ON THE ORIGIN OF GRAVITATIONAL THERMODYNAMICS

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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	THERMODYNAMICS
$\Delta M = \kappa \, \Delta A + \cdots$	$\Delta E = T \Delta S + \cdots$
$\Delta A \geq 0$	$\Delta S \geq 0$
κ = CONST ON HORIZON	T = CONST. IN EQUILIBRIUM
(κ = surface gravity)	

- BLACK HOLE RADIATION

$T = \kappa$ (Thermal)

$\Rightarrow$ BLACK HOLES ACT LIKE BLACK BODIES

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

$$\boxed{\therefore \quad \text{THERMO} \rightarrow \text{STAT. MECH?}}$$

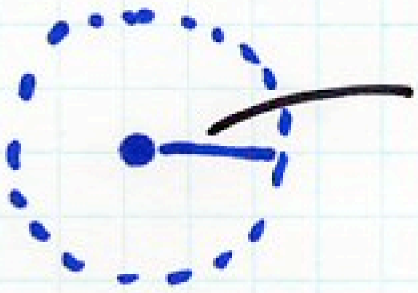
Is empty, ~~space~~ curved space the universal effective description of e^S complex microstates?

ACCELERATING UNIVERSES

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

- THE INERTIAL OBSERVER SEES THE PATCH

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

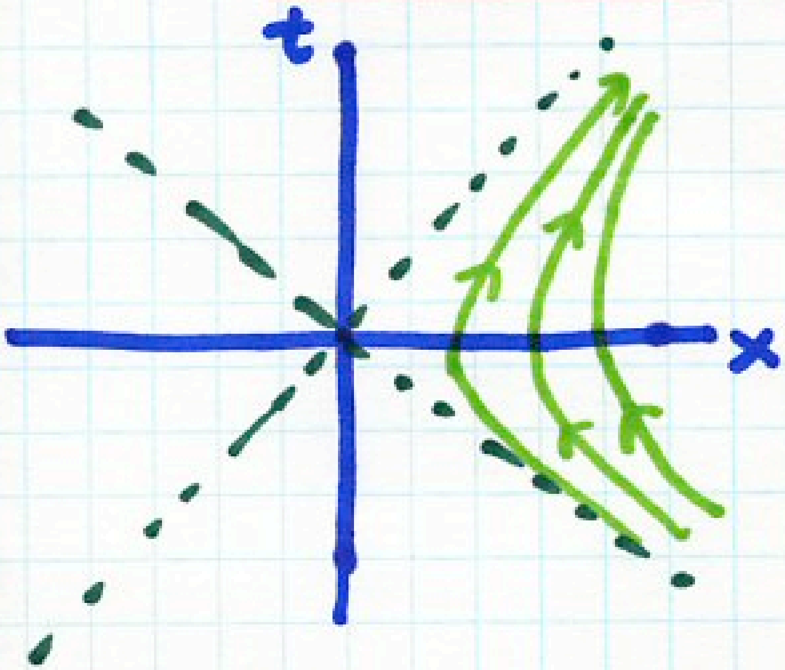


$r = \ell$ = COSMOLOGICAL HORIZON

$$\left.\begin{array}{l} S \sim \ell^{d-1} \\ T = \dfrac{1}{2\pi\ell} \end{array}\right\} \text{ENTROPY \& TEMP SEEN BY INERTIAL OBSERVERS}$$

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

ACCELERATED OBSERVERS IN FLAT SPACE

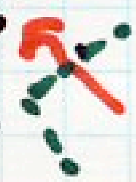


FAMILY OF ACC. OBSERVERS SEES A HORIZON OBEYING LAWS OF HORIZON MECHANICS + UNRUH RADIATION

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

JACOBSON'S ARGUMENT

ASSUME ACCELERATED OBSERVERS SEE HORIZON THERMODYNAMICS

( $\delta M = \kappa\, \delta A$; $\delta A \geq 0$ ....)

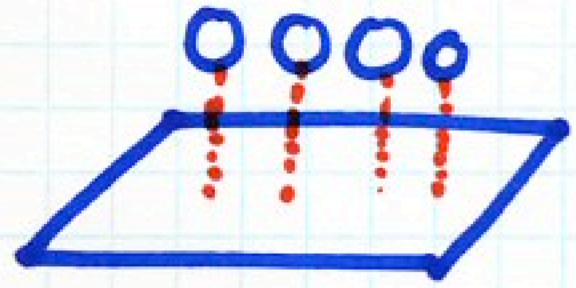
↳ EINSTEIN'S EQUATIONS OF MOTION

EQUATIONS OF STATE	$\Longleftrightarrow$	EQUATIONS OF MOTION ?

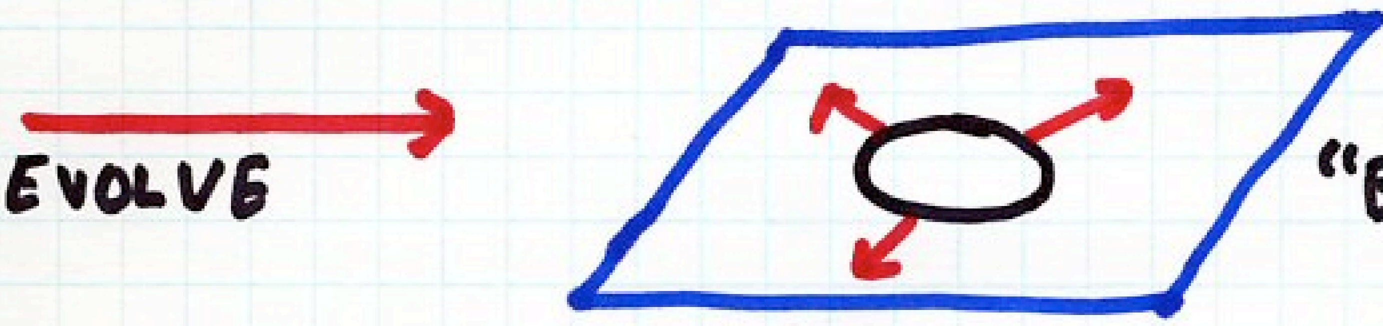
THE NOTHING STATE

- KALUZA-KLEIN COMPACTIFICATION OF FLAT SPACE ON A CIRCLE

  $R^{3,1} \times S^1$



- THIS SPACE CAN DECAY BY TUNNELING TO "NOTHING"



