(A) D-Sitter:

Flux Compactifications, QFT_3 and 4d Holography

D-Sitter space hep-th/0304220 M. Fabinger & E.S.

+ ongoing work w/ S. Hellerman, X. Liu

using Maloney ES Strominger 0205316
Kachru Kallosh Linde Trivedi 0301240

The Cosmological Term

$\Lambda(\Phi_I)$

scalars (moduli, tachyons)

is interesting because it

a) Has crucial observable effects (acceleration, inflation)

b) Carries information about high energies

UV sensitive

$\Lambda_{hard} > 0 \Rightarrow dS$

$\Rightarrow$ horizon

area $\frac{A}{4G_N} = S_{entropy}$

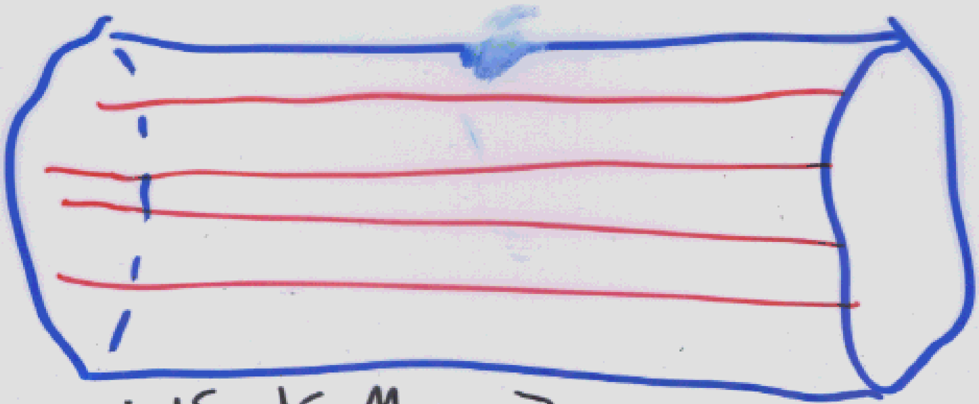
In order to obtain a (metastable) de Sitter solution in string theory, we must fix the moduli.

In recent years, this has been accomplished by balancing enough independent forces acting on the moduli coming from canonical ingredients in string compactifications

asymmetric orbifolds,
tree level c.c. from $D \neq D_{crit}$ } Maloney, E. S., Strominger

$\boxed{\text{Fluxes}}$

gaugino condensates,
antibranes,
* low energy SUSY EFT } Kachru, Kallosh, Linde, Trivedi



$\uparrow X$

AdS, dS, M $\longrightarrow$

Flux compactifications

$$\int_{C\subset X} F^{i} = Q^{i}_{\gamma}$$

+ other forces from O-planes, curvature, branes, supercriticality, instantons, ...
$\Downarrow$
fixed moduli

Strominger
⋮
Acharya
Kachru Kallosh Linde Trivedi
Maloney E.S. Strominger
...

Freund-Rubin
⋮
Maldacena ...

$$\left\{\begin{matrix} AdS \\ \boxed{dS} \\ M \end{matrix}\right\} \times X$$

$\nearrow$

$\left\{\begin{matrix} \text{Calabi Yau} \\ \text{Orientifold} \\ \text{etc.} \end{matrix}\right\}$ with fixed moduli, $\boxed{\text{small volume}}$

Realistic Physics, dS

AdS/CFT

$$AdS_p \times S^q$$

$\nearrow$

large Einstein space

$\boxed{\text{Comes from } \cancel{\text{realistic}} \text{ near horizon limit of D-branes}}$

Holography,
Q. Gravity

Fluxes, in particular Ramond-Ramond fluxes, play a crucial role.

