Title: Chiral Symmetry Breaking via Gauge/Gravity Duality

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Abstract: TBA

Chiral Symmetry Breaking from Gauge/Gravity Duality

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August 2, 2012

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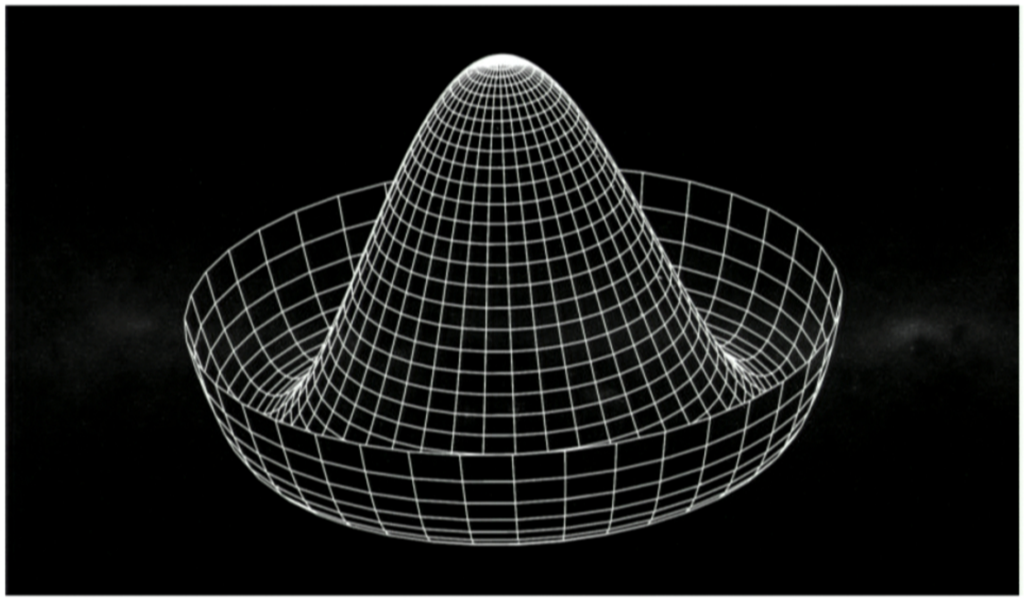
WHAT IS THE ORIGIN OF MASS IN PARTICLE PHYSICS?



Spontaneous Symmetry Breaking

Electroweak symmetry breaking

- The standard model of Particle Physics is a quantum field theory with gauge group $G_{\text{SM}} = SU(3)_C \times SU(2)_W \times U(1)_Y$

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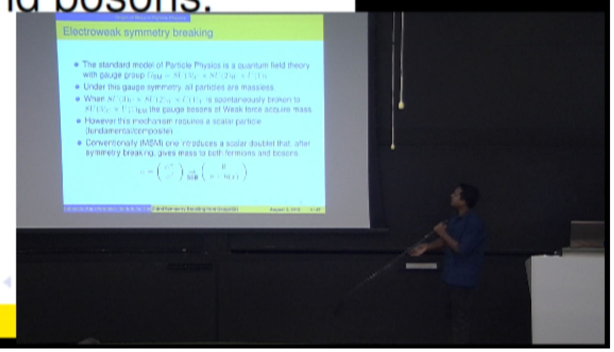
- When $SU(3)_C \times SU(2)_W \times U(1)_Y$ is spontaneously broken to $SU(3)_C \times U(1)_{\text{EM}}$ the gauge bosons of Weak force acquire mass.
- However this mechanism requires a scalar particle (fundamental/composite)
- Conventionally (MSM) one introduces a scalar doublet that, after symmetry breaking, gives mass to both fermions and bosons.

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \underset{\text{SSB}}{\rightarrow} \begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix}$$



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- $H \to \gamma\gamma$ decay channel.
- Observed significance of 4.1 σ excess around 125 GeV compared to an expected 2.8 σ excess!