EXPANDING "BUBBLE OF NOTHING

$\Rightarrow$ $\boxed{\text{FLAT SPACE IS NOT THE GROUND STATE OF GRAVITY WHEN THERE ARE EXTRA DIMS. (AND SUSY IS BROKEN)}}$

GROUND STATE OF 3d GRAVITY

$$S \sim \int (R + \Lambda)\sqrt{g}$$

NO GRAVITON IN 3d

$$\sim \int A_+ dA_+ + A_+ \wedge A_+ \wedge A_+ + \int A_+ \to A_-$$

$$A_\pm = e \pm \omega$$

CHERN - SIMONS THEORY

VIELBEIN

SPIN CONNECTION

GROUND STATE: $A_\pm = 0 \Rightarrow$ NOTHING STATE

CLAIMS

$\boxed{1}$ VERY HEAVY PURE STATES IN GRAVITY APPEAR MIXED TO ALMOST ALL PROBES

$\boxed{2}$ THE UNDERLYING PURE MICROSTATES FORM A TOPOLOGICALLY COMPLEX "QUANTUM FOAM"

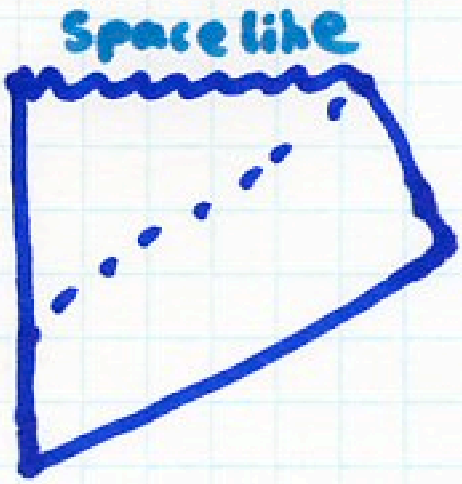
$\boxed{3}$ THE UNIVERSAL LONG-DISTANCE EFFECTIVE DESCRIPTION OF SUCH FOAMS IS VIA THE USUAL SINGULAR GEOMETRIES, PERHAPS WITH HORIZONS

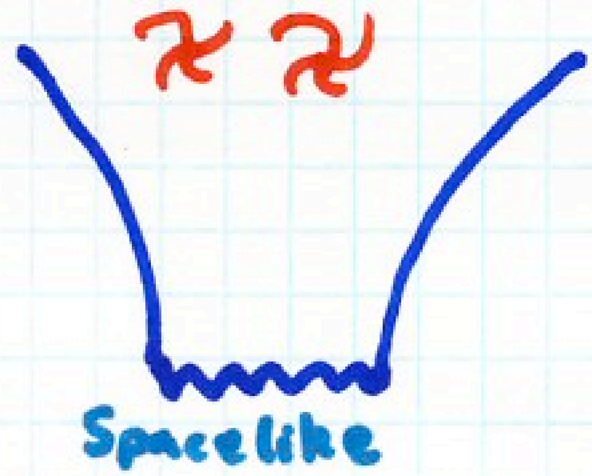
$\boxed{4}$ THIS IS THE GENERAL MECHANISM FOR THE EMERGENT THERMODYNAMICS OF GRAVITY

> Space-time is an emergent phenomenon?
> — A Long-distance description of a complex underlying quantum state which may not have a geometric description

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 SCENARION: $\ell_P \gg \ell_{P4}$

  ↳ PHENOMENA DESCRIBED HERE ARE MORE ACCESSIBLE.

THE SETUP

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

- STEP 1: PUT BLACK HOLE IN A BOX
  $\Rightarrow$ 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

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

(GEOMETRY MAKES POT. BARRIER)

- BLACK HOLES

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

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

KEY TOOL

STRING THEORY WITH $\Lambda < 0$ $\underset{\text{DUAL}}{\Longleftrightarrow}$ A QUANTUM FIELD THEORY

GRAVITY $\Leftrightarrow$ GAUGE THEORY

- 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 $S^3 \times$ TIME

THE DICTIONARY

AdS SCALE ℓ

- STRING COUPLING g_s

STRING LENGTH ℓ_s

$G_5 \sim \dfrac{g_s^2 \ell_s^8}{\ell^5}$

$$g^2_{YM} = g_s$$

$$N = \frac{1}{g_s}\left(\frac{\ell}{\ell_s}\right)^4$$

- SPACETIME ISOMETRIES } GLOBAL SYMMETRIES (Super-Conformal ...)

- STATES IN GRAVITY WITH MASS M } STATES OF FIELD THEORY WITH $E = M$

[$\Delta = M\ell$ = CONF. DIM. OF OPERATOR]

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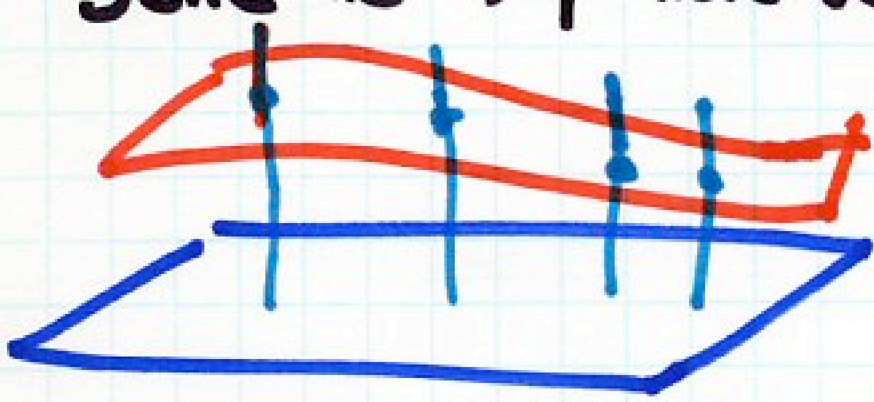
- SEMICLASSICAL LIMIT: $\frac{\ell}{\ell_s} \gg 1$, $g_s \ll 1$