In all known examples, the dilaton is stabilized as follows:

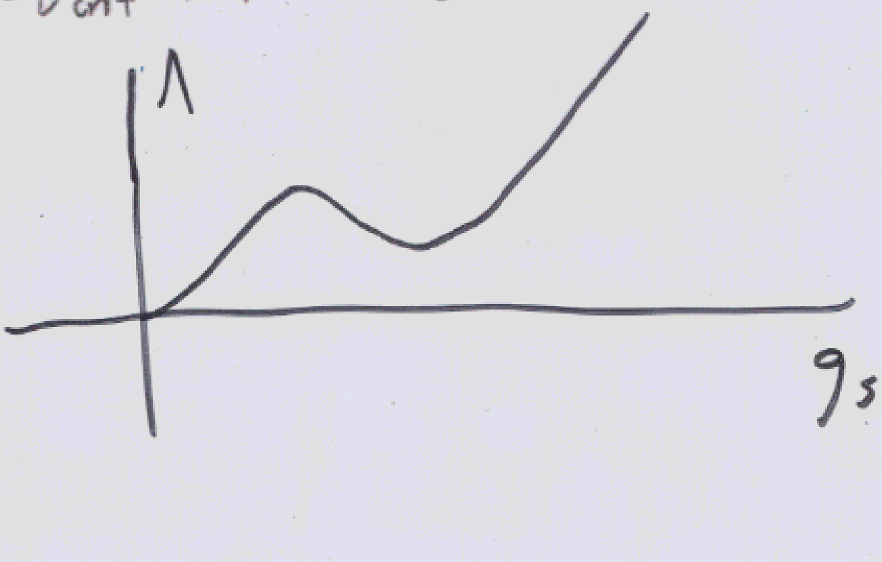
Einstein-frame potential

$$\Lambda = \frac{g_s^{\frac{4}{d-2}}}{l_d^2}\left(a - b g_s + Q_{RR}^2 g_s^2\right)$$

$\int R$ Einstein curvature
$\int H_{NS}^2$ Neveu-Schwarz flux
$D - D_{crit}$ supercriticality

orientifolds + D-branes

RR flux
$\int F_{RR}^2$
cycles



If we scale up the RR flux Q_{RR} leaving other parameters fixed, This potential fixes the dilaton at

$$\boxed{g_s \sim \frac{1}{Q_{RR}}}$$

This simple relation coming from the flux compactification plays a large role in cleanly relating macroscopic GR area entropy $\longleftrightarrow$ microphysical entropy

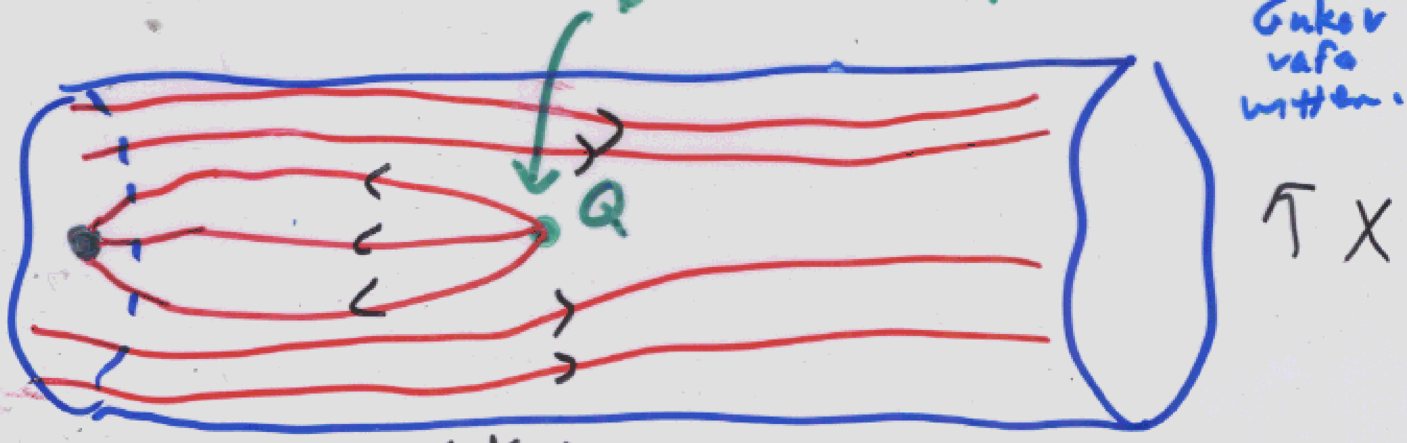
In AdS/CFT, we have a microscopic understanding of the gravity background via low energy limit of Q_γ (D-) branes

e.g. entropy Q_γ^2
(Susskind - Witten)

* In generic flux compactifications, including dS cases, we can also trade flux for D-branes in a useful sense:

Q D-branes : domain wall in AdS, dS, M

Gukov Vafa Witten...



