Title: Aspects of Hagedorn Holography

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Abstract:

J. L. F. BARBON, C. FUERTES, E. R.

ON LITTLE HAGEDORN

HOLOGRAPHY

OVERCOME PREJUDICE – ENLIGHTMENT

CONFIRM PREJUDICE – "PLEASURE"

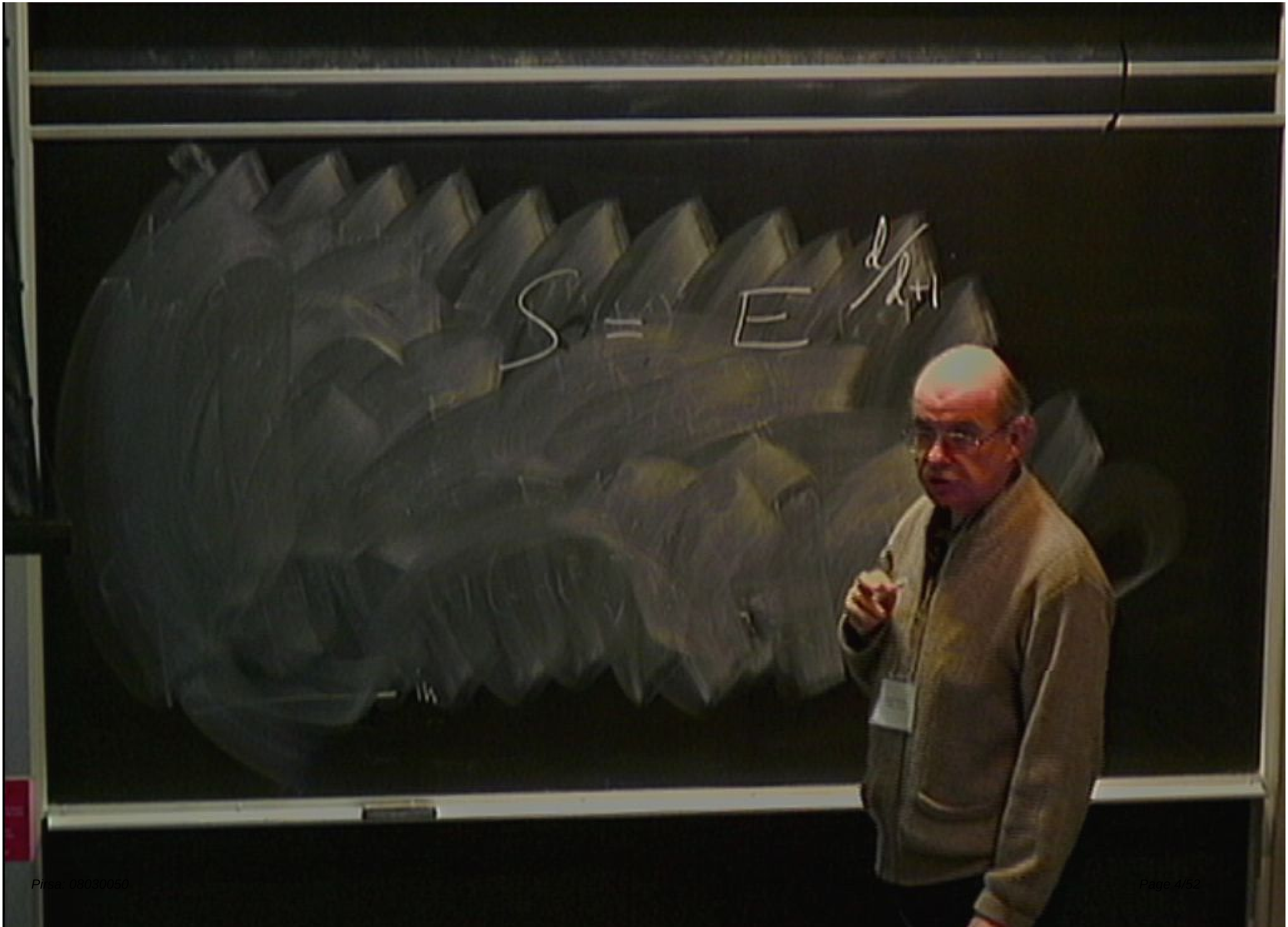
LST

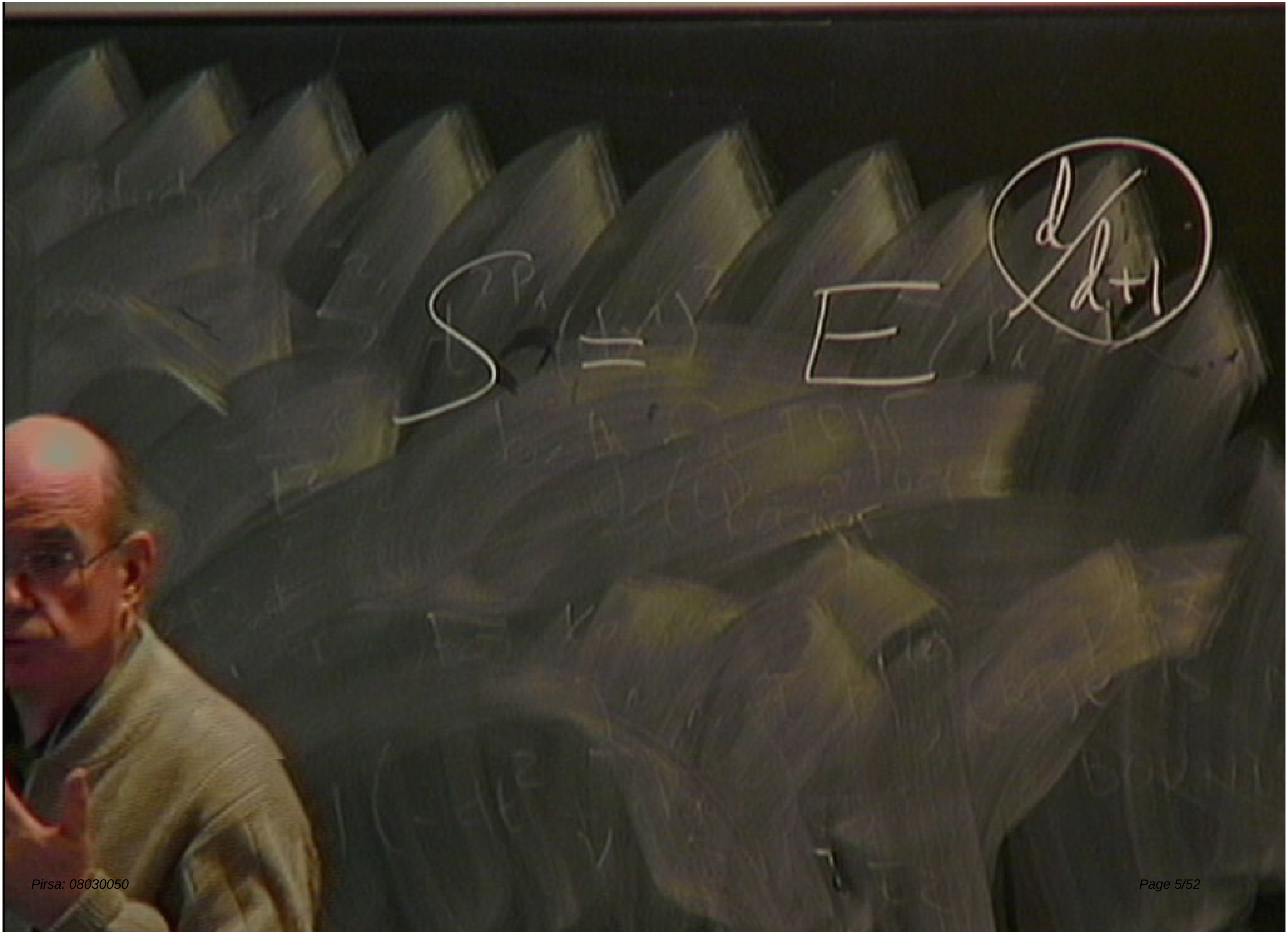
SEIBERG

AHARONY, BERKOOZ, KUTASOV, SEIBERG

MALACENA, MINWALLA, STROMINGER

MANY MORE...


