

IS SPACETIME AN  
EMERGENT PHENOMENON?

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## PUZZLE: EMPTY SPACE CAN ACT LIKE A THERMAL BODY

- ASSOCIATED TO EXISTENCE OF SPACETIME SINGULARITIES
- SOURCE OF "INFORMATION LOSS" PROBLEM

SUGGESTS: Spacetime is a coarse-grained effective description of a complex underlying structure

## TODAY

- ① REVIEW OF SEMICLASSICAL EVIDENCE
- ② EVIDENCE FOR COMPLEX MICROSTATES
- ③ MICROSTATE DETECTABILITY
- ④ WHAT DO MICROSTATES LOOK LIKE?

# BLACK HOLES

## BLACK HOLES

$$\Delta M = \kappa \Delta A + \dots$$

$$\Delta A \geq 0$$

$\kappa = \text{CONST ON HORIZON}$

( $\kappa = \text{surface gravity}$ )

## THERMODYNAMICS

$$\Delta E = T \Delta S + \dots$$

$$\Delta S \geq 0$$

$T = \text{CONST. IN EQUILIBRIUM}$

- BLACK HOLE RADIATION



$$T = \kappa \quad (\text{Thermal})$$

⇒ BLACK HOLES ACT LIKE BLACK BODIES

- BUT BLACK HOLES ARISE AS SOLUTIONS TO THE VACUUM EQUATIONS OF MOTION

∴ THERMO → STAT. MECH?

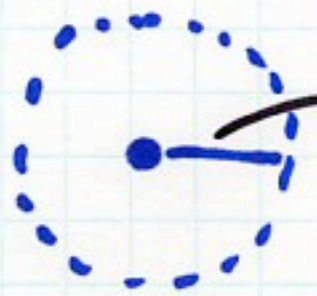
Is empty, ~~space~~ curved space the universal effective description of  $e^S$  complex microstates?

# ACCELERATING UNIVERSES

- EMPTY,  $\Lambda > 0$ :  $S = \frac{1}{16\pi G} \int d^{d+1}x (R + \ell^2)$
- VACUUM SOLUTION = de Sitter SPACE
  - Ⓐ INFLATION ( $ds^2 = -dt^2 + e^{2t/\ell} d\vec{x}^2$ )
  - Ⓑ OUR FATE IF DARK ENERGY EXISTS

• THE INERTIAL OBSERVER SEES THE PATCH

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



$r = \ell =$  COSMOLOGICAL HORIZON

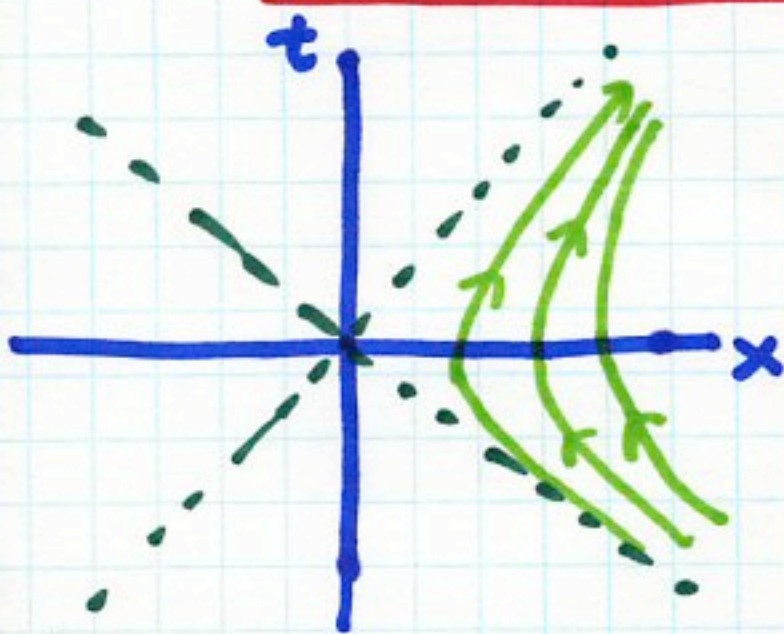
$$S \sim \ell^{d-1}$$

$$T = \frac{1}{2\pi\ell}$$

} ENTROPY & TEMP SEEN BY INERTIAL OBSERVERS

WHAT DOES THIS MEAN?  
HOW CAN EMPTY ACCELERATING UNIVERSES HAVE AN ENTROPY?

