER de WIT EQUATION?
  ↓

  HARTLE-HAWKING → USE EUCLIDEAN SOLUTIONS WITH
         NO BOUNDARY

  TO DETERMINE THE WAVE FUNCTION
  IN THE FORBIDDEN REGIONS
  ↕
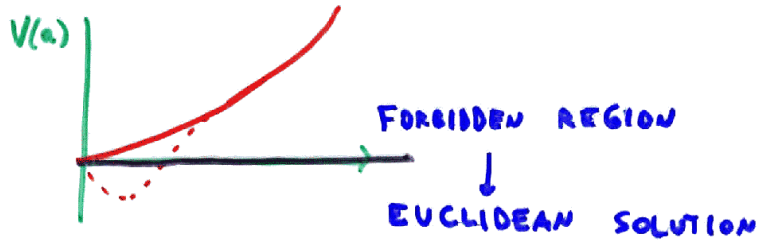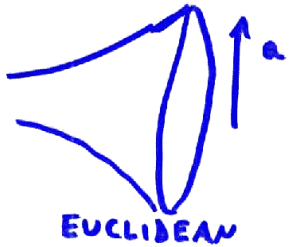 & THIS SHOULD DETERMINE IT IN
    THE LORENTZIAN REGIONS

  → THERE IS A UNIQUE WAVE FUNCTION.

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· CONSIDER $\Lambda < 0$ — COMPACT SPATIAL SECTIONS

$V(a)$

FORBIDDEN REGION

$\downarrow$

EUCLIDEAN SOLUTION

LARGE a :

a

EUCLIDEAN

$$\Psi = e^{a^3 \sqrt{g} + \ldots} \times A(a, \hat{g})$$

EUCL. AdS/CFT

$$\lim_{a \to \infty} A(a, \hat{g}) = Z[\hat{g}] = \text{PARTITION FUNCTION OF A CFT.}$$

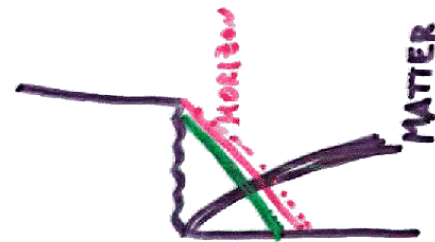CFT: DEPENDS ON ASYMPTOTIC B.C. → SAME ARGUMENTS AS Ψ

· INTERIOR OF EVAPORATING BLACK HOLES

w/ G. HOROWITZ.

HAWKING RADIATION

INTERIOR $\approx$ COMPACT SPATIAL SECTIONS

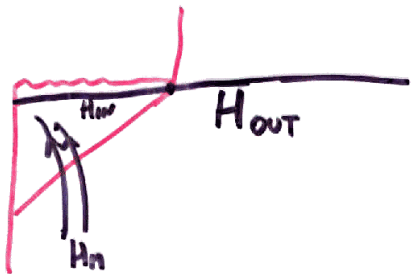$\downarrow$

UNIQUE WAVE FUNCTION

HORIZON

MATTER

· SIMPLE WAY OF SOLVING THE INFORMATION PUZZLE

STANDARD DESCRIPTION

$$|\Psi_m\rangle \otimes |U\rangle$$

$\underset{\text{UNRUH}}{\downarrow} \rightarrow |U\rangle = \sum_i |i\rangle_{IN} \otimes |i\rangle_{OUT}$

$\underset{\text{ENTANGLED}}{}$

INTERIOR OF BH:

$$H_{INTERIOR} = H_M \otimes H_{IN}$$

• TRACE ↗

⟹ THERMAL DENSITY MATRIX IN H_{OUT}

• INTERIOR → UNIQUE STATE

$$|BH\rangle = S_{m\,i}\, |m\rangle_M \otimes |i\rangle_{IN}$$
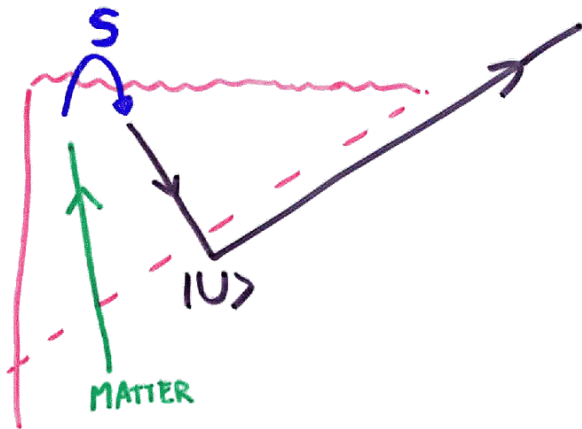
$$S = . \text{UNITARY MATRIX}$$