AdS, dS, M ⟶

L

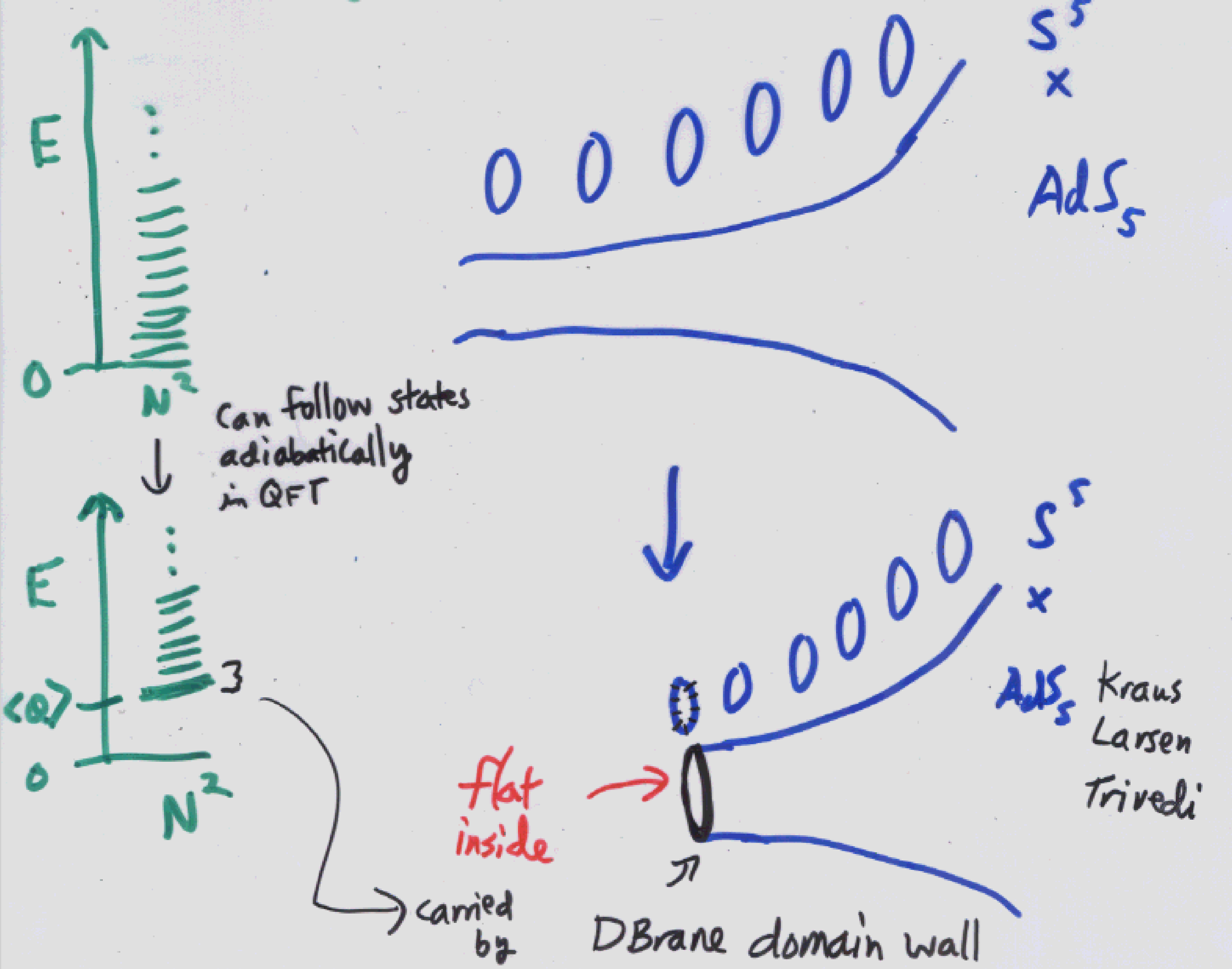
$$\int_{c<X} F = Q_L = Q_R + Q$$

R

$$\int_{c<X} F = Q_R$$

In AdS/CFT this deformation corresponds to giving VEVs to scalars on the gauge theory side. e.g. in $AdS_5 \times S^5 / \mathcal{N}=4$ SYM