# ACCELERATED OBSERVERS IN FLAT SPACE



FAMILY OF ACC. OBSERVERS  
SEES A HORIZON OBEYING  
LAWS OF HORIZON MECHANICS  
+ UNRUH RADIATION

● ASSUME EINSTEIN'S EQNS. OF MOTION  $\Rightarrow$  THERMO. IN ACCELERATED FRAMES (EQNS. OF STATE)

## JACOBSON'S ARGUMENT

ASSUME ACCELERATED OBSERVERS SEE HORIZON THERMODYNAMICS

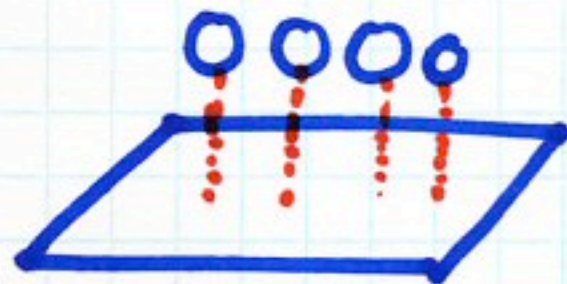
(  $\nearrow$   $SM = \kappa SA$  ;  $SA \geq 0 \dots$  )

$\searrow$  EINSTEIN'S EQUATIONS OF MOTION



# THE NOTHING STATE

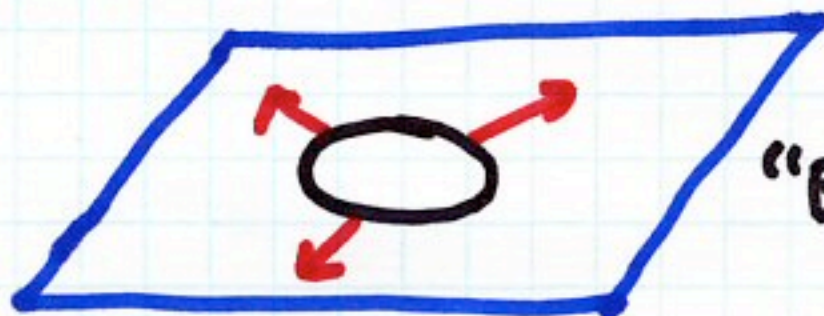
- KALUZA-KLEIN COMPACTIFICATION OF FLAT SPACE ON A CIRCLE  
 $R^{3,1} \times S^1$



- THIS SPACE CAN DECAY BY TUNNELING TO  
★ "NOTHING"



EVOLVE →



EXPANDING  
"BUBBLE OF  
NOTHING"



FLAT SPACE IS NOT THE GROUND STATE OF GRAVITY WHEN THERE ARE EXTRA DIMS. (AND SUSY IS BROKEN)

## 3d GRAVITY

$$S \sim \frac{1}{16\pi G} \int d^3x (R + \Lambda) \quad \text{NO GRAVITON IN 3d}$$

DEFINE:

- $\{e_\mu^i\}$  = "Vielbein";  $e_\mu^i e_\nu^j \eta_{ij} = g_{\mu\nu}$
- $\omega_\mu^i =$  "Spin Connection"  
= Connection for transport of  $e_\mu^i$

LET:  $A_\pm \approx e \pm \omega$

$$\Rightarrow S = \frac{1}{16\pi G} \int \text{Tr} (A_+ dA_+ + A \wedge A \wedge A) + \int (A_+ \rightarrow A_-)$$

CHERN-SIMONS GAUGE THEORY  
( $\Lambda < 0 \Rightarrow SL(2, \mathbb{R}) \times SL(2, \mathbb{R})$ )

EOM:  $dF = 0$

GROUND STATE IS  $A_\pm = 0$

$\Rightarrow$  "NOTHING" STATE

MACROSCOPIC SPACETIME  
ARISES AS SOME SORT OF  
COLLECTIVE PHENOMENON?