$S = E^{d/d+1}$


S = E
d/d+1

HAGEDORN

$g_s \neq 0$

* $S = \beta E$ $T_H = T_{MAX}$

STRINGS ~ COMPOSITES

* $C_v < 0$

MORE THAN PRESUMCE

BOX OF SIZE R , $l_s = 1$

$$S_g \sim (E_g R)^{9/10}, \; S_s \sim E_s, \; S_b \sim \frac{1}{g_s^2}\left(g_s^2 E_b\right)^{8/7}$$

$$x_g = \frac{E_g}{E}, \; x_s = \frac{E_s}{E}, \; x_b = \frac{E_b}{E}$$

E GIVEN.

$$S(x_g, x_s, x_b) =$$

$$S_g(E)\, x_g^{9/10} + S_s(E)\, x_s + S_b(E)\, x^{8/7}$$

MAXIMIZE

$$x_g + x_s + x_b = 1$$

GENERICALLY ONE CAN NEGLECT

ONE COMPONENT.

i.e.

$$S_g(E_{gb}) \equiv S_b(E_{gb})$$

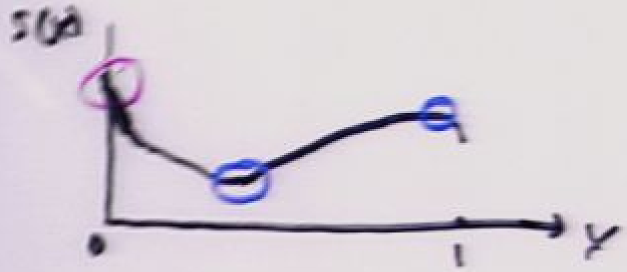
$$E_{gb} \sim \frac{1}{g_s^2}\left(g_s^2 R^9\right)^{7/17}$$

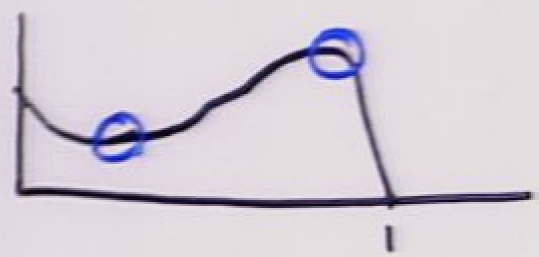
$$E_{gs} \sim R^9$$

$$E_{bs} \sim \frac{1}{g_s^2}$$

TRIPLE POINT

$$E_{Triple} \sim R^9 = \frac{1}{g_s^2} \qquad g_s^2 R^9 = 1$$





BH DOMINATES

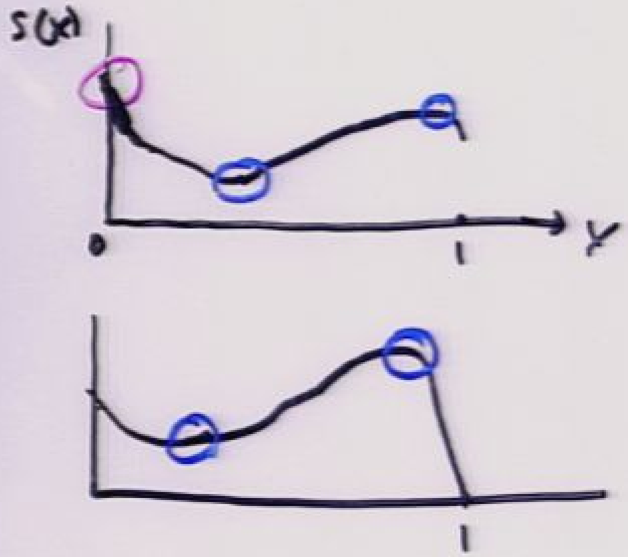
FOR $E \sim E_{gG}$

$$R_s = \left(g_s^2 E_{gG}\right)^{1/7} \sim R\left(\frac{g_s^2}{R^8}\right)^{1/17} \ll R$$

EVENTUALLY R_s BECOMES $O(R)$

AND WILL GROW [illegible] ALL.

NE[illegible]



BH
DOMINATES

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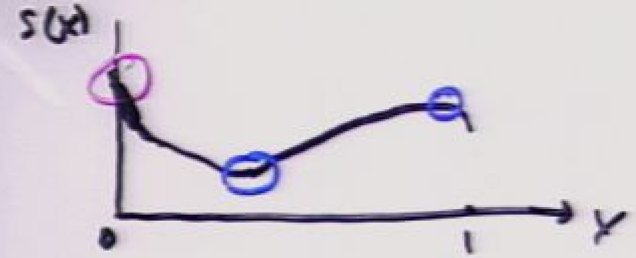
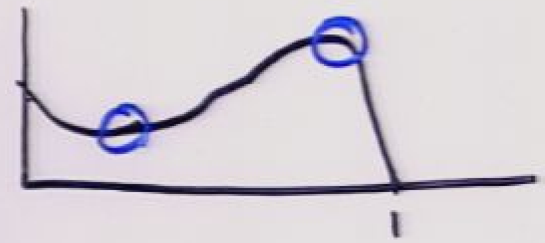
A DD [illegible] ALL.

WE





BH DOMINATES

FOR $E \sim E_{gb}$

$$R_s = \left(g_s^2 E_{gb}\right)^{1/7} \sim R\left(\frac{g_s^2}{R^8}\right)^{1/17} \ll R$$

EVENTUALLY R_s BECOMES $O(R)$

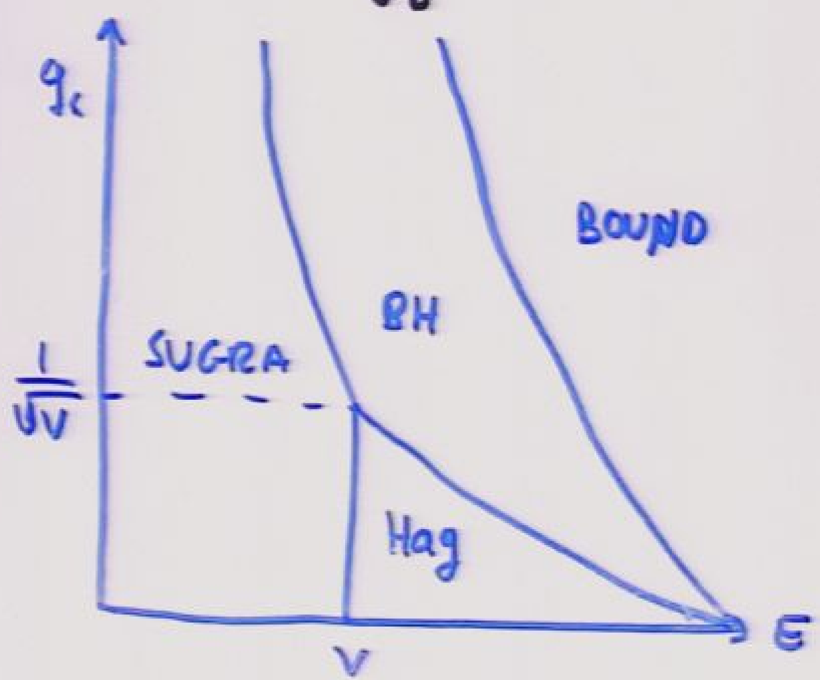
AND WILL CRUSH THE WALL.