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- Triviality problem

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- Chiral Symmetry and Symmetry Breaking
- Aspects of Technicolor

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- Aspects of Technicolor
- Gauge/Gravity duality

Chiral symmetry of the QCD Lagrangian

Consider the fermionic part of the QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD,f}} = \bar{q}\, i \not{D}\, q, \quad q = \begin{bmatrix} u \\ d \end{bmatrix}$$

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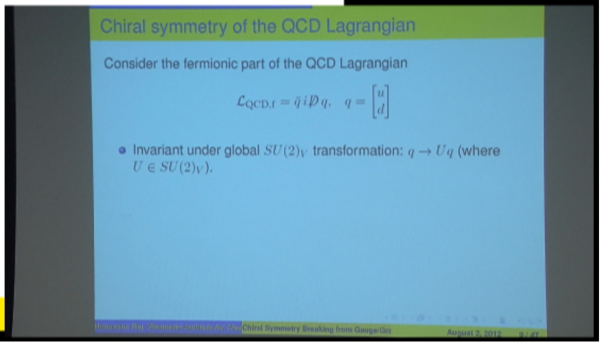

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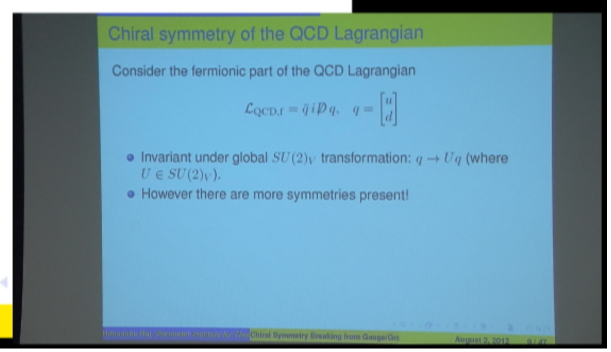

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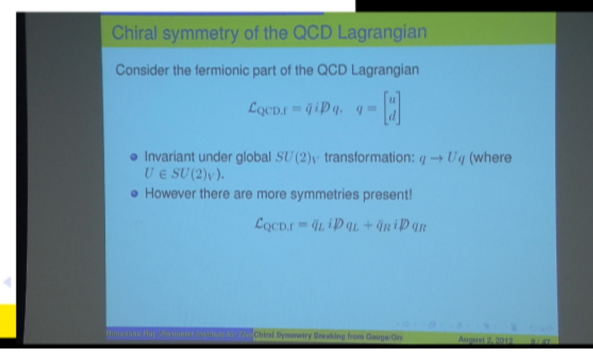

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This is called ***chiral symmetry*** of the QCD Lagrangian.

Massless Fermions $\Longrightarrow$ Chiral symmetry

- Let us introduce a fermion mass term into the Lagrangian.

$$\mathcal{L}_{\text{mass,f}} = -m\bar{q}q$$

can be chirally decomposed:

$$\mathcal{L}_{\text{mass,f}} = -m(\bar{q}_L q_R + \bar{q}_R q_L)$$

- The original $SU(2)_L \times SU(2)_R$ chiral symmetry of the massless theory has now broken to a residual $SU(2)_V$ vectorial symmetry.
- The vector current is still conserved but the axial-vector current is not, thereby spoiling the chiral symmetry.
- Infact its divergence is proportional to the Dirac mass.

Hence presence of massive fermions explicitly breaks chiral symmetry.

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Chiral Condensates

- This non-zero vacuum expectation value signals the spontaneous breaking of the full $SU(2)_L \times SU(2)_R$ to its diagonal subgroup $SU(2)_V$.