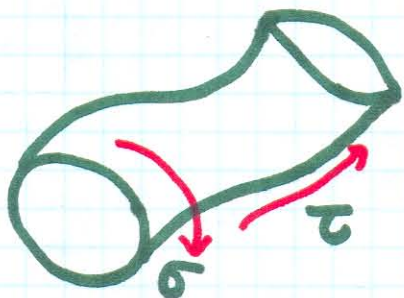


REQUIRES A QUANTUM  
THEORY OF GRAVITY.



# STRINGS: PERTURBATION THEORY

- A QUANTIZED STRING IS A RELATIVISTIC RUBBER BAND



$$Z = \int \mathcal{D}X^\mu(\sigma, \tau) e^{\frac{i}{\alpha'} \int \sqrt{-\det g_{\alpha\beta}} \partial_\alpha X^\mu \partial_\beta X^\nu g_{\mu\nu} \eta^{\alpha\beta}}$$
$$= \int \mathcal{D}X^\mu(\sigma, \tau) e^{\frac{i}{\alpha'} (\text{Area})}$$

$\Leftrightarrow$  2d FIELD THEORY OF  $X^\mu$

[ COMPARE FOR A PARTICLE :  $Z = \int \mathcal{D}X^\mu(\tau) e^{\frac{i}{\alpha'} (\text{Length})}$  ]

$\Leftrightarrow$  1d FIELD THEORY OF  $X^\mu$

- THE BACKGROUND SPACETIME IS GIVEN & EQUIPPED WITH A METRIC  $g_{\mu\nu}$
- THIS IS A PERTURBATIVE QUANTIZATION OF SMALL FLUCTUATIONS (STRINGY QUANTA) AROUND  $g_{\mu\nu}$

HOW DO EOMS FOR  $g_{\mu\nu}$  COME ABOUT?

# EOM FOR THE BACKGROUND SPACETIME

## EXAMPLE: SCALAR FIELD THEORY

$$S = \int d^4x \partial_\mu \phi \partial^\mu \phi + V(\phi) = \int \mathcal{L}$$

LET:  $\phi = \phi_B + \psi$

$$\Rightarrow S \approx S(\phi_B) + \int \frac{\delta \mathcal{L}}{\delta \phi} \Big|_{\phi_B} \psi + \frac{1}{2} \int \frac{\delta^2 \mathcal{L}}{\delta \phi^2} \psi^2 + \dots$$

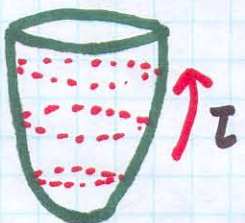
• IF  $\phi_B$  SOLVES EOMS:  $\frac{\delta \mathcal{L}}{\delta \phi} \Big|_{\phi_B} = 0$

$$\Rightarrow S = S(\phi_B) + \int \dots \psi^2 + \dots$$

$\Rightarrow$   $\phi_B$  SOLVES EOMS  $\iff \langle \psi \rangle_{\phi_B} = 0$   
NO TADPOLES (x---)  
 $\phi_B$  IS "MEAN BACKGROUND FIELD"

## STRING THEORY

$g_{\mu\nu}$  SOLVES EOMS  $\Rightarrow$  NO TADPOLES, i.e.; NO SPONTANEOUS EMISSION OF GRAVITONS

$\Rightarrow$   ~~WANTS~~ HAS VANISHING AMPLITUDE GIVEN  $g_{\mu\nu}$

$\Rightarrow$  2d FIELD THEORY ON STRING WORLD SHEET HAS  $\langle \theta \rangle = 0 \quad \forall \theta$

## PERTURBATIVE STRING THEORY

SMALL FLUCTUATIONS (STRINGS/  
GRAVITONS) AROUND A "MEAN  
FIELD" (SMOOTH SPACETIME)

## TO ADDRESS EMERGENCE

WHAT IS THE UNDERLYING  
QUANTUM MECHANICAL CONFIGURATION  
~~FOR WHICH IT~~ SPACE FOR WHICH  
THE SMOOTH SPACETIME IS A  
"MEAN FIELD" ?