one can go on the Coulomb branch



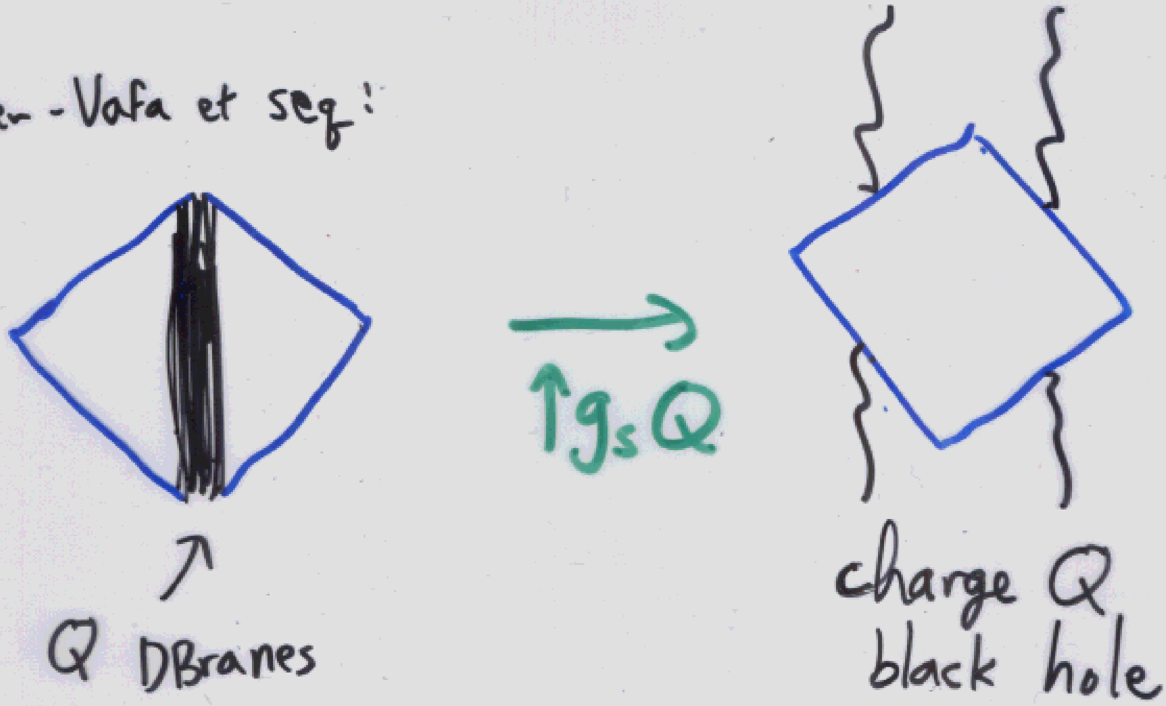
With enough information about the Coulomb branch deformations of a theory, one may be able to reconstruct the theory itself

We can obtain this type of deformation to a D-brane system, "DS" in de Sitter space obtained via flux compactification. (& AdS)

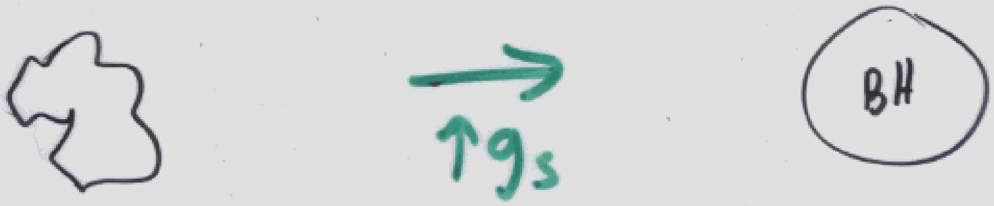
1) DS causal structure, thermodynamics
2) DS entropy ↔ dS entropy
3) Work in progress on larger (dual?) QFT containing (A)DS configurations as deformations