NEED AdS REGULATOR.

$g_s^2 R^8 \ll 1$ STRING PHASE ENTERS.

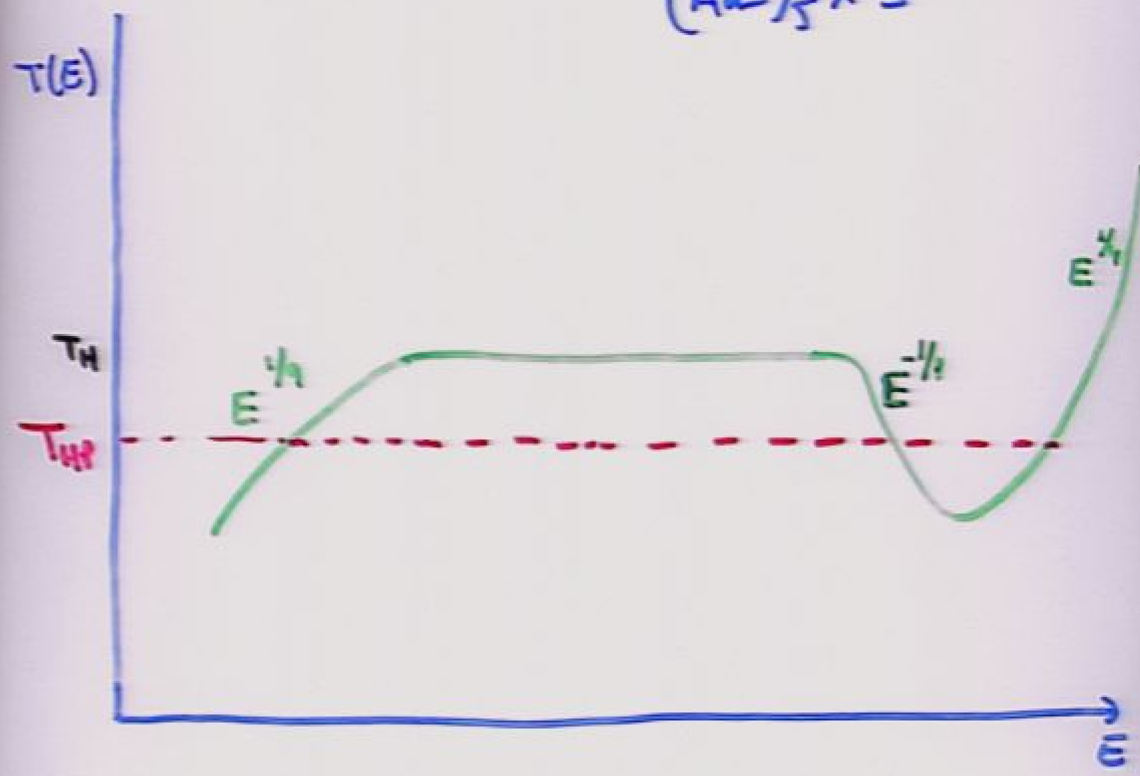
$$V_{JEANS} \simeq (G_D E)^{\frac{D-1}{D-3}}$$

$$E < \frac{V^{\frac{D-3}{D-1}}}{G_D}$$



$\Rightarrow \rho = \frac{E}{V} \rightarrow \ldots \rightarrow 0 \Rightarrow$ THERMO

$(AdS)_5 \times S^5$

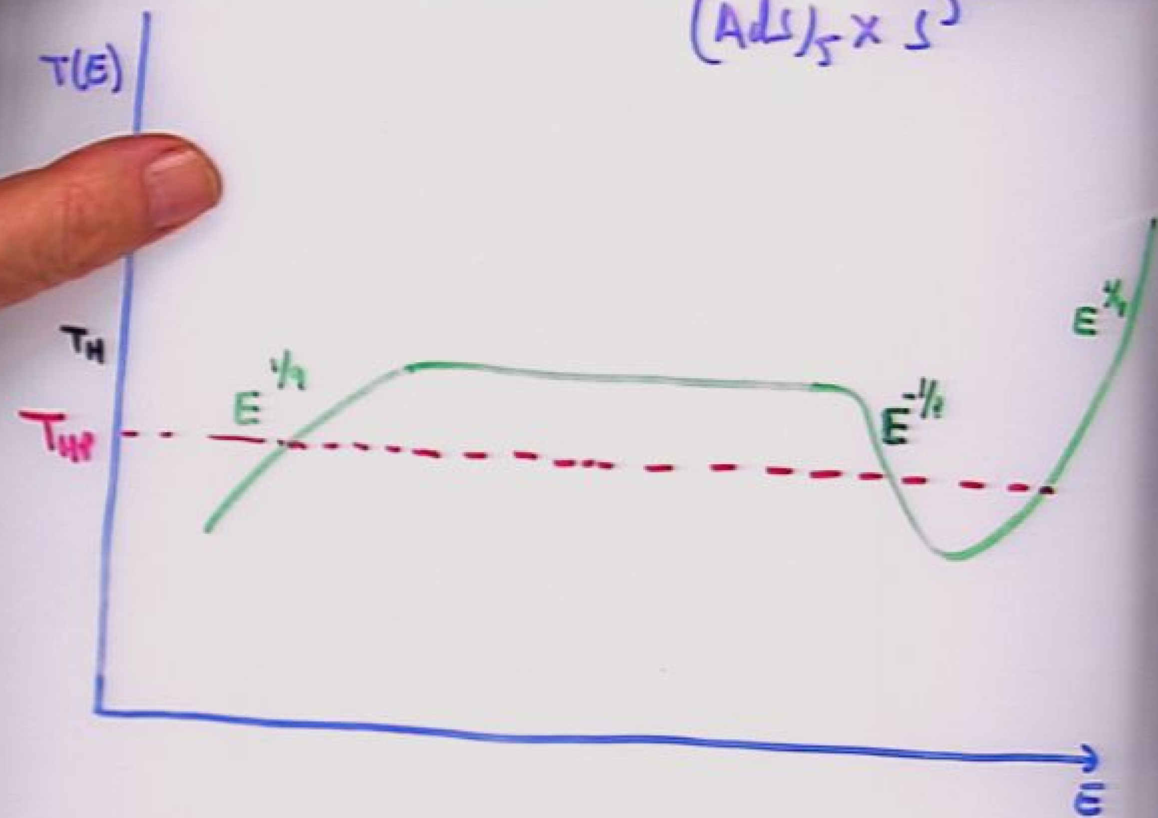


FOR LST ?

NO GRAVITY

HAGEDORN

$(AdS)_5 \times S^5$



FOR LST ?