# THE SETUP

- WHAT ARE THE COMPLEX MICROSTATES?  
WHY ARE THEY HARD TO DETECT?

- STEP 1: PUT BLACK HOLE IN A BOX  
⇒ EQUILIBRIUM WITH RADIATION

- COVARIANT WAY TO DO THIS:  $\Lambda < 0$

$$S = \frac{1}{16\pi G} \int d^{d+1}x \sqrt{g} (R - \Lambda)$$

- VACUUM = AdS SPACE

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



(GEOMETRY MAKES POT. BARRIER)

- BLACK HOLES

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

- LARGE ( $r_0 \gtrsim \ell$ ) AdS BLACK HOLES COME INTO EQUILIBRIUM WITH RADIATION

## KEY TOOL

STRING THEORY  
WITH  $\Lambda < 0$



A QUANTUM FIELD  
THEORY

# GRAVITY $\leftrightarrow$ GAUGE THEORY

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- STRING THEORY IN ASYMP. AdS SPACETIMES  $\leftrightarrow$  QUANTUM FIELD THEORY

## • EXAMPLE:

- STRING THEORY IN  $AdS_5 \times S^5$   $\leftrightarrow$   $SU(N)$  GAUGE THEORY WITH 16 SUPERCHARGES ON A CYLINDER  $S^3 \times \text{TIME}$

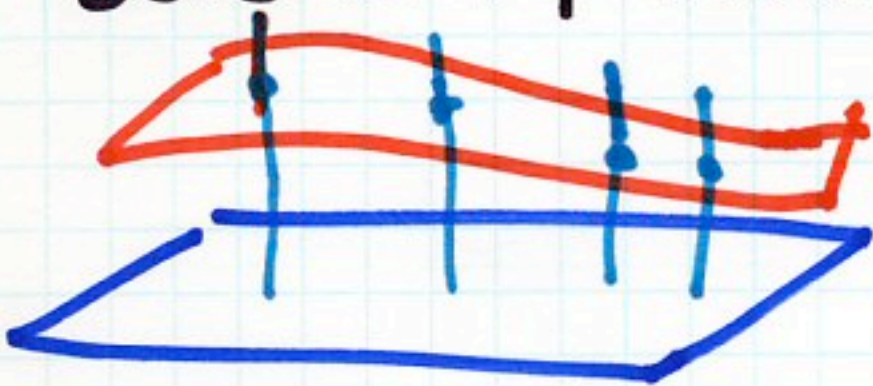
## THE DICTIONARY

- AdS SCALE  $l$
  - STRING COUPLING  $g_s$
  - STRING LENGTH  $l_s$
  - $G_5 \sim \frac{g_s^2 l_s^8}{l^5}$
  - SPACETIME ISOMETRIES
  - STATES IN GRAVITY WITH MASS  $M$
  - SEMICLASSICAL LIMIT
- $g_{\text{YM}}^2 = g_s$
- $N = \frac{1}{g_s} \left(\frac{l}{l_s}\right)^4$
- GLOBAL SYMMETRIES (Super-Conformal ...)
- STATES OF FIELD THEORY WITH  $E = M$
- $[\Delta = Ml = \text{CONF. DIM. OF OPERATOR}]$
- $\frac{l}{l_s} \gg 1, g_s \ll 1$
- $\Rightarrow N \gg 1$

## REMARK

- 3+1d FIELD THEORY  $\Leftrightarrow$  10d GRAVITY
- WHERE DO THE EXTRA 6 DIMS. & THE GRAVITON EMERGE FROM?
- COUPLINGS  $\Rightarrow$  BOUNDARY VALUES
- Renormalization Group Equations of QFT  $\Rightarrow$  E.O.M. OF GRAVITY

Scheme Dependence  $\Rightarrow$  Diffeomorphism Invariance



- TODAY WE'LL FOLLOW A DIFFERENT ROUTE — USE FIELD THEORY DUAL TO DIRECTLY EXAMINE SPACETIME MICROSTATES.