Before proceeding, it is instructive to compare this to the black hole entropy counts

Strominger - Vafa et seq:



Susskind - Horowitz - Polchinski



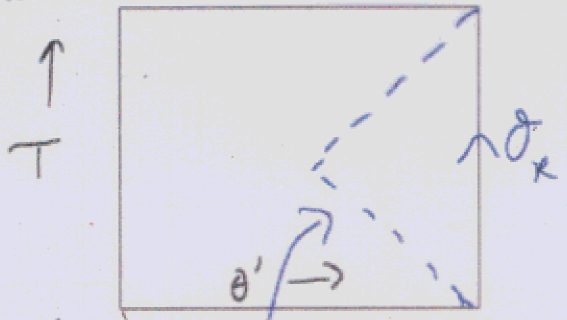
$S_{str} \sim S_{BH}$ at $R_{BH} \sim l_s$

Ours is also a deformation from "D-Sitter" to de Sitter, but by changing $\langle Q_i \rangle$ (VEVs of worldvolume scalars) rather than g_s

1) DS causal structure, thermodynamics

$$ds^2 = \frac{1}{\cos^2 T}\left(-dT^2 + d\theta'^2 + \sin^2\theta' \, d\Omega^2_{d-2}\right)$$

dS Penrose diagram



static causal patch

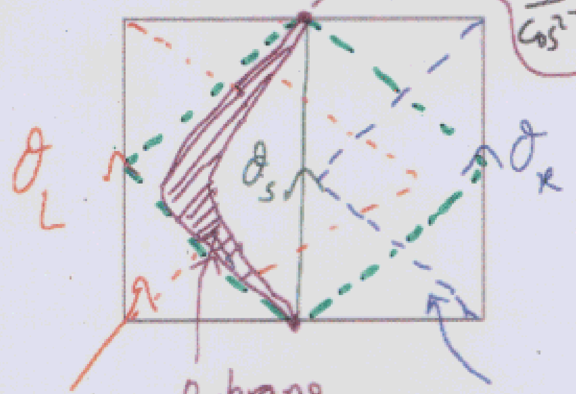
hot horizon, area $A \sim R_{dS}^{d-2}$

suggest entropy $S \sim \frac{R_{dS}^{d-2}}{l_d^{d-2}}$

$\downarrow \langle Q \rangle$

identification $\frac{1}{\cos^2 T_L} = 1 + \frac{R_R^2}{R_L^2}\left(\frac{1}{\cos^2 T_R} - 1\right)$

DS Penrose diagram



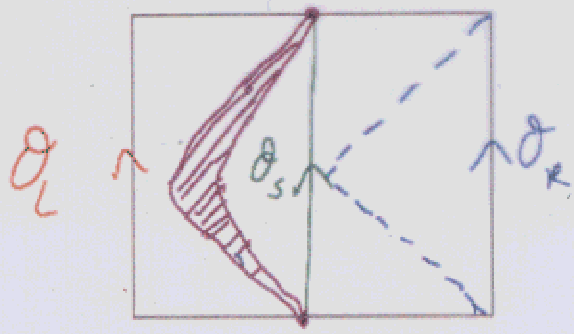
dS_L
Λ_L
Q_L

0-brane bubble wall temperature
$T \sim \frac{1}{2\pi R_B}$

dS_R
Λ_R
Q_R

↑ acceleration + ambient dS temperature

2) DS ↔ dS entropy



Using the temperature derived from the geometry, the QFT living on the D-branes, and the geometry of the D-branes as a function of their tension $T_D = \frac{Q}{g_s l_s^{d+1}}$, we can evaluate how much entropy can be transmuted into D-brane states for each observer