NO GRAVITY

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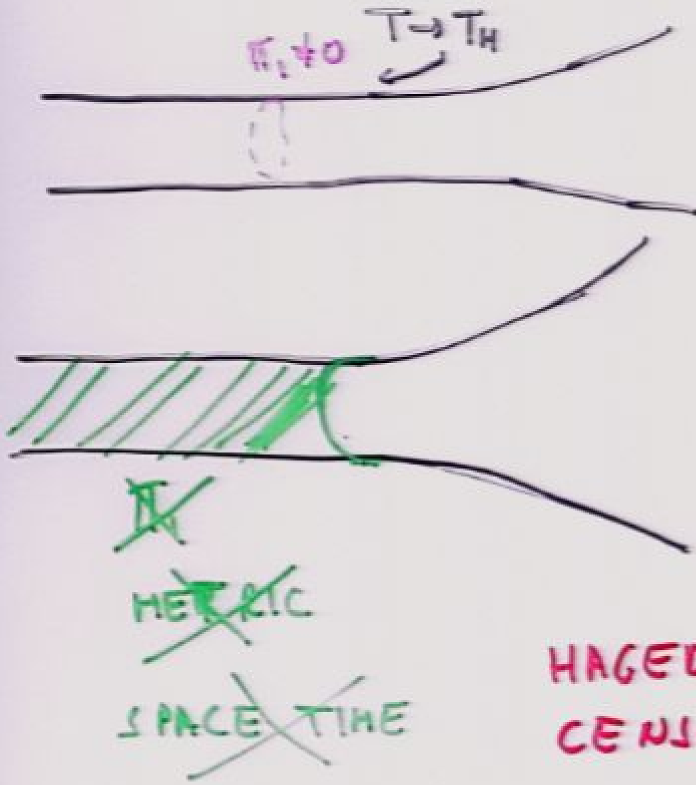


EXIT STRATEGY

HAGEDORN CENSORSHIP

J. BARBON, E.R.

* LST GEOMETRY
* LST THERMODYNAMICS

* HORIZON DEGENERACY – CLASSICAL
* QUANTUM RADIATION
  NON RELATIVISTIC
  NON HOLOGRAPHIC (AdS $\neq$)
* CANONICAL – PROBLEMS..
* MICROCANONICAL – LIMITS DON'T
  COMMUTE.

* UV COMPLETION

NON COMMUTING LST
QUANTUM FIRST ORDER TRANSITION
[illegible]

* LST THERMODYNAMICS

* HORIZON DEGENERACY – CLASSICAL

* QUANTUM RADIATION
  NON RELATIVISTIC
  NON HOLOGRAPHIC (AdS $\neq$)

* CANONICAL – PROBLEMS..

* MICROCANONICAL – LIMITS DON'T COMMUTE.

* UV COMPLETION

NON COMMUTING LST
QUANTUM FIRST ORDER TRANSITION
HAGEDORN TRANSIENT/CENSORED

LST

I.E. $g_s \to 0$ $R = \ell_s \sqrt{N}$ FIXED

OF N NS5 BRANES IN IIA.

RESULTS IN:

$$M^{5,5}\ R_\phi\ S^3_R$$

$\uparrow$ N UNITS OF NS5 FLUX.

$$ds^2 = -dt^2 + dy_5^2 + dz^2 + R^2 d\Omega_3^2$$

$$e^\phi = \exp(-z/R)$$

LIMIT RETAINS

T- DUALITY , NON LOCAL

? QFT < LST < ST

BY

$$r = g_s R \exp\left(\frac{z}{R}\right)$$

AND BEING NON-EXTREMAL ONE

OBTAINS THE THERMAL BEHAVIOR

$$ds^2 = -dt^2\left(1 - \frac{r_0^2}{r^2}\right) + dy_5^2 + \frac{R^2 dr^2}{r^2 - r_0^2} + R^2 d\Omega_3^2$$

$$e^{\phi} = g_s R/r$$

$$S = \beta_H E$$

$$T \equiv T_H = \frac{1}{2\pi R} = \frac{1}{\ell_s}\frac{1}{2\pi\sqrt{N}}$$

$$\frac{\partial T}{\partial r_0} = 0 \Rightarrow I(r_0) = \beta_H E(r_0) - S(r_0) = 0$$

$$\beta_H E(r_0)$$

$$\frac{\partial I}{\partial r_0} = 0$$

$$E(r_0) = \frac{V_5\, m_s^8\, r_0^2}{(2\pi)^5\, g_s^2} \qquad \text{FIXED}$$

$$\tilde{E} = \frac{V_5\, m_s^6\, N}{(2\pi)^5} + E(r_0)$$

NON DECOUPLED METRIC, DILATON

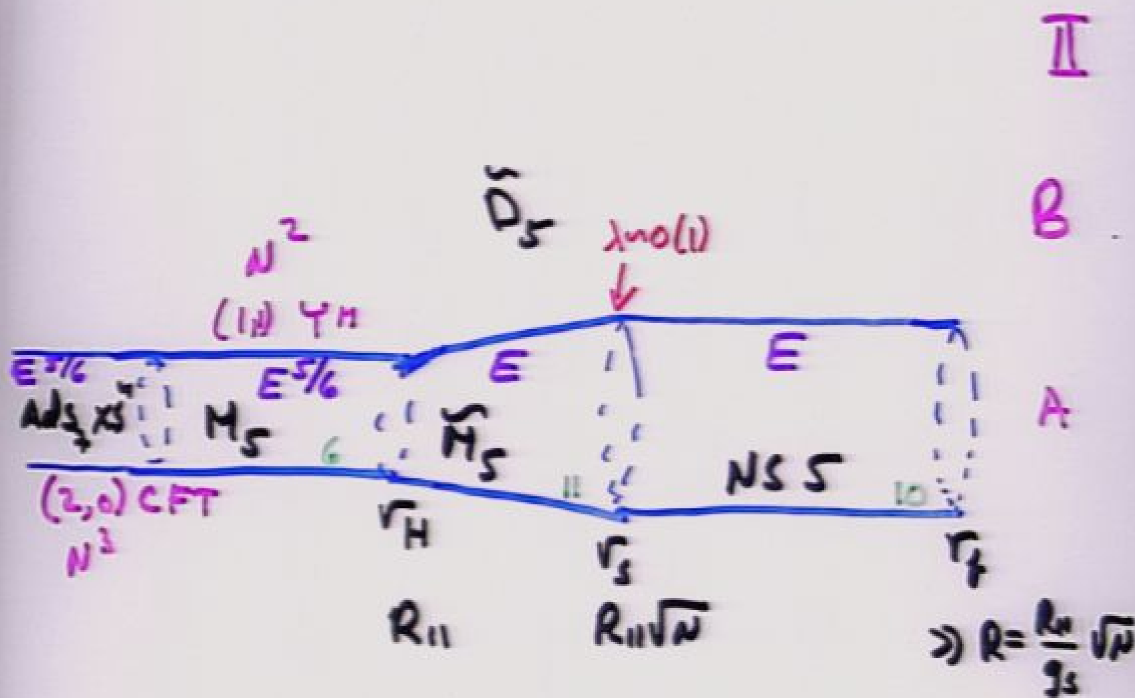
$$ds^2 = -dt^2\left(1-\frac{r_0^2}{r^2}\right) + dy_5^2 +$$

$$+ \left(1+\frac{R^2}{r^2}\right)\left(\frac{dr^2}{1-\frac{r_0^2}{r^2}} + r^2\, d\Omega_3^2\right)$$

$$e^{2\phi} = g_s^2\left(1+\frac{R^2}{r^2}\right) \sim O(1) \text{ FOR } r \sim g_s R$$

$$g_s R = g_s \ell_s \sqrt{N} = R_{11}\sqrt{N}$$

$$R_{11} = g_s \ell_s$$



$$R = \ell_s \sqrt{N}$$

$$R_{11} = g_s \ell_s$$

BACK TO "FULL METRIC"

$$T(r_0) = \frac{1}{2\pi\sqrt{r_0^2 + R^2}}$$

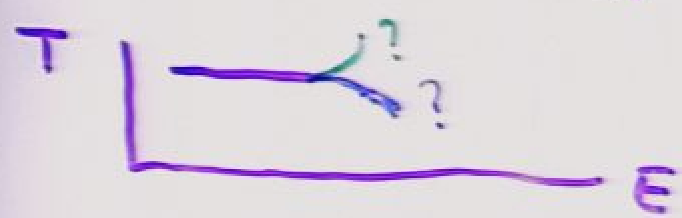
$$E(r_0) = \frac{V_5\, m_s^8\, r_0^2}{(2\pi)^5\, g_s^2}$$

$$\Rightarrow \frac{\partial T}{\partial E} < 0 \qquad C_v < 0$$

PROBLEM.