$\Rightarrow N \gg 1$

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 ~~AS~~ MICROSTATES

- $ds^2 = -\left[1+\frac{r^2}{\ell^2}-\frac{r_0^2}{\ell^2}\right]dt^2 + [\cdots]^{-1}dr^2 + r^2 d\Omega_3^2$
- $M \sim \frac{r_0^2}{G_5} \Rightarrow \Delta \sim M\ell \sim N^2$ IN DUAL

  $S \sim \frac{A}{G_5} \sim N^2 \Rightarrow e^{N^2}$ SUCH MICROSTATES
- $|\text{BH microstate}\rangle = \mathcal{O}|0\rangle$; $\Delta(\mathcal{O}) \sim N^2$

  SUGRA STATES: $\Delta \sim \mathcal{O}(1)$

  STRINGS : $\Delta \sim (g_s N)^{1/2}$

  D-BRANES : $\Delta \sim N$

- WHAT DO MICROSTATES OPERATORS LOOK LIKE?

LONG, GAUGE-INVARIANT POLYNOMIALS IN THE FIELDS $\{ \underbrace{A_\mu}_{\text{GAUGE FIELD}}, \underbrace{\psi}_{\text{FERMION}}, \underbrace{X, Y, Z}_{\text{ADJOINT SCALARS.}} \}$

$\boxed{\text{e.g.}}$ $\mathcal{O} = \text{Tr}[XXY\bar{X}ZZ\bar{X}\cdots]$ — $O(N^2)$ LETTERS

Sprinkle Traces, Derivatives, Other Fields

- BUT? (i) No SUSY — RENORMALIZATION?

  (ii) MIXING

  (iii) TRACES SPLIT UP

CLAIM: LET $|\mathcal{O}\rangle = \mathcal{O}|0\rangle$; $\mathcal{O}_p$ = ANY PROBE

THEN $\langle \mathcal{O}| \mathcal{O}_p \cdots \mathcal{O}_p |\mathcal{O}\rangle$ DEPENDS ONLY ON Δ & GLOBAL CHARGES OF $\mathcal{O}$ & $\mathcal{O}_p$ UP TO $\mathcal{O}(e^{-N^2})$ CORRECTIONS. [MICROSTATE DETAILS ESSENTIALLY INVISIBLE]

WHY?

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

e.g. $\text{Prob}[\text{Rand. lett.} = X] = \frac{1}{|\text{Alphabet}|} \equiv p(x)$

ⓑ SANOV'S THEOREM

$$\Pr\left[\begin{smallmatrix}\text{LETTER}\\ \text{DIST.}\end{smallmatrix} = q(x)\right] = e^{-\Delta D(p\|q)}$$

$$D(p\|q) = \sum_i p(i) \ln \frac{p(i)}{q(i)}$$

ATYPICAL FRACTION $\to 0$

ⓒ STATISTICS CONTROLS CORRELATORS

$$\langle 0|\, \mathrm{Tr}(XYZ\,XX\,YYX)^{+}\, \mathrm{Tr}(XX)^{+}\, \mathrm{Tr}(XX)\, \mathrm{Tr}(\cdots)\,|0\rangle$$

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

  $\Rightarrow$ EACH MICROSTATE HAS A UNIQUE MASS [UP TO ROTATIONS ...]

$\Rightarrow$ 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) δM = 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
  $\hbar \to 0 \Rightarrow \Delta t \to \infty$

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

EFFECTIVE BLACK HOLE

- DOES THE UNIVERSAL PART OF A TYPICAL CORRELATOR LOOK LIKE A MEASUREMENT IN A BLACK HOLE BACKGROUND?

- e.g. BTZ BLACK HOLES IN 2+1 DIMS. WITH $\Lambda < 0$

- EMBED IN

STRING THEORY ON $AdS_3 \times S^3 \times T^4$ $\Longleftrightarrow$ (4,4) SUSY σ-MODEL ON $(T^4)^N/S_N$

SCALE ℓ $\qquad$ $\ell \sim N^{1/4}$

- MICROSTATE OPERATORS FOR THE EXTREME BTZ BLACK HOLE ($M=0$) ARE CONSTRUCTED FROM THE "TWIST OPERATORS" OF THE σ-MODEL

$$\{ \underbrace{\sigma^{\mu}_{n}}_{\text{BOSONIC}} , \underbrace{\tau^{\mu}_{n}}_{\text{FERMIONIC}} \} \qquad \begin{array}{l} n = 1 \cdots N \\ \mu = 1 \cdots 8 \end{array}$$

$$\boxed{\begin{gathered} \sigma = \prod_{n\mu} (\sigma^{\mu}_{n})^{N_{n\mu}} (\tau^{\mu}_{n})^{N'_{n\mu}} \\ \sum_{n\mu} n (N_{n\mu} + N'_{n\mu}) = N \end{gathered}}$$