• RANDOM & COMPLICATED IN THE
   USUAL FOCK SPACE BASIS FOR H_M & H_W
   • SHOULD BE DETERMINED BY QUANTUM GRAVITY

• Q.M. WITH FINAL STATE BOUNDARY

CONDITIONS WAS STUDIED IN THE PAST HARTLE

• THIS IS <u>NOT</u> STANDARD Q.M.

$$|\Psi_M\rangle \otimes |U\rangle \rightarrow \langle BH| \, \downarrow \Psi_m\rangle \otimes |U\rangle =$$

$$= S^*_{m\,i}\, \Psi^n_- \, |i\rangle_{OUT}$$
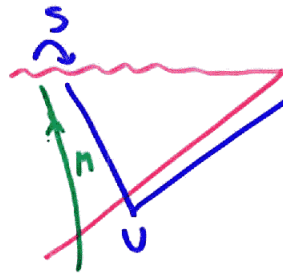
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8.5

S

$|U\rangle$

MATTER

· NOTHING WEIRD HAPPENING AT THE HORIZON

· ALL WEIRDNESS → AT THE SINGULARITY

COMPLEMENTARITY

S

m

U

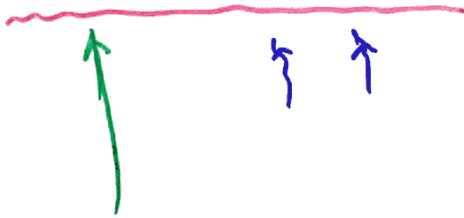$|\Psi_m\rangle \longrightarrow U S |\Psi_m\rangle$

P_{OUT}

P_M

$P_{OUT} U S P_M |\Psi_m\rangle$

↑

SINCE S IS COMPLICATED

$\Rightarrow P^i_{OUT}$ & P^j_M → DO NOT DECOHERE

↓

CANNOT BE MEASURED

SIMULTANEOUSLY

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• ARROW OF TIME

INFALLING EXPERIMENTALIST HAS ACCESS TO

A SMALL NUMBER OF DEGREES OF

FREEDOM

$$N_{dof} \ll e^S \sim \dim(H_{IN}) \sim \dim(H_{OUT})$$

⇒ WILL NOT MEASURE THE WHOLE STATE $|BH\rangle$

→ AVERAGE OVER LARGE PART OF H_{IN}

⇒ FINAL STATE ≈ DENSITY MATRIX

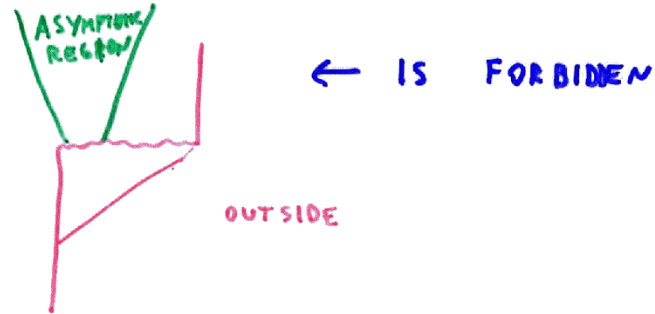↓ S RANDOM

↓

IDENTITY IN THE EXPERIMENTALIST'S

SUBSPACE

⇒ FORWARD ARROW OF TIME

• OBSERVATION
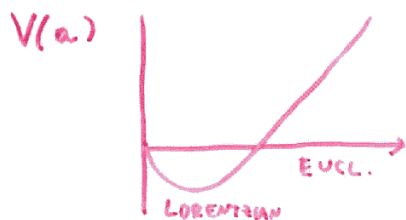
ASYMPTOTIC REGION

← IS FORBIDDEN

OUTSIDE

MORE PRECISELY: ANY INFORMATION TRANSFER

FROM THE OUTSIDE TO THE SECOND

ASYMPTOTIC REGION IS FORBIDDEN

⇒ WE COULD JUST AS WELL THINK

ABOUT THE CREATION OF THE ASYMPTOTIC
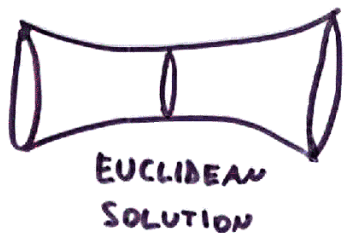
REGION FROM NOTHING...