* HOW TO REMOVE r_0 DEGENERACY

* $C_v > 0$? $\quad C_v < 0$



CORRECTIONS:

* α'
* g_s
  - → HORIZON
  - → TUBE

HOLOGRAPHY OF RADIATION

* BH

$(AdS)_{\substack{5 \\ d+1}} \times S^5$

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

$(AdS)_{BH}$ HORIZON $r_0 = 2\pi R^2 T$

LEADING TERM FOR ENTROPY $\frac{\partial r_0}{\partial T} \neq 0$

$$S_{BH} = \frac{V_{d-1}\, r_0^{d-1}}{4 G_{d+1} R^{d-1}} = \underbrace{\frac{(2\pi R)^{d-1}}{G_{d+1}}}_{N_{eff}} V_{d-1} T^{d-1}$$

HOLOGRAPHIC

HOLOGRAPHY OF RADIATION

* BH

$$(AdS)_{5 \atop d+1} \times S^5$$

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

$$r_0 = 2\pi R^2 T$$

TERM FOR ENTROPY $\frac{\partial r_0}{\partial T} \neq 0$

$$= V \ldots \frac{r_0^{d-1}}{\ldots G_{d+1} R^{d-1}} = \underbrace{\frac{(2\pi R)^{d-1}}{G_{d+1}}}_{N_{eff}} V_{d-1} T^{d-1}$$

HOLOGRAPHIC

* RADIATION

$$S_r \sim \int_{r>r_0} d\vec{V} \left(\frac{T}{\sqrt{-g_{tt}}}\right)^d$$

OPTICAL VOLUME!

$$S_r = \# \, T^{d+1} \, V_{\text{OPTICAL}}(AdS(T)) =$$

$$\sim V_{d-1} T^{d-1}$$

* NO RADIAL EXTENSIVITY
* NO KK S^5
* WORKS FOR Dp BRANES

$$p < 5$$

$p = 5$ D5 NS5

V_{eff}

CONSIDER

$$ds^2 = -f(r)\,dt^2 + \frac{dr^2}{g(r)} + \sum_i \rho_i^2(r)\,\underbrace{ds_i^2}_{\substack{d_i \text{ dimensional} \\ \text{Riemannian} \\ \text{space}}}$$

$$S_\psi = -\frac{1}{2}\int d^D x\,\sqrt{-g}\,e^{-2\phi}\left(g^{\mu\nu}\partial_\mu\psi\,\partial_\nu\psi + m^2\psi^2\right)$$

ψ SCALAR FROM NSNS MINIMALLY COUPLED.

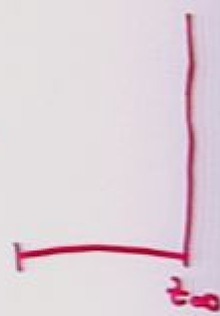
$\Longrightarrow$

$$V_{eff} = \frac{1}{2}\partial_z^2 \log(\rho_\pi) + \frac{1}{4}\left(\partial_z \log \rho_\pi\right)^2$$

$$+ f(z)\left(\tilde{m}^2 + \sum_i \frac{\Delta_i}{\rho_i^2(z)}\right)$$

* $(AdS)_5$

$$V_{eff}(z) \sim \frac{\Lambda^2}{(z - z_\infty)^2} \quad \text{"BOX"}$$



* Dp $\quad p<5 \quad$ BOX

$$\frac{r}{R_{Dp}} = \left(\frac{2}{5-p}\right)^{\frac{2}{5-p}} \left(\frac{R_{Dp}}{z_\infty - z}\right)^{\frac{2}{5-p}}$$

R ... $\sim (g_s N)^{\frac{1}{7-p}}$

$$V_{eff} = \frac{1}{2}\,\partial_z^2 \log(\rho_\pi) + \frac{1}{4}\left(\partial_z \log \rho_\pi\right)^2$$

$$+\, f(z)\left(\tilde{m}^2 + \sum_i \frac{\Delta_i}{\rho_i^2(z)}\right)$$

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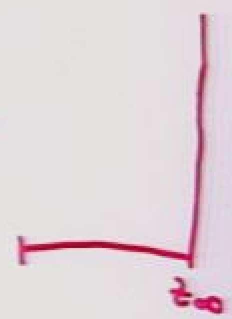


* Dp $\quad p<5 \quad$ BOX

$$\frac{r}{R_{Dp}} = \left(\frac{2}{5-p}\right)^{\frac{2}{5-p}} \left(\frac{R_{Dp}}{z_\infty - z}\right)^{\frac{2}{5-p}}$$

R_{Dp} = CHARGED RADIUS OF $Dp \sim (g_s N)^{\frac{1}{7-p}}$

* NS5

$$ds^2 = f(z)(-dt^2 + dz^2) + \sum_i \rho_i^2(z)\, ds_i^2$$

$f(z)=1$ $\quad S^3 \quad \rho(z) = R$

$\quad R^5 \quad \rho(z) = 1$

$$V_{eff}(z) = \tilde{m}^2 + \vec{p}^{\,2} + \frac{\Delta_{S^3}}{R^2}$$

$$\tilde{m}^2 = m^2 + \frac{1}{R^2} \longrightarrow$$ DILATON SLOPE

DIAGONALIZE BY $\exp(i p_z z)$

$$\omega^2 = p_z^2 + \vec{p}^{\,2} + m^2 + \frac{1}{R^2} + \frac{\Delta_{S^3}}{R^2}$$