OPERATORS CREATING BTZ BLACK HOLE MICROSTATES

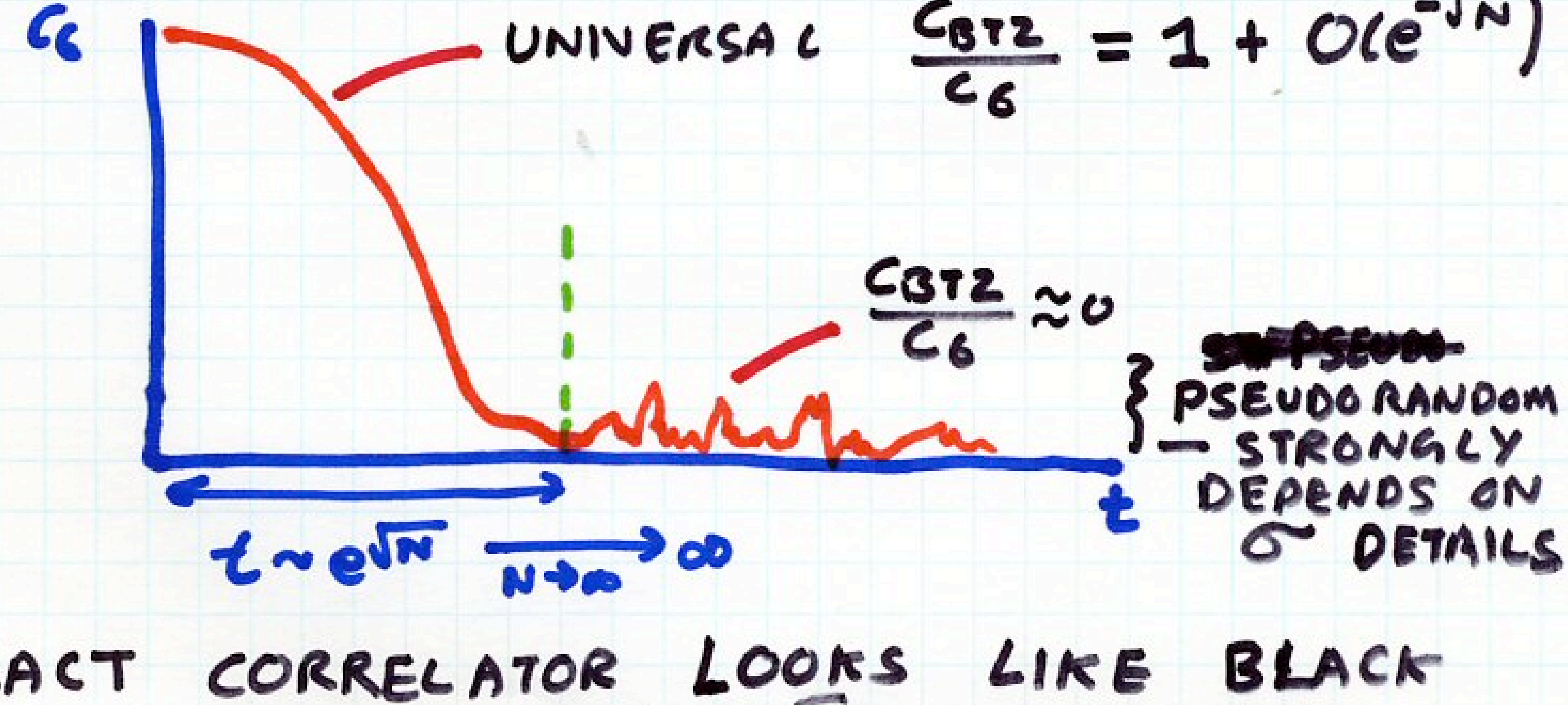
EACH MICROSTATE IS DEFINED BY ITS TWIST DISTRIBUTION $\{N_{n\mu}, N'_{n\mu}\}$

$\boxed{\text{CLAIM 1:}}$ AT LARGE N ALMOST ALL MICROSTATES HAVE TWIST DISTRIBUTIONS THAT ARE SMALL PERTURBATIONS OF

$$N_{n\mu} = \frac{1}{e^{\beta n} - 1} \quad ; \quad N'_{n\mu} = \frac{1}{e^{\beta n} + 1}$$

- PROVE THIS BY STATISTICAL ANALYSIS OF STRUCTURE OF $\sigma = \prod_{n\mu} (\sigma_n^{\mu})^{N_{n\mu}} (\tau_n^{\mu})^{N'_{n\mu}}$
- DEGENERACY: $d_N \sim e^{\sqrt{N}} \Rightarrow S \sim \sqrt{N}$

$\boxed{\text{CLAIM 2}}$ LET A BE ANY (UNTWISTED) OPERATOR, (e.g. OPERATOR DUAL TO GRAVITON). THEN $C_\sigma = \langle \sigma | A(0)\, A(t) | \sigma \rangle$ FOR A TYPICAL STATE IS GIVEN BY



EXACT CORRELATOR LOOKS LIKE BLACK HOLE RESULT FOR $t \sim e^{\sqrt{N}}$ AND DEVIATES STRONGLY AFTERWARDS

LESSON

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

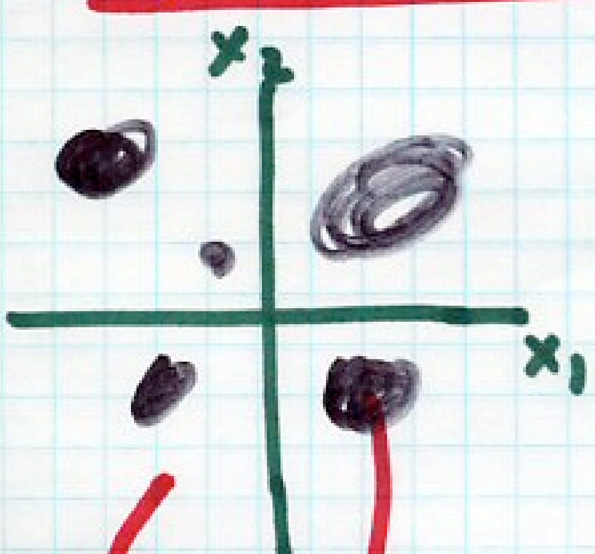
BUT EXTREMELY PRECISE MEASUREMENTS SEE MICROSTATE DETAILS.

- 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 IN GRAVITY

- TECHNICAL CONTROL: BPS STATES OF GRAVITY WITH $\Lambda<0$ IN $D=3,5$
- BLACK OBJECTS
  - $D=3$: EXTREME BTZ, BLACK RINGS ...
  - $D=5$: EXTREME "SUPERSTAR" ...
- CLASSICAL MODULI SPACES OF CANDIDATE BLACK HOLE MICROSTATES WITHOUT HORIZONS OR SINGULARITIES
  - $2+1d$, $\Lambda<0$: MATUR, LUNIN, ...
  - $4+dd$, $\Lambda<0$: LIN, LUNIN, MALDACENA ...
- CORE OF "MICROSTATES" CONTAINS REGION OF COMPLEX TOPOLOGY, WITH PLANCK-SCALE DETAILS

Eg. ½ BPS ASYMP. $AdS_5 \times S^5$ SOLUTIONS



COLLAPSING S^3 IS AdS_5 & S^5

- SPECIAL TWO-PLANE NEAR ORIGIN
- DIFFERENT S^3 COLLAPSE OVER EACH POINT
- TYPICAL STATE FOR FIXED MASS IS A "FOAM" OF S^3 BUBBLES AT PLANCK SCALE

CLASSICAL GRAVITY APPLIES AT $L > \ell_P$

$\Rightarrow$ MUST QUANTIZE "FOAM"; THEN COARSE-GRAIN

Q1: HOW DO WE QUANTIZE THIS CLASSICAL MODULI SPACE?