- Thus there should be correspondingly 3 massless goldstone bosons.
- In QCD there are no massless scalars. Pions are the lightest ones.
- The chiral condensates of QCD does break the SM gauge symmetry spontaneously,
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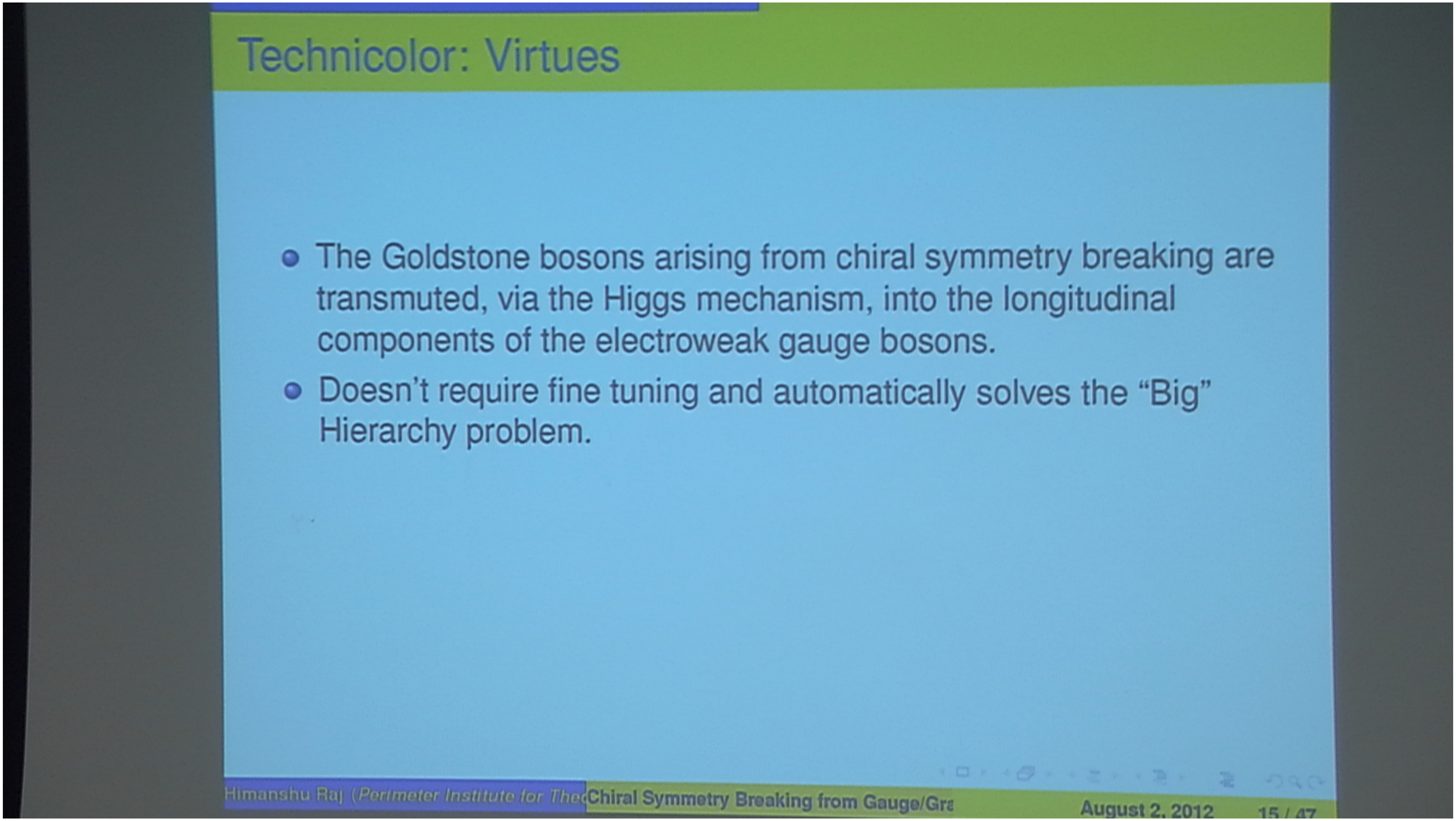
Induced Electroweak Symmetry Breaking:

EWSB induced via dynamical chiral symmetry breaking of a new set of strong interactions!

Technicolor

- Introduce a new strongly interacting $SU(N_{TC})$ gauge theory acting on new degrees of freedom (techni-fermion) transforming in the fundamental representation of this new gauge symmetry.
- These new *techniquarks* carry an $SU(N_{TC})_L \times SU(N_{TC})_R$ global symmetry the analog of the (approximate) chiral symmetry of the light quarks in QCD.
- Just as in QCD, the low-energy ($\sim$EW scale) strong dynamics of this new gauge theory is expected to cause chiral symmetry breaking. (Non-perturbative VEV for the chiral condensates)
- If the left-handed techniquarks form an $SU(2)_W$ doublet, while the right-handed techniquarks are weak singlets carrying hypercharge, technicolor chiral symmetry breaking will result in electroweak symmetry breaking.