* NS5

$$ds^2 = f(z)(-dt^2 + dz^2) + \sum_i \rho_i^2(z)\, ds_i^2$$

$f(z) = 1$ $\quad S^3 \quad \rho(z) = R$

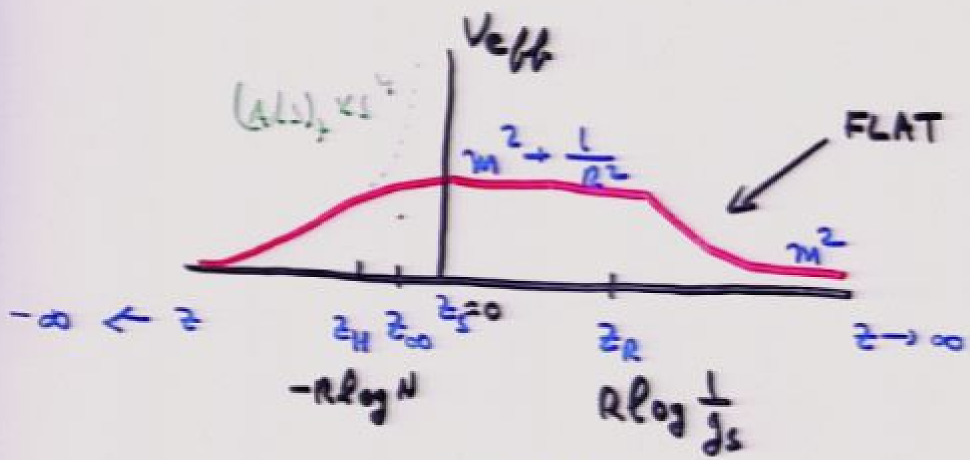
$\quad R^5 \quad \rho(z) = 1$

$$V_{eff}(z) = \tilde{m}^2 + \vec{p}^{\,2} + \frac{\Delta_{S^3}}{R^2}$$

$\tilde{m}^2 = m^2 + \frac{1}{R^2} \longrightarrow$ DILATON SLOPE

DIAGONALIZE BY $e^{x}p(i p_z z)$

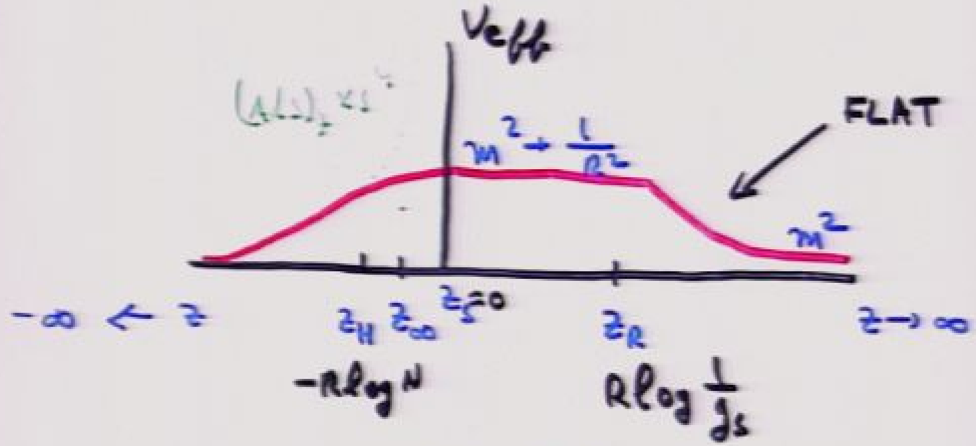
$$\omega^2 = p_z^2 + \vec{p}^{\,2} + m^2 + \frac{1}{R^2} + \frac{\Delta_{S^3}}{R^2}$$



$r_s = g_s R$

NO HOLOGRAPHY IN RADIAL DIRECTION

ONE



$r_s = g_s R$

NO HOLOGRAPHY IN RADIAL DIRECTION

ONE NEEDS TO PROBE WITH
A CUTOFF

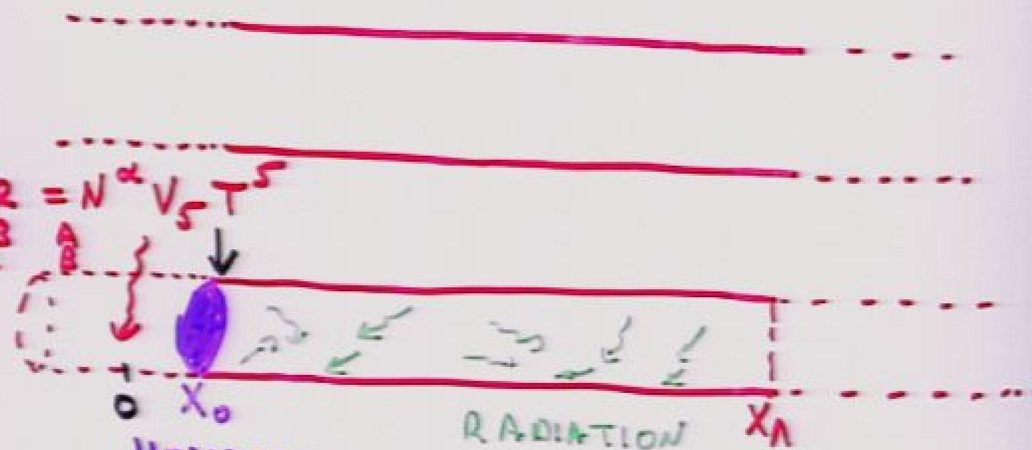
THERMODYNAMICS OF CUTOFF LST

"PISTON" MODEL

$S_{SR} = N^{\alpha} V_5 T^5$

$\alpha = 3$ A

$\alpha = 2$ B



HORIZON

BLACK BRANE

$S = E_\ell(X_0)\,\beta_H$

$E_\ell(X_0) = E_H \exp(2X_0)$

$E_H = N^{\alpha} V_5 T_H^6$

$T_H = \frac{1}{2\pi R}$

$R = \ell_s \sqrt{N}$

$T < T_H$

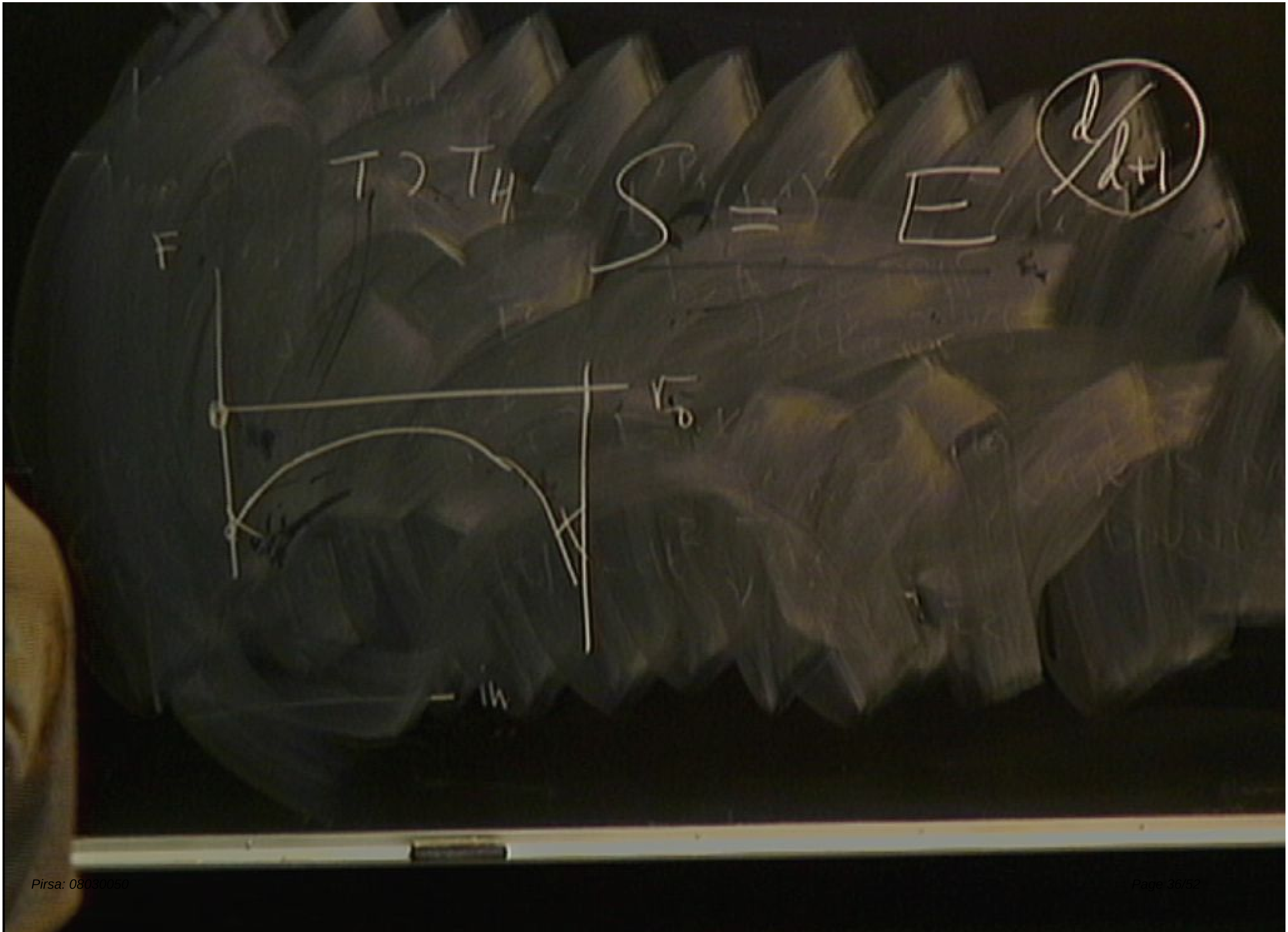
NR RADIATION

$I_R = (X_\Lambda - X_0) R^{-1} V_5 T^3 \exp\left(-\frac{1}{TR}\right)$

$T < T_H$

$T > T_H$

$I \simeq (X_\Lambda - X_0) R^{3} V_5 T^9$



$$\beta(E) = \frac{1}{T_H}\left(1 - \frac{1}{20}\left(\frac{9}{10}\right)^9 \frac{1+2\delta}{N^\alpha \varepsilon}\right)$$