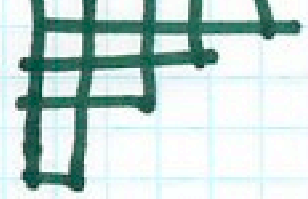
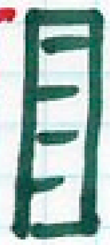
Q2: WHAT IS THE RELATION TO BLACK HOLES?

A1: USE THE AdS/CFT DUALITY TO QUANTIZE

A2: THE BLACK HOLE IS THE UNIVERSAL ~~ST~~ EFFECTIVE DESCRIPTION OF ALMOST ALL QUANTIZED MICROSTATES FOR ALMOST ALL PROBES

HALF-BPS STATES OF $\mathcal{N}=4$ SYM

- FIELDS $\{A_\mu, \psi, X, Y, Z\}$, SO(6) R-SYMMETRY
- $\frac{1}{2}$ BPS: (0, p, 0) REPS OF SO(6), $\Delta = J$

  $\Rightarrow$ HIGHEST WEIGHT STATES ARE POLY. IN X
- $\mathcal{O}_T = \sum_\sigma a(\sigma)\, X^{i_1}_{i_{\sigma(1)}} \cdots X^{i_N}_{i_{\sigma(N)}}$; T=  CJR
- eg: N $\Big\{$  = 1 D-BRANE $\quad \mathcal{O}_T = \det X$; $|s\rangle = \mathcal{O}_T |0\rangle$

SIMPLER FORMULATION

- $\boxed{\begin{array}{lcl} \tfrac{1}{2}\text{ BPS STATES} & & \text{STATES OF N FERMIONS} \\ \text{OF } \mathcal{N}=4 & \Longleftrightarrow & \text{IN A HARMONIC} \\ \text{ON } S^3 \times R & & \text{POTETIAL} \end{array}}$

- WHY? ONLY ZERO-MODE OF X CAN CONTRIBUTE TO 1/2 BPS STATE

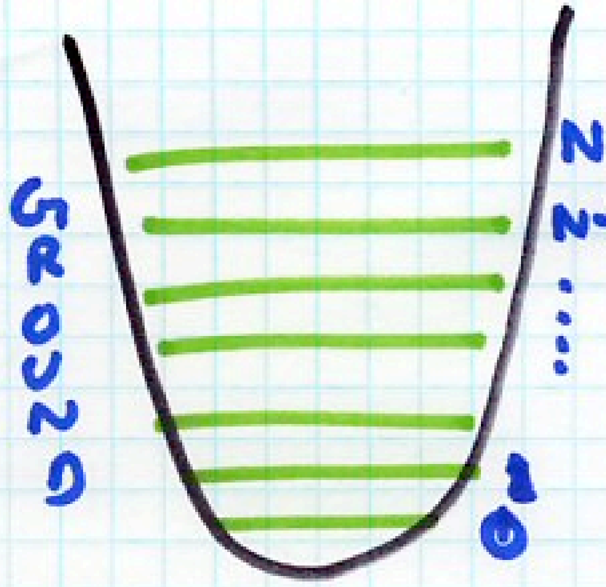
$$\underbrace{X}_{\Delta = J} = \underbrace{X_0}_{\Delta = J} + \sum_i \underbrace{(\partial_1 \cdots \partial_i X)}_{\Delta > J}\, y^i$$

- ALSO ONLY X, NOT $\bar{X}$

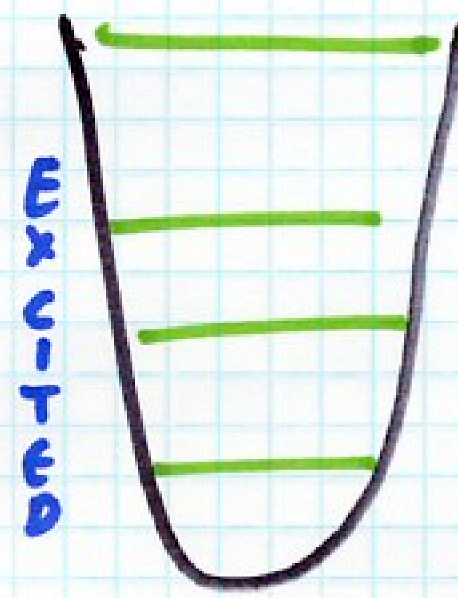
$\Rightarrow$ HERMITIAN MATRIX MODEL
$\Rightarrow$ EIGENVALUES ARE FERMIONS

$$\left.\right\} Z = \int \mathcal{D}X\, e^{i\int dt\, \dot{X}^2 + \frac{1}{2}RX^2}$$

CURVATURE OF S^3



$\Rightarrow$



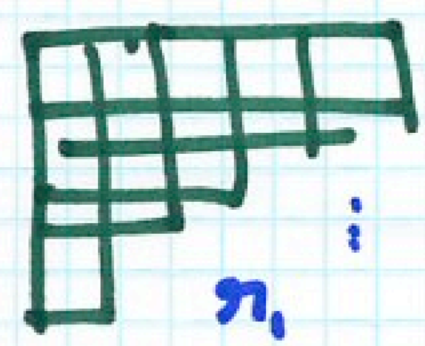
$r_N = E_N - (N-1)$

$r_{N-1} = E_{N-1} - (N-2)$

$\vdots$

$r_N \geq r_{N-1} \geq \cdots r_1$

$$\psi = \begin{vmatrix} H_{E_1}(x_1) & H_{E_1}(x_2) \cdots \\ H_{E_2}(x_1) & \cdots \\ \vdots & \end{vmatrix} \; ; \; T =$$