PRE BIG-BANG

• EKPYROTIC / CYCLIC → SINGULARITIES SIMILAR TO

THE SINGULARITIES OF SOME BLACK HOLES

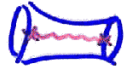IN AdS_3 ⤳ SUGGEST NO INFORMATION TRANSFER.

WORMHOLES IN EADS   W/ LIAT MAOZ

$V(a)$

$\Lambda < 0$

$ds^2 = a^2 ds_3^2 + da^2$

EUCL.

LORENTZIAN

EUCLIDEAN SOLUTION

LORENTZIAN SOLUTION

. THESE GEOMETRIES ARE PUZZLING FROM THE POINT OF VIEW OF AdS/CFT.

  . 2 SIDES SEEM CORRELATED FROM THE GRAVITY POINT OF VIEW

. FIELD THEORY DEPENDS ONLY ON BOUNDARY CONDITIONS → SHOULD NOT BE CORRELATED

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WITTEN-YAU NO GO:

a) IF BOUNDARIES HAVE POSITIVE CURVATURE

b) PURE GRAVITY IN THE BULK.

⇒ NO EUCLIDEAN GEOMETRIES WITH MULTIPLE BOUNDARIES

. HOW DO WE GO AROUND THIS?

a) $ds^2 = d\rho^2 + \cosh^2\rho \; dS^2_{H^d/\Gamma}$

$\underbrace{\qquad}_{COMPACT.}$

. NEGATIVE CURVATURE & CONFORMAL COUPLING :

$$\int (\partial\phi)^2 + R\phi^2$$

⇒ UNBOUNDED ACTION

. NOT IN AdS_3 — 2d CFT → CAN EXIST ON ANY RIEMANN SURFACE.

($AdS_3 \times S_3 \times K3$, $(Q_1, , Q_5)$ COPRIME , GENERIC POINT IN MODULI SPACE)

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- · SECTIONS → S^n

→ ADD GAUGE FIELDS

SU(2) GAUGE FIELDS

① MERON : $A_m^a = \frac{1}{2} w_m^a$

S^3

S^3

→ EMBEDDED IN ≃ AdS$_4$ × S$_4$

② INSTANTON   (& ANTI-INSTANTON ...)

S^4

ENBED IN AdS$_5$ × S$_5$

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SOME FEATURES

1- ASYMPTOTICALLY → WELL DEFINED
              ↘ WELL DEFINED CFT.

2- TYPICALLY → PERTURBATIVE NEGATIVE
         MODES
         ↝ SADDLES ?

3- IN SOME CASES → WE HAVE NO PERTURBATIVE
              INSTABILITIES

→ UNSTABLE UNDER CREATION OF BRANES

4- WE DID NOT FIND ANY SUSY EXAMPLE
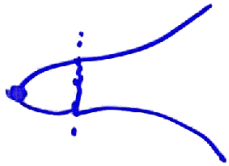
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IS

- POSSIBLE INTERPRETATION:

  - TRUST FIELD THEORY INTUITION
    → DECOUPLED

  → NO INFORMATION TRANSFER

  ≈ UNIQUE WAVE FUNCTION FOR LORENTZIAN
    GEOMETRY

- BETTER UNDERSTANDING OF THESE GEOMETRIES
MIGHT LEAD TO A METHOD FOR COMPUTING
THE WAVEFUNCTIONS OF CLOSED UNIVERSES

CONCLUSIONS

- WE SAW HOW THE IDEA OF UNIQUENESS
FOR THE WAVEFUNCTION OF THE UNIVERE
FITS WELL WITH VARIOUS PROPERTIES
OF QUANTUM GRAVITY THAT WE EXPECT IN
STRING THEORY.

1 _ BLACK HOLES   → NO UNITARITY PROBLEM

2 _ WORM HOLES   → NO "NON LOCAL" CORRELATIONS
↑
DESERVES BETTER STUDY...

- SINGLE WAVE FUNCTION ⇏ SINGLE MACROSCOPIC
                                STATE

- WHAT IS THE RIGHT LANGUAGE TO
DESCRIBE ψ ? CAN IT BE DEFINED IN A
MATHEMATICALLY PRECISE WAY FOR $a \neq \infty$?