$$\delta = \frac{1}{2}\left(\frac{9}{10}\right)^{10}\left(\frac{x_\Lambda - \frac{1}{2}\log\frac{E}{E_H}}{N^\alpha \frac{E}{E_H}}\right)$$

* $C_v < 0$ $\quad \frac{1}{2}\log\frac{E}{E_H} < X_\Lambda \ll N^\alpha \frac{E}{E_H}$

UV COMPLETION

* SUPPLY CUTOFF + D.O.F

* FIRST ORDER TRANSITION.

* RADIATION WILL BE HOLOGRAPHIC

DECONSTRUCTION:

N. DOREY

ARKANI-HAMED, COHEN, KARCH, MOTL, KAPLAN

DECONSTRUCTION:

N. DOREY

ARKANI-HAMED, COHEN, KARCH, MOTL, KAPLAN

* THERMODYNAMICS OF $\widetilde{LST}$ II A

CLASSICAL AND QUANTUM

CLASSICAL

* $\widetilde{LST}$ B

* $N=4$ SUSY YM β DEFORMED

* HIGGS BRANCH GIVES

DECONSRUCTED $D=6$ YM.

* DUAL GEOMETRY HAS D5 S

S DUALITY

* TOUGH ON SUSY YM

WORKS ON GEOMETRY D5S $\leftrightarrow$ NS5

BUT TYPE B.

T DUALITY

* • CLASSICAL $\widetilde{LST}$ II A. NC HOLO

* CLASSICAL THERMO + QUANTUM

II B

D=4 $\quad$ N=4 $\quad$ $U(\hat{N})$ SUSY YM

$$W = i\kappa\left(\exp(i\bar{\beta}/2)\,\phi_1\phi_2\phi_3 - \exp\left(-\frac{i\bar{\beta}}{2}\right)\phi_1\phi_3\phi_2\right)$$

PARAMETERS $\quad g, \kappa, \bar{\beta}$

$$\tau = \frac{4\pi i}{g^2} + \frac{\theta}{2\pi}$$

* EXACTLY MARGINAL OPERATOR

* DUALITY : $\quad SL(2,\mathbb{Z})$

$$\tau_R = \tau + \frac{i\hat{N}}{\pi}\log\kappa$$

$$\det\begin{pmatrix} a & b \\ c & d \end{pmatrix} = 1 \quad \tau_R \to \frac{a\tau_R + b}{c\tau_R + d} \; ; \; \beta \to \frac{\beta}{c\tau_R + d} \; ; \; \kappa^2 \sin\beta \to \frac{\kappa^2 \sin\beta}{c\tau_R + d}$$

S DUALITY INCLUDED

* FOR $\beta = \frac{2\pi}{n}$ $\hat{N} = Nn$

(S DUAL) $\tilde{\beta} = \frac{i 8\pi^2 n}{g^2}$ $\tilde{g}^2 = \frac{16\pi^2}{g^2}$

$U(\hat{N}) \rightarrow U(N)$ BY NON COMMUTING ϕ_i

HIGGS BRANCH

WHEN

$\langle \phi_1 \rangle = \alpha_1 I_{N \times N} \otimes \Gamma_{1\, n \times n}$

$\langle \phi_2 \rangle = \alpha_2 I_{N \times N} \otimes \Gamma_{2\, n \times n}$

$\langle \phi_3 \rangle = \alpha_3 I_{N \times N} \otimes \Gamma_2^{+} \Gamma_1^{+}{}_{n \times n}$

$(\Gamma_1)_{ij} = \delta_{ij} w^i$ $(\Gamma_2)_{ij} = \delta_{i, j-1}$

$w^i = \exp\left(\frac{2\pi i}{n}\right)$

* P 'S AT

* FOR $\beta = \frac{2\pi}{n}$ $\hat{N} = Nn$

(S DUAL) $\tilde{\beta} = \frac{i 8\pi^2 n}{g^2}$ $\tilde{g}^2 = \frac{16\pi^2}{g^2}$

$U(\hat{N}) \rightarrow U(N)$ BY NON COMMUTING ϕ_i

HIGGS BRANCH

WHEN

$\langle \phi_1 \rangle = \alpha_1 I_{N \times N} \times \Gamma_{1\, n \times n}$

$\langle \phi_2 \rangle = \alpha_2 I_{N \times N} \times \Gamma_{2\, n \times n}$

$\langle \phi_3 \rangle = \alpha_3 I_{N \times N} \times \Gamma_2^\dagger \Gamma_1^\dagger{}_{n \times n}$

$(\Gamma_1)_{ij} = \delta_{ij} w^i \quad (\Gamma_2)_{ij} = \delta_{i, j-1}$

$w^i = \exp\left(\frac{2\pi i}{n}\right)$

* 'S AT

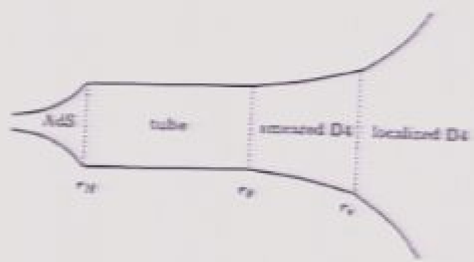


Fig. 6: *Rendering of the background profile in IIA deconstruction.*

We may summarize the energy hierarchies for both IIA ($\alpha = 3$) and IIB ($\alpha = 2$) cases by the relations

$$\frac{E_g}{E_H} \sim \left(\frac{n}{n_{\rm eff}^{4-\alpha}}\right)^2, \qquad \frac{E_s}{E_H} \sim \left(\frac{n}{n_{\rm eff}^{3-\alpha}}\right)^2. \tag{6.19}$$

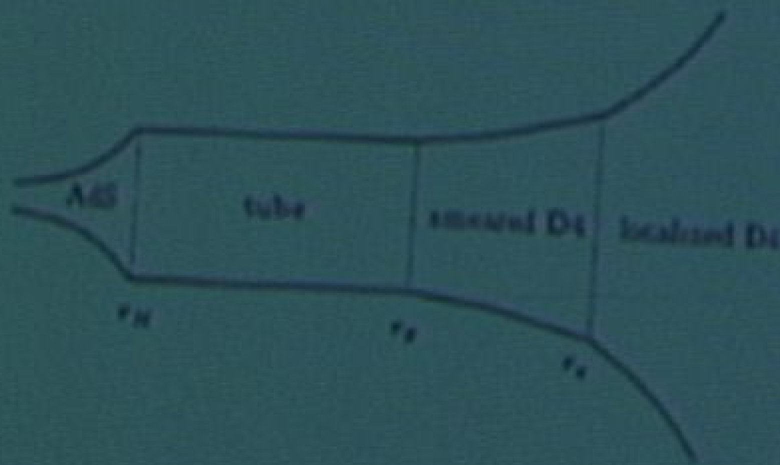


Fig. 6: *Rendering of the background profile in IIA deconstruction.*

We may summarize the energy hierarchies for both IIA ($a = 3$) and IIB ($a = 2$) cases by the relations

$$\frac{E_g}{E_H} \sim \left(\frac{n}{n_{\rm eff}^{4-a}}\right)^3, \qquad \frac{E_s}{E_H} \sim \left(\frac{n}{n_{\rm eff}^{3-a}}\right)^2. \qquad (6.19)$$