CLAIM (CJR, BERENSTEIN)

$$\psi \Longleftrightarrow \mathcal{O}_T|0\rangle$$

$$\sum_i r_i \Longleftrightarrow \Delta(\mathcal{O}_T)$$

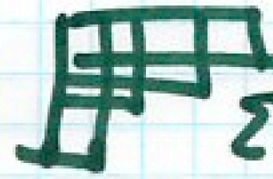
$$\mathcal{O}_T = \sum_\sigma a(\sigma)\, X^{i_1}_{i_{\sigma(1)}} \cdots X^{i_N}_{i_{\sigma(N)}}$$

$\boxed{\text{FOR CONFORMAL DIMENSION } \Delta \sim N^2 \text{ (BLACK HOLE MASSES) WHAT IS THE TYPICAL STATE?}}$

TYPICAL HALF-BPS STATES

- GIVEN $\Delta \sim N^2$ WHAT IS THE TYPICA STATE?

$\Longleftrightarrow$ TYPICAL PARTITION OF $\Delta \sim N^2$ INTO N INTEGERS



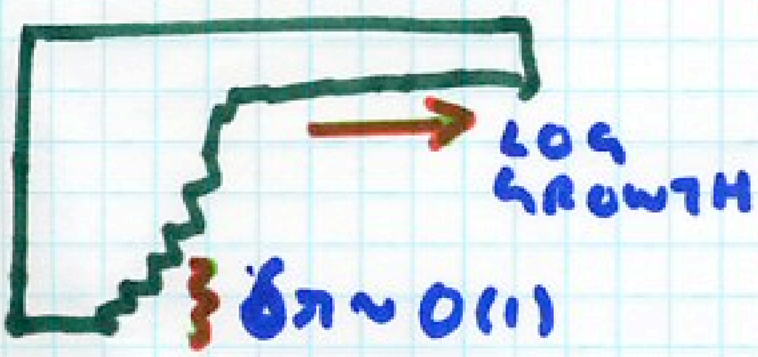
$\sum n_i = \Delta$

- SOLVE USING CANONICAL ENSEMBLE

(1) $\langle c_i \rangle = \left\langle \begin{matrix} \text{\# OF COLUMNS} \\ \text{OF LENGTH } i \end{matrix} \right\rangle = \dfrac{e^{-\beta i}}{1 - e^{-\beta i}}$ } LIKE A PHOTON GAS

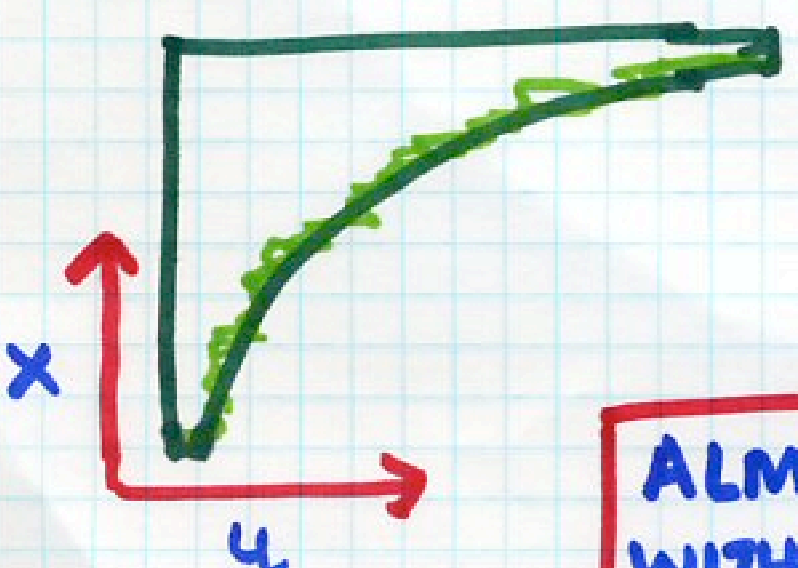
(2) $\Delta = N^2 \gamma \Rightarrow \beta \sim \frac{1}{N\gamma}$

(3) $\mathrm{Var}(c_i) = \dfrac{e^{-\beta i}}{(1 - e^{-\beta i})^2} = \dfrac{\langle c_i \rangle}{1 - e^{-\beta i}}$

- 

} SEMICLASSICAL LIMIT: $N \to \infty$, $\hbar N$ FIXED

$\Downarrow$



SMOOTH LIMIT CURVE

$$e^{-\beta(N-x)} + C(N)\, e^{\beta y} = 1$$

$$\boxed{\text{ALMOST ALL HALF-BPS STATES WITH } \Delta \sim N^2 \text{ ARE SMALL FLUCTUATIONS AROUND THIS STATE.}}$$

$\frac{1}{2}$-BPS OF 5d, $\Lambda < 0$ GRAVITY

FOR OUR PURPOSES

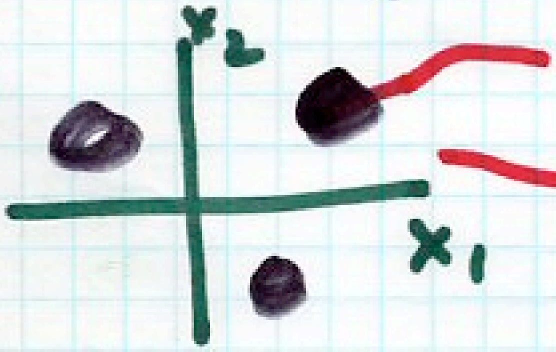
(i) COMPLICATED, ASYMP. $AdS_5 \times S^5$

(ii) RADIAL COOR ⓓ y ; METRIC FUNCTION $u(y)$

(iii) $y \to 0$: (x_1, x_2) WITH COMPLEX TOPOLOGY

(iv) $u(0, x_1, x_2)$ FIXES FULL SOLUTION $(\nabla_y^2 u = 0)$

(v) $u \xrightarrow[y \to 0]{} \begin{matrix} 0 \\ 1 \end{matrix} \Rightarrow$ NON-SINGULAR