# BLACK HOLES & MICROSTATES

- $ds^2 = -\left[1 + \frac{r^2}{\ell^2} - \frac{r_0^2}{\ell^2}\right] dt^2 + [\dots]^{-1} dr^2 + r^2 d\Omega_3^2$
- $M \sim \frac{r_0^2}{G_5} \Rightarrow \Delta \sim M \ell \sim N^2$  IN DUAL
- $S \sim \frac{A}{G_5} \sim N^2 \Rightarrow e^{N^2}$  SUCH MICROSTATES
- |BH microstate  $\rangle = |\Theta\rangle$  ;  $\Delta(\Theta) \sim N^2$

SUGRA STATES:	$\Delta \sim \Theta(1)$
STRINGS:	$\Delta \sim (g_5 N)^{1/2}$
D-BRANES:	$\Delta \sim N$

• WHAT DO MICROSTATES OPERATORS LOOK LIKE?  
LONG, GAUGE-INVARIANT POLYNOMIALS IN  
THE FIELDS  $\{ A_\mu, \psi, X, Y, Z \}$   
GAUGE FIELD      FERMION      ADJOINT SCALARS.

e.g.  $\Theta = \text{Tr} [X X Y \bar{X} Z Z \bar{X} \dots]$  —  $O(N^2)$  LETTERS

Sprinkle Traces, Derivatives, Other Fields

- BUT?
  - (i) NO SUSY — RENORMALIZATION?
  - (ii) MIXING
  - (iii) TRACES SPLIT UP

**CLAIM:** LET  $|\theta\rangle = \theta|0\rangle$ ;  $\theta_p =$  ANY PROBE  
 THEN  $\langle \theta | \theta_p \dots \theta_p | \theta \rangle$  DEPENDS ONLY ON  
 $\Delta$  & GLOBAL CHARGES OF  $\theta$  &  $\theta_p$  UP TO  
 $\theta(e^{-N^2})$  CORRECTIONS. [MICROSTATE ESSENTIALLY INVISIBLE]

**WHY?**

a) ALMOST ALL LONG STRINGS  $\in$  { TYPICAL SET } OF  
 STATISTICALLY RANDOM STRINGS

eg. Prob [Rand. lett. = X] =  $\frac{1}{|\text{Alphabet}|} \equiv P(X)$

b) SANON'S THEOREM

$P_r[\text{LETTER DIST.} = q(x)] = e^{-\Delta D(p||q)}$  } ATYPICAL FRACTION  $\rightarrow 0$   
 $D(p||q) = \sum_i p(i) \ln \frac{p(i)}{q(i)}$

c) STATISTICS CONTROLS CORRELATORS

$\langle 0 | \text{Tr}(XYZ \text{ XX YY X }^\dagger \text{Tr}(XX)^\dagger \text{Tr}(XX) \text{Tr}(\dots) | 0 \rangle$

- EACH TERM IN CORRELATOR IS DETERMINED BY THE PATTERN OF CONTRACTION — COMPLETELY DETERMINED BY STATISTICS OF RANDOM POLYNOMIALS
- TRUE FOR ALL PROBES (STRINGS  $\Delta \sim (gN)^{1/4}$ ; BRANES  $\Delta \sim N$ )
- HEAVY PROBES DO NOT DECOUPLE — LIKE A BLACK HOLE, NOT LIKE A THERMAL GAS



BOTTOM LINE: (a) ESSENTIALLY UNIVERSAL PROBE MEASUREMENTS OF VERY COMPLEX STATES.