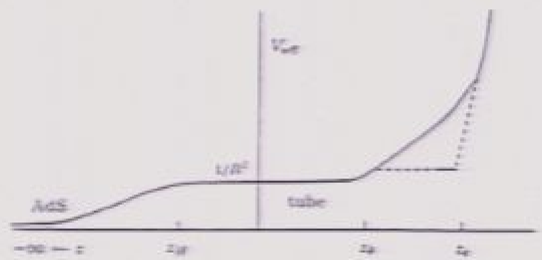


Fig. 7: Effective radiation potential in the deconstructed type IIA LST background. For $z_a \ll z \ll z_e$ the tube plateau steps up to $(3/2R)^2$ for modes with zero momentum in the noncommutative direction, whereas we encounter an exponential wall for non-vanishing momentum modes.

$$V_{eff}(z) = \vec{k}_c^{\,2} + f^2(z)\,\vec{q}^{\,2} + \frac{\Delta_s^2}{R^2} + \left(\frac{\alpha}{2R}\right)^2$$

C   NC $q \neq 0$

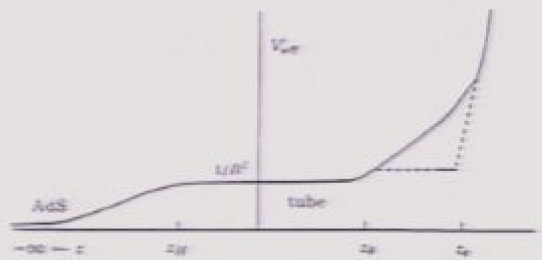


Fig. 7: Effective radiation potential in the deconstructed type IIA LST background. For $z_a \ll z \ll z_e$ the tube plateau steps up to $(3/2R)^2$ for modes with zero momentum in the noncommutative direction, whereas we encounter an exponential wall for non-vanishing momentum modes.

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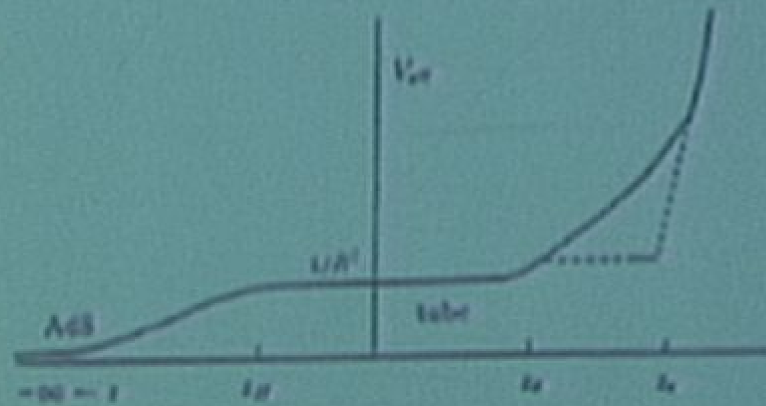

Fig. 7: *Effective radiation potential in the deconstructed type IIA LST background. For $z_a \ll z \ll z_s$ the tube plateau steps up to $(3/2R)^2$ for modes with zero momentum in the noncommutative direction, whereas we encounter an exponential wall for non-vanishing momentum modes.*

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$$V_{eff}(z) = \vec{p}_c^{\,2} + f^2(z)\,\vec{q}^{\,2} + \frac{\Delta_s^2}{R^2} + \left(\frac{\alpha}{2R}\right)^2$$

c NC $q \neq 0$

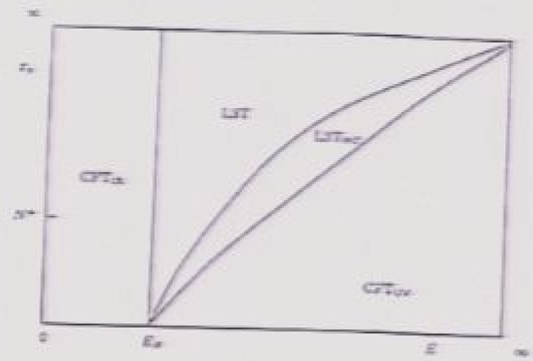

Fig. 8: *Phase diagram of the deconstructed LST theory, as a function of the energy and the effective length of radiation tube, z_e, in the classical approximation. The noncommutative LST transient is supported by the ratio $n_{eff} = L/\epsilon \gg 1$, disappearing when it approaches unity.*

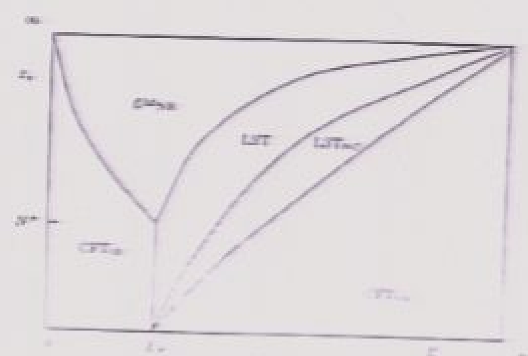

Fig. 9: The complete phase diagram of the deconstructed LST theory, as a function of the energy and the tube cutoff z_e. Comparing with the phase diagram in the classical approximation, we see that the main effect of the radiation corrections is [illegible] N^*, dominated by the seven-[illegible]

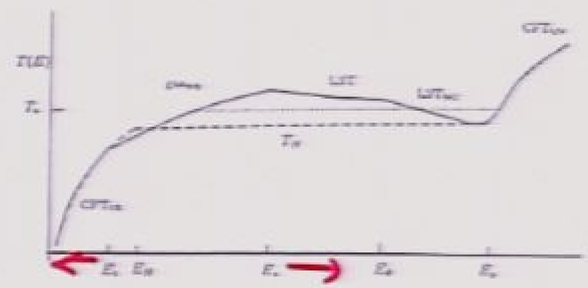

Fig. 10: *The microcanonical temperature function, showing stable, unstable and metastable phases, as a function of the important thresholds in the system. The dashed line represents the classical approximation, with a Hagedorn plateau extending from E_H out to E_s. The dotted line gives the Maxwell construction of the first-order phase transition at the critical temperature T_c. In the limit when we decouple the UV fixed point, $E_s \to \infty$, the high-energy thresholds of the tube E_c and E_s diverge, whereas the low-energy threshold E_t vanishes. In this limit, only the nonrelativistic gas remains.*

FIRST ORDER PHASE
TRANSITION RADIATION "EFFECTS"

* "THROW THE BABY WITH BATH WATER"

$z_\varepsilon \to \infty$

* CENSORSHIP

CONCLUSIONS:

* LST CAN BE EMBEDDED IN UV COMPLETE SYSTEM.
  - HAGEDORN IS TRANSIENT.
  - FIRST ORDER TRANSITION
  - HAGEDORN CENSORSHIP

* ON ITS OWN HAS IR DEPENDENCE.

* FOLLOW V