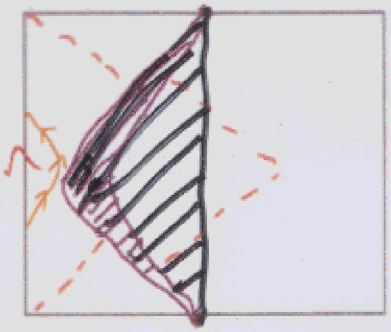
θ_L : stringy "correspondence point" at which $R_{dS_R} \sim l_s$
- $S_D \sim S_{GR}$
- Bousso bound saturated

* θ_s : QFT modes on horizon from D-branes + $g_s \sim \frac{1}{Q_{RR}}$ ⇒ correct entropy $\xrightarrow{?}$ 4d holographic $R_{dS} \gg l_s$

the results are:

① for $\mathcal{O}_L$:

can send spherically symmetric probe out to the bubble e.g. at $T=0$



$$S_D = f(g_{eff})\, Q^2 \underbrace{R_B^{d-2}\; T_B^{d-2}}_{1} \sim Q^2$$

$$\frac{R_R}{l_s} \sim \frac{1}{g_s Q} \qquad S_R \sim \frac{Q^2}{(g_s Q)^d}$$

$\downarrow$

S_D for $R_R \to l_s$

string-scale "correspondence point" at which the entropies agree

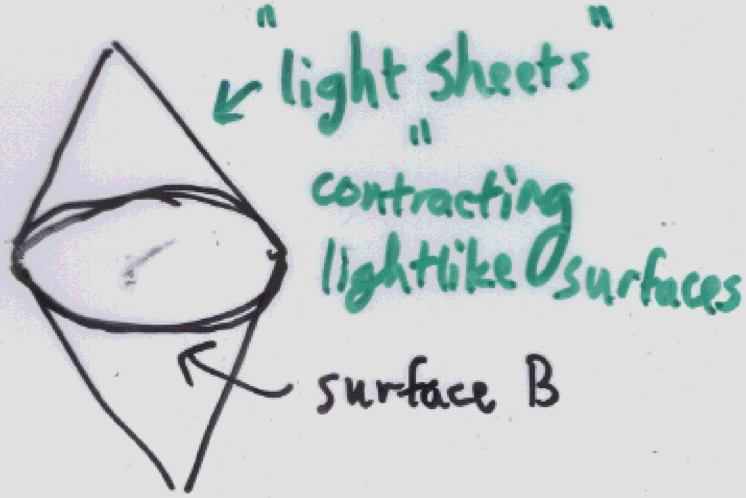
cf. Susskind Horowitz Polchinski BH correspondence point

Bousso's Bound

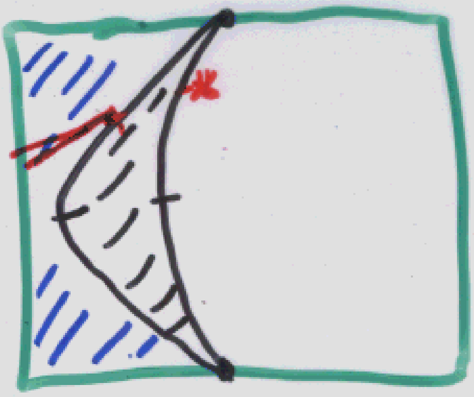
→ Conjecture:

Entropy on any light sheet of B cannot exceed

$$\frac{A_B}{4 l_d^{d-2}}$$



- covariant
- tested in many examples



Bousso conjecture $\Rightarrow S_D < \dfrac{A_*}{4 l_d^{d-2}} \Rightarrow g_s^2 < \dfrac{1}{Q^2}\left(\dfrac{R_B}{l_s}\right)^{d-2}$

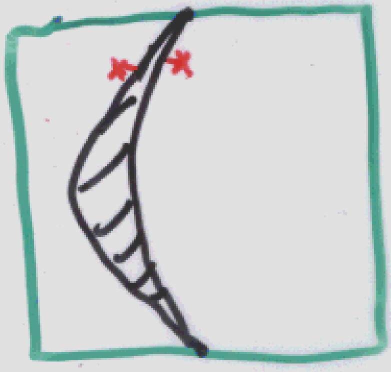
$$Q^2 A_* \propto T_B^{d-2}$$

Sharpest at correspondence point

$R_B \sim l_s \Rightarrow g_s^2 < \dfrac{1}{Q^2} \sim \dfrac{1}{Q_\gamma^2}$

Indeed since $g_s \sim \dfrac{1}{Q_\gamma}$ Bousso's bound is saturated for all time at corr. pt.