Technicolor: Virtues
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- There is no problem of Naturalness
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- All the scales are generated dynamically and naturally stablized.

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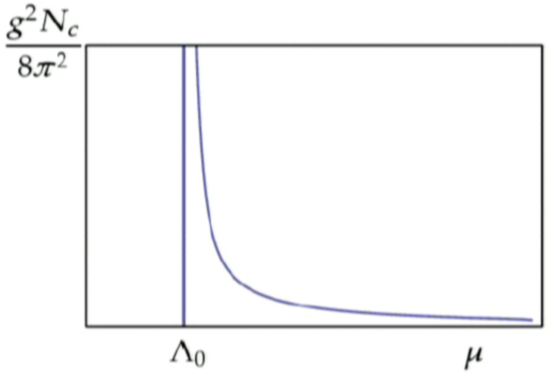
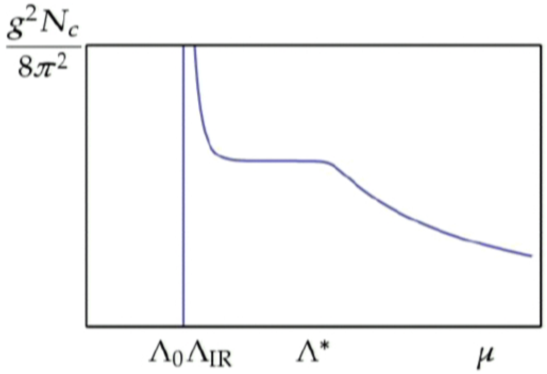
- The simplest version of this theory (as a scaled-up version of QCD) is not compatible with precision electroweak data and cannot accommodate the masses of the heavy quarks and Leptons.
- It needs to be modified into what is known as Walking Technicolor, i.e. a gauge theory with a conformal window where the gauge coupling is strong but approximately constant over the EW scale.
- The Gauge coupling is strong implies that the conventional tools of perturbative QFT break down!

Walking Technicolor

Gauge Coupling as a function of energy





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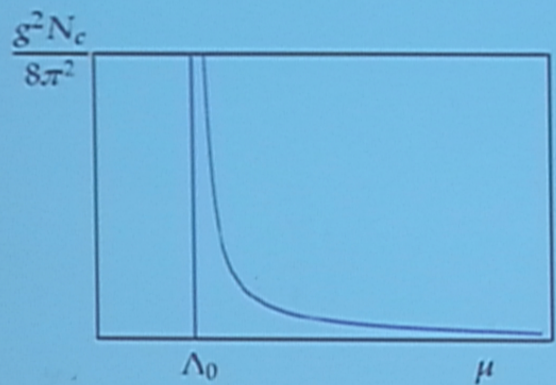

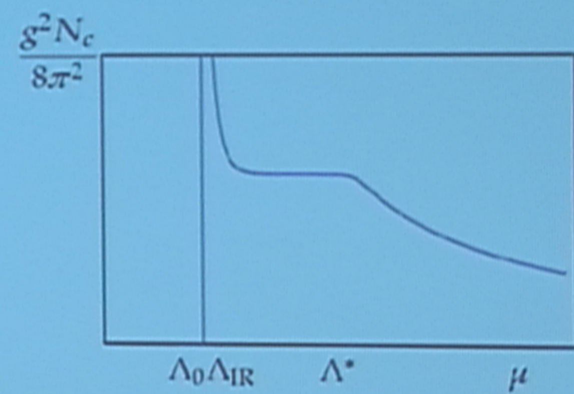

The soft breaking of scale invariance produces a PNGB.

Precision Electroweak experiments and oblique parameters

Prior to LHC, experiments did not offer direct evidence of the nature of the Higgs sector. So it was important to make the best use of all sources of indirect information that measurements provided. The most important of these indirect constraints come from the precision measurements of the weak interaction parameters. The familiar ones are:

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- α the fine structure
- m_Z mass of the Z-boson
- G_F fermi coupling

However if we consider leading order corrections to EW theory beyond tree level we find that 3 more parameters become important.