S^3 IN S^5 SHRINKS
S^3 IN AdS^5 SHRINKS. $\Big\}$ THREADED BY FLUXES

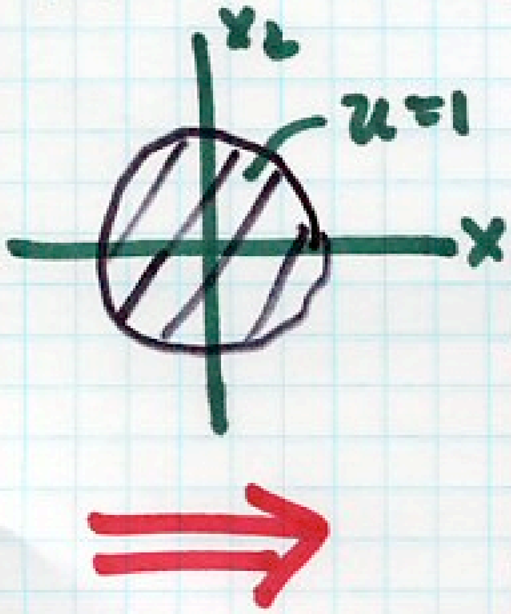
- FLUX QUANTIZATION $\Rightarrow$

(i) GRAVITY $\longleftrightarrow$ SYM

ℓ_p^4 $\quad\quad\quad\quad$ $\hbar$

(ii) ENERGY $\approx \int_{R^2} (x_1^2 + x_2^2)\, u(0, x_1, x_2) = \Delta$

(iii) UNITS OF FLUX $\sim \int_{R^2} u(0, x_1, x_2) = N =$ # OF FERMIONS



$= AdS_5 \times S^5 =$ GROUND STATE (FERMI SEA)

$\Rightarrow$

$$\boxed{\begin{array}{lcl} (x_1, x_2) & \Longleftrightarrow & (q, p) \text{ SHO PHASE SPACE} \\ \ell_p^4 & \Longleftrightarrow & \hbar \end{array}}$$

PHASE SPACE DISTRIBUTION (WIGNER)

- $\rho = |\psi(x_1 \cdots x_N)\rangle\langle\psi(y_1 \cdots y_N)|$

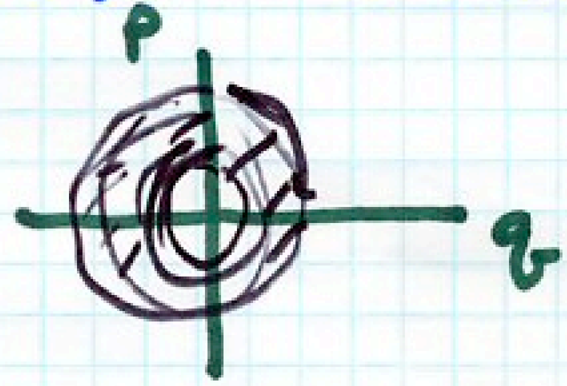
  INTEGRATE OUT FERMIONS $2 \cdots N$

  FOURIER TRANSFORM $x_1 - y_1 \to p$; $x_1 + y_1 \sim q$

  $\Rightarrow W(p, q)$

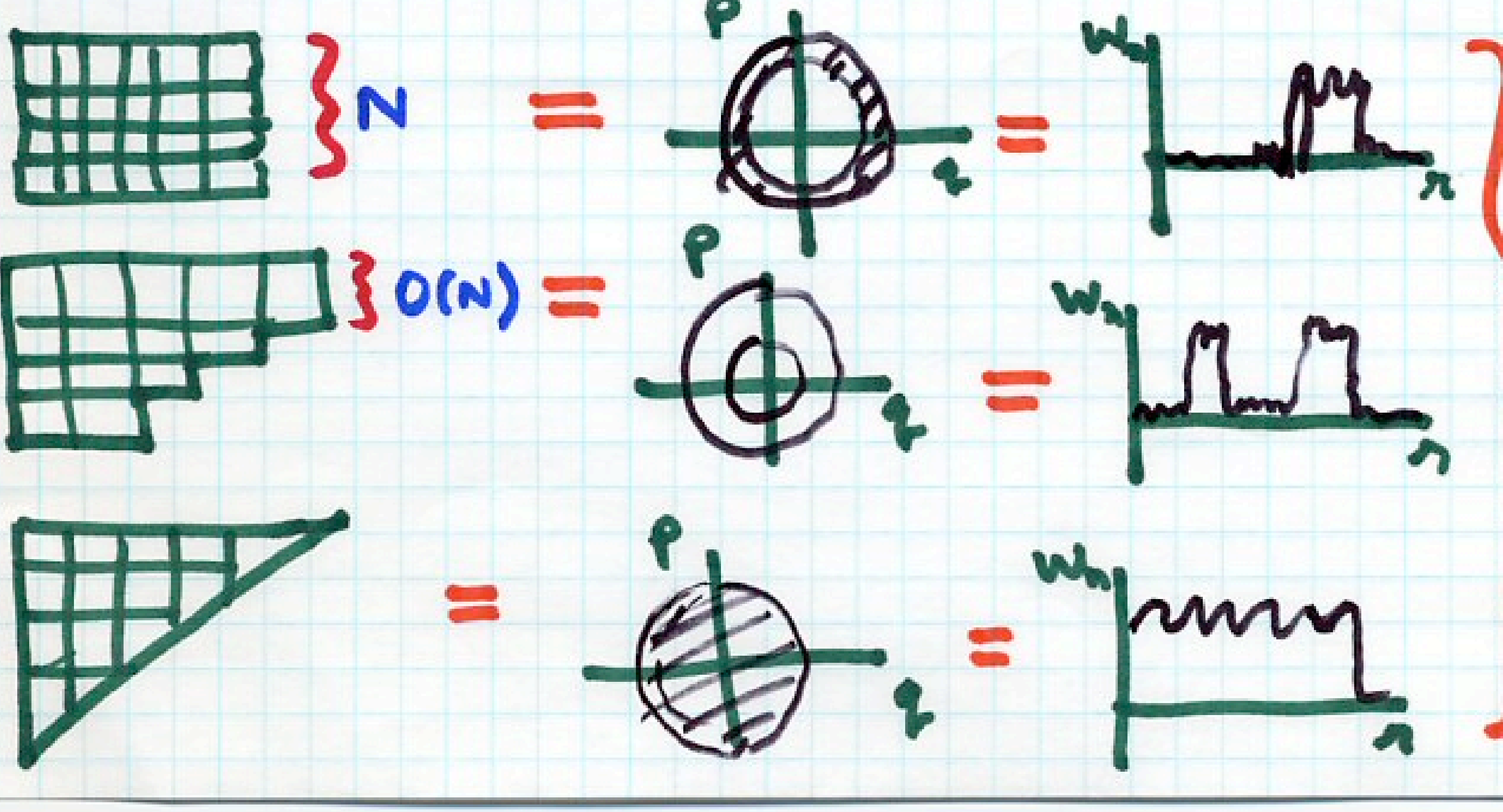
  $$\langle \mathcal{O}_F(p, q)_{\text{Weyl}} \rangle = \int dp\, dq\ F(p, q)\ W(p, q)$$