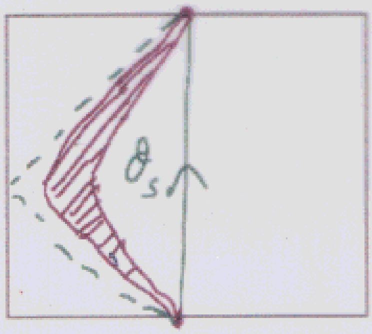
A refinement of Bousso's bound (Flanagan et al) can also be applied. e.g.



$$\frac{\Delta A}{4\, l_d^{d-2}} > S_D \Rightarrow Q^2 (g_s Q)^{-\frac{3d}{4}} > Q^2$$

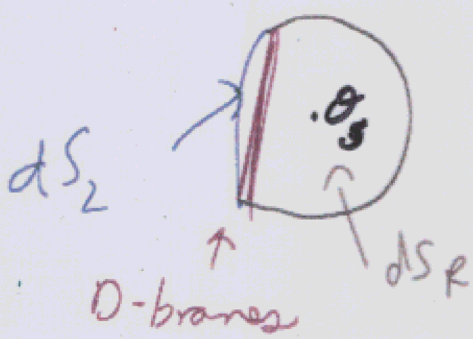
$$\checkmark \quad g_s Q \le 1 \Leftrightarrow R_R \gtrsim l_s$$

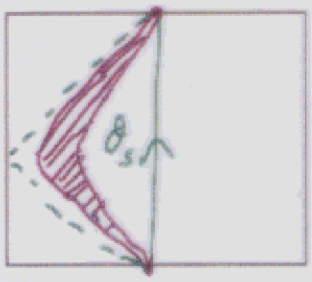
* ② For $\mathcal{O}_s$:



$\mathcal{O}_s$ is an observer staying a fixed proper distance from the branes. $\mathcal{O}_s$ has a static (time-independent) coordinate system covering its causal patch.

spatial slice:

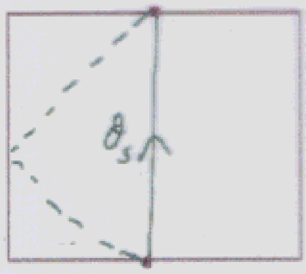




* As we deform the system back to dS_R; the D-branes approach (a patch of) the horizon for all time

Suggests open string theory (or its low energy QFT limit) living on the horizon cf Susskind Uglum

Taking this possibility seriously leads to tantalizing numerology for entropy arising from $g_s \sim \frac{1}{Q_{RR}}$ in flux models:



Back to dS

QFT with Q_{RR}^2 degrees of freedom (from low energy limit of open strings ending on $Q \sim Q_{RR}$ D-branes)

at a temperature $T_{QFT} \sim \frac{1}{l_s}$

on S^{d-2} with area $A_{horizon} \sim R_{dS}^{d-2}$

(These are the natural naive assumptions one would make)

$\rightarrow$ entropy

$$S_{\substack{QFT \\ \text{on horizon}}} = Q_{RR}^2 R_{dS}^{d-2} T^{d-2}$$

$$= Q_{RR}^2 R_{dS}^{d-2} \frac{1}{l_s^{d-2}} \sim \frac{R_{dS}^{d-2}}{l_d^{d-2}} \sim \frac{A}{G_N} \sim S_{dS}$$

$Q_{RR}^2 \rightarrow$ * $\frac{1}{g_s^2}$ from flux stabilization of dilaton

$l_s^{d-2} \sim \frac{g_s^2}{l_d^{d-2}}$

Together, these results for the static observer $\mathcal{O}_s$ suggest a dual description of the dS static patch based on a finite temperature field theory w/ Q_{RR}^2 degrees of freedom.

→ What is this QFT?