(b) VERY PRECISE (ATYPICAL) MEASUREMENTS CAN DETECT THE ~~STATE~~ MICROSTATE

MICROSTATE DETECTION

• WITHOUT EXTRA SYMMETRIES, SPECTRUM OF HAMILTONIAN IS NON-DEGENERATE

⇒ EACH MICROSTATE HAS A UNIQUE MASS [UP TO ROTATIONS]

⇒ PRECISE MASS MEASUREMENT DETERMINES STATE

• HOW PRECISE?

(i) BETWEEN  $M$  &  $M + \Delta M \sim e^{S(M)}$  STATES

(ii)  $\Delta M \sim M_p c$

(iii)  $\Delta M =$  LEVEL SPACING  $\sim M_p e^{-S}$

• TO MEASURE WITH SUCH PRECISION

$\Delta t \Delta E \geq \hbar \Rightarrow \Delta t \sim \frac{\hbar}{M_p} e^S$

ALSO  $S \sim \frac{A}{G \hbar} \Rightarrow$  AT FIXED  $A, G$   
 $\hbar \rightarrow 0 \Rightarrow \Delta t \rightarrow \infty$

• VERY ATYPICAL MEASUREMENTS ARE NEEDED TO DETECT STATE. INFO. LOST WHEN  $\hbar \rightarrow 0$ , ALWAYS AVAILABLE OTHERWISE.

## LESSON

UNIVERSAL EFFECTIVE BLACK HOLE BEHAVIOUR FOR "TYPICAL" CORRELATORS IN A "TYPICAL" STATE.

BUT EXTREMELY PRECISE MEASUREMENTS SEE MICROSTATE DETAILS.

- What do the microstates "look like"?
- How can the "measurement of the state" be happening ~~in view of~~ if the black hole has horizon?

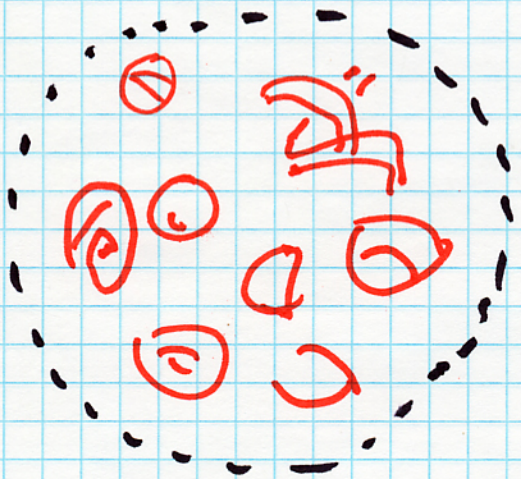
# MICROSTATES AS SPACETIME FOAM

- STUDY SUPERSYMMETRIC, EXTREMAL ( $Q=M$ ) BLACK HOLES

(a) STABLE (NO HAWKING RADIATION)

(b) SUSY  $\Leftrightarrow$  LOTS OF CONTROL

- CLASSICAL CONFIGURATION SPACE IN 3, 4, 5d



— ASYMPTOTICALLY FLAT ( $\Lambda=0$ )  
OR ASYMPTOTICALLY AdS ( $\Lambda<0$ )

— MASS & CHARGE OF  
A LARGE BLACK HOLE

— INTERIOR REGION OF  
COMPLEX TOPOLOGY

- FOAMY STRUCTURE: HOLES, BUBBLES & WORMHOLES IN A DENSE GAS AT PLANCK SCALE.

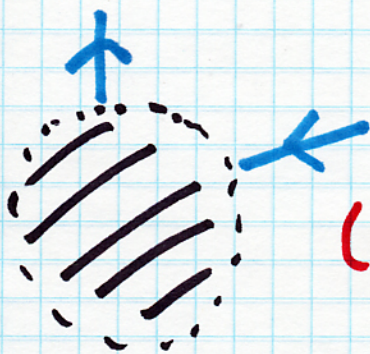
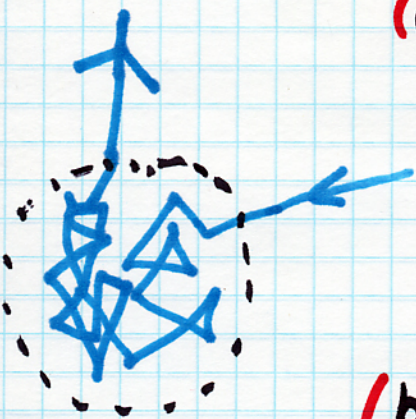
- MUST QUANTIZE: QUANTUM FOAM?