- $\left| \begin{matrix}\text{nth SHO} \\ \text{EIGENSTATE}\end{matrix} \right\rangle \longrightarrow W_n(p, q) =$ LAGUERE POLYNOMIAL



QUANTUM OSCILLATIONS AT $\hbar$ SCALE
($(q, p) \to (x_1, x_2) \Rightarrow$ OSC. AT ℓ_p SCALE)

- SEMICLASSICAL LIMIT: $\hbar \to 0$; $N \to \infty$

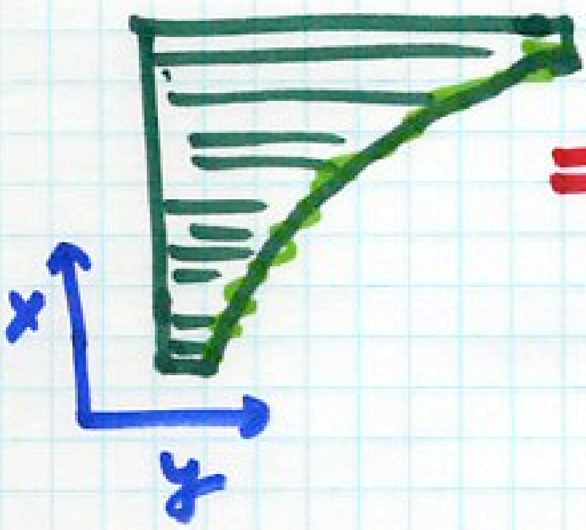


$\hbar$ (ℓ_p) SCALE OSCILLATIONS

COARSE GRAINING

- SEMICLASSICAL OBSERVABLES PROBE SCALES $\gg \hbar$
- COARSENING SCALE ΔE $\left(\frac{\Delta E}{\hbar} \xrightarrow[\hbar \to 0]{} \infty\right)$
- LET g = COARSE-GRAINED FERMION PHASE SPACE DISTRIBUTION

$$g(E) = \frac{\int_E^{E+\Delta E} dp\, dq\, W}{\int_E^{E+\Delta E} dp\, dq}$$



$$\Rightarrow \quad g(E) \sim \frac{\Delta X}{\Delta E} = \frac{1}{\Delta E / \Delta x}$$

$$E = x + y$$

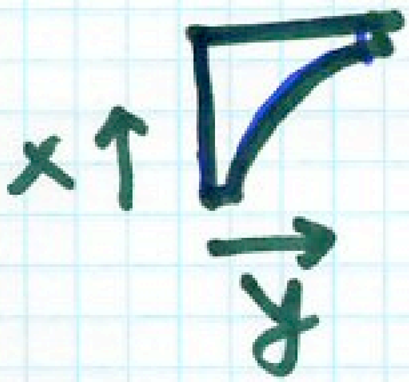
$$\Downarrow$$

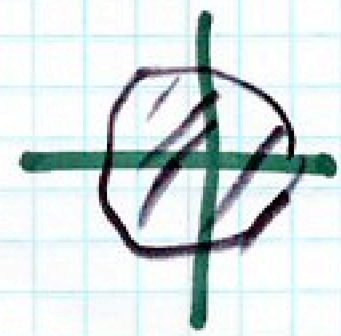
$$\boxed{g(E) = \frac{1}{1 + y'}}$$

CLAIM:
- SEMICLASSICAL OBSERVABLES ONLY SENSE $g(E)$,
- ALMOST ALL $\frac{1}{2}$-BPS STATES HAVE THE SAME $g(E)$

MAP TO GRAVITY

FIELD THEORY		GRAVITY
• $\cancel{E=p^2+q^2}$ (p,q)	$\longleftrightarrow$	(x_1, x_2)
• $E = p^2 + q^2$	$\longleftrightarrow$	$r^2 = x_1^2 + x_2^2$
• $g(E) = \frac{1}{1+y'}$	$\longleftrightarrow$	$u(r^2)$





• TYPICAL STATES

$$e^{-\beta(N-x)} + C(N)\, e^{-\beta y} = 1$$

$\Rightarrow$ UNIVERSAL $u(r^2) \neq 0,1$

$\Downarrow$

$\boxed{\text{UNIVERSAL SINGULAR EFFECTIVE DESCRIPTION OF SMOOTH QUANTUM STATE}}$

LESSONS & QUESTIONS

a) UNIVERSAL (PERHAPS SINGULAR) EFFECTIVE DESCRIPTIONS IN GRAVITY OF UNDERLYING SMOOTH QUANTUM STATES

b) GENERIC ORIGIN OF GRAVITATIONAL THERMODYNAMICS?
NO DECOUPLING IN GRAVITY $\Rightarrow$ INTEGRATING OUT ℓ_p LEADS TO MIXED EFFECTIVE STATE?

QUESTIONS

a) "FOAM" FOR NON-SUSY STATES?

b) CLASSICAL MANIFESTATIONS OF UNDERLYING QUANTUM STATES (INTERFERENCE)

c) FLAT SPACE

d) RESOLVING BIG BANG SINGULARITIES