Our situation is analogous to deducing the $\mathcal{N}=4$ Super-Yang-Mills theory as dual to $AdS_5 \times S^5$ from knowledge of its Coulomb branch, visible on D-brane domain walls.

We are in the process of working this out in our case:

4d holography from (A)dS flux compactifications

with M. Fabinger
S. Hellerman
X. Liu

From the D-brane domain walls in KKLT models (D5-branes and NS 5-branes wrapped on 3-cycles of the CY, with 3-branes ending on them according to the anomaly $\frac{1}{2(2\pi)^2\alpha'^2}\int H\wedge F = \frac{N_{O3}}{4} - N_{D3} + N_{\overline{D3}}$)

we obtain a $d=3$ QFT with the following content: (trading all flux for branes)

$$\prod_{I=1}^{h_{3/2}} U(Q_A^I)\times U(Q_B^I)\times U(N_A^I)\times U(N_B^I)\times U(N_3^I)$$

Φ adjoint scalars

$C^{a\bar{b}}$ bifundamental + fermions

$$\prod_{I=1}^{h_{3/2}} U(J_A^I)\times U(J_B^I)\times U(N_3^I)$$

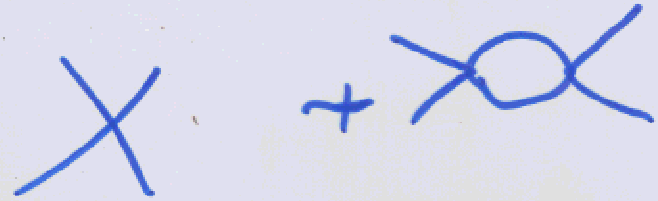
from (p,q) "bound states" A & B 3-cycles

$J^I_{A(B)}$ = g.c.f. of $N^I_{A(B)}, Q^I_{A(B)}$

3d gauge theories with enough matter have nontrivial IR fixed points

Appelquist et al e.g.

Φ^4



$$-\lambda + Q\lambda^2 \to \boxed{\begin{array}{l} \lambda_* \sim \frac{1}{Q} \\ g_s \sim \frac{1}{Q_{RR}} \end{array}}$$

The <u>KKLT SUGRA equations of motion</u> fixing the moduli take the form of β function equations ($\beta_I = 0$) when translated into the parameters of our QFT:

cycle volumes

$$D_Q W = 0 \Rightarrow \beta_Q \equiv -2\frac{N_J V_J}{g_D^2} + \frac{Q^J V_J}{g_N^2} = 0$$

g_s ; 1

$$D_i W = 0 \Rightarrow \beta_i \equiv \frac{\tilde{Q}^i}{g_N^2} - \frac{\tilde{N}^i}{g_D^2} + \frac{V_i}{V}\left(\frac{Q^J V_J}{g_N^2} - \frac{N^J V_J}{g_D^2}\right)$$

To sum up:

$$(A)dS_4 \text{ flux compactifications}$$
$$\Big\updownarrow$$
$$QFT_3$$

Evidence: dS entropy

(A)dS large N β functions

Strong analogy to derivation of ordinary AdS/CFT via Coulomb branch

Still to do: • precise dictionary in dS case: is QFT_3 really enough or do we need full open string theory + ?

• $\exists$ several other simple features to match to QFT_3 side e.g.

- Bousso-Polchinski mechanism • Internal Gauss Law
- field content $\leftrightarrow$ operators
- distribution of domain walls (# of vacua in a large theory)

There has been concern about the potential lack of predictivity arising from the discretuum of vacua

(don't really know until we study distribution of vacua) Bousso-Polchinski Maloney E.S. Strominger Kachru Kallosh Linde Trivedi Susskind Giddings Douglas Frey Lippert Williams ...

"Polyvacuism makes String Theory Vacuous" -Sandip Trivedi

In any case, in the context of flux compactifications we obtain a rather specific picture of the dark energy - as I've argued here not just its equation of state but a microphysical interpretation of its entropy & potentially more of its physics

Since this is 70% of the energy in the universe, I think this is a big positive opportunity for string theory coming from the discretuum of flux vacua