- DIRECT COMPUTATION OF WAVEFUNCTION OVER TOPOLOGIES / GEOMETRIES IS DIFFICULT
- FOR  $\lambda < 0$  USE DUAL FIELD THEORY TO QUANTIZE.
- UNIVERSAL STATISTICAL STRUCTURE OF VERY LARGE OPERATORS LEADS TO:

(a) UNIVERSAL RESPONSE OF TYPICAL PROBES OF TYPICAL STATES  $\Rightarrow$  "EFFECTIVE BLACK HOLE"

(b) VERY ATYPICAL & PRECISE MEASUREMENTS SENSE THE STATE

(c) CLASSICAL SINGULARITY ARISES FROM IGNORING PLANCK<sup>2</sup> SCALE WAVEFUNCTION

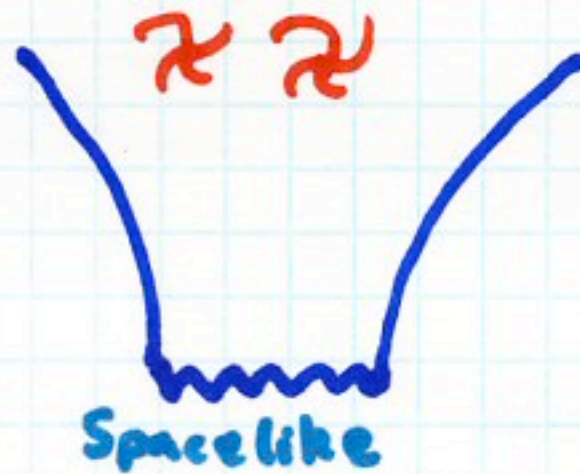
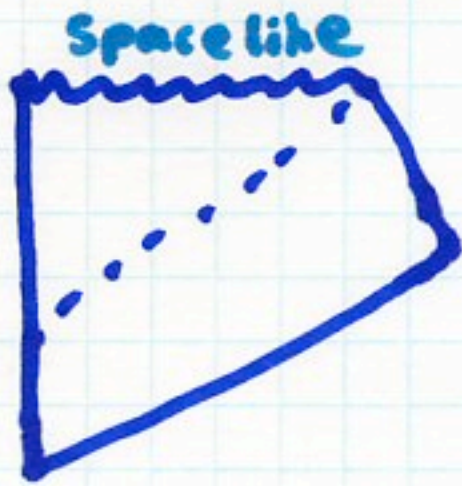


## FOR THE FUTURE

- ① SPACETIME FOAM & BLACK HOLES FROM COLLAPSE — THE EMERGENCE OF LARGE HORIZONS & SINGULARITIES.
- ② WHAT ABOUT ACCELERATION HORIZONS AND THEIR ENTROPY?
- ③ CONSEQUENCES FOR THE BIG BANG SINGULARITY & THE ORIGIN OF SPACE & TIME?  
A PRIMORDIAL QUANTUM FOAM?

# MEASURABILITY?

- SCHWARZSCHILD BLACK HOLE SINGULARITY & BIG BANG SINGULARITY ARE SIMILAR



INFLATION  $\sim e^{60}$   
 $\sim 10^{30}$

- INFLATION MIGHT BE ABLE TO TRANSPORT & IMPRINT PLANCK SCALE PHENOMENA INTO THE CMBR
- WHAT IS THE RELEVANT PLANCK SCALE PHYSICS? "QUANTUM FOAM"?
- ALTERNATIVELY, LARGE EXTRA DIMENSION SCENARIO:  $l_p \gg l_{p4}$ 
  - ↳ PHENOMENA DESCRIBED HERE ARE MORE ACCESSIBLE.