S, T, U (oblique parameters) [Peskin-Takeuchi (1992)]

Oblique corrections

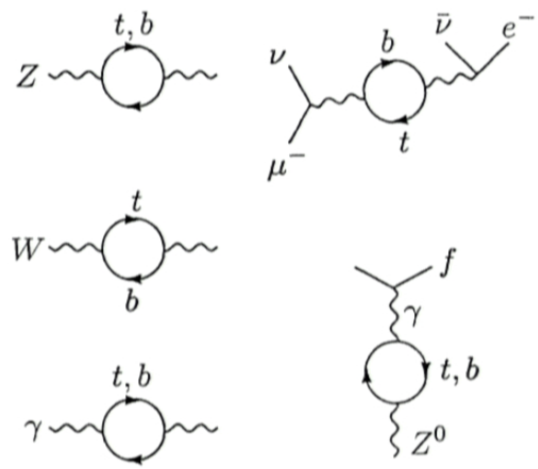

Figure: Vacuum polarization

At low energies heavy quarks do not appear in the final state. However they do contribute to vacuum polarization amplitudes via internal loops that might contain new strongly coupled degrees of freedom.

Introduction to Gauge/Gravity duality

It is an important theoretical tool to solve models of strong coupling dynamics. Originally discovered in the context of AdS/CFT,

AdS/CFT correspondence:

$\mathcal{N} = 4$, $SU(N_C)$ superconformal YM in $4D$ is dual to Type IIB Superstring theory in an $AdS_5 \times S^5$ background

this powerful computational tool finds application in

- Quark/Gluon Plasma
- Hydrodynamics
- High T_c Superconductivity
- Technicolor

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- An example is the Maldecena-Nunez background (wrapped D5 branes on S^2)
  - dual to $\mathcal{N} = 1$ 4D theories
  - shows confinement in the IR and asymptotic freedom.

Main objective

Features of the desired field theory

- “QCD like”, i.e., must show confinement and asymptotic freedom
- Chiral Symmetry Breaking
- Must have a conformal window around the Electroweak scale.

Type IIB String theory

- The spectrum of type IIB superstring theory contains the following sector:

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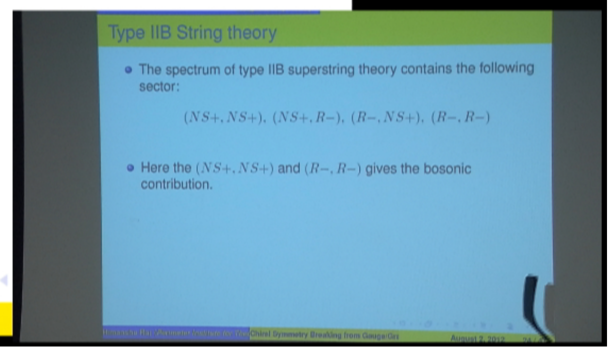

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- Here the $(NS+, NS+)$ and $(R-, R-)$ gives the bosonic contribution.
- The massless fields in the $(NS+, NS+)$ sector are:

$$g_{\mu\nu},\ B_{\mu\nu},\ \Phi$$

and for the $(R-, R-)$ are

$$C_0,\ \ C_2,\ \ C_4$$

Type IIB SUGRA

The low energy effective action (in the string frame) is:

$$S_{IIB} = S_{NS} + S_R + S_{CS}$$

$$S_{NS} = \frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-G}e^{-2\Phi}\left(R + 4\partial_\mu\Phi\partial^\mu\Phi - \frac{1}{2}|H_3|^2\right)$$

$$S_R = -\frac{1}{4\kappa_{10}^2}\int d^{10}x\sqrt{-G}\left(|F_1|^2 + |\tilde{F}_3|^2 + \frac{1}{2}|\tilde{F}_5|^2\right)$$

$$S_{CS} = -\frac{1}{4\kappa_{10}^2}\int C_4\wedge H_3\wedge F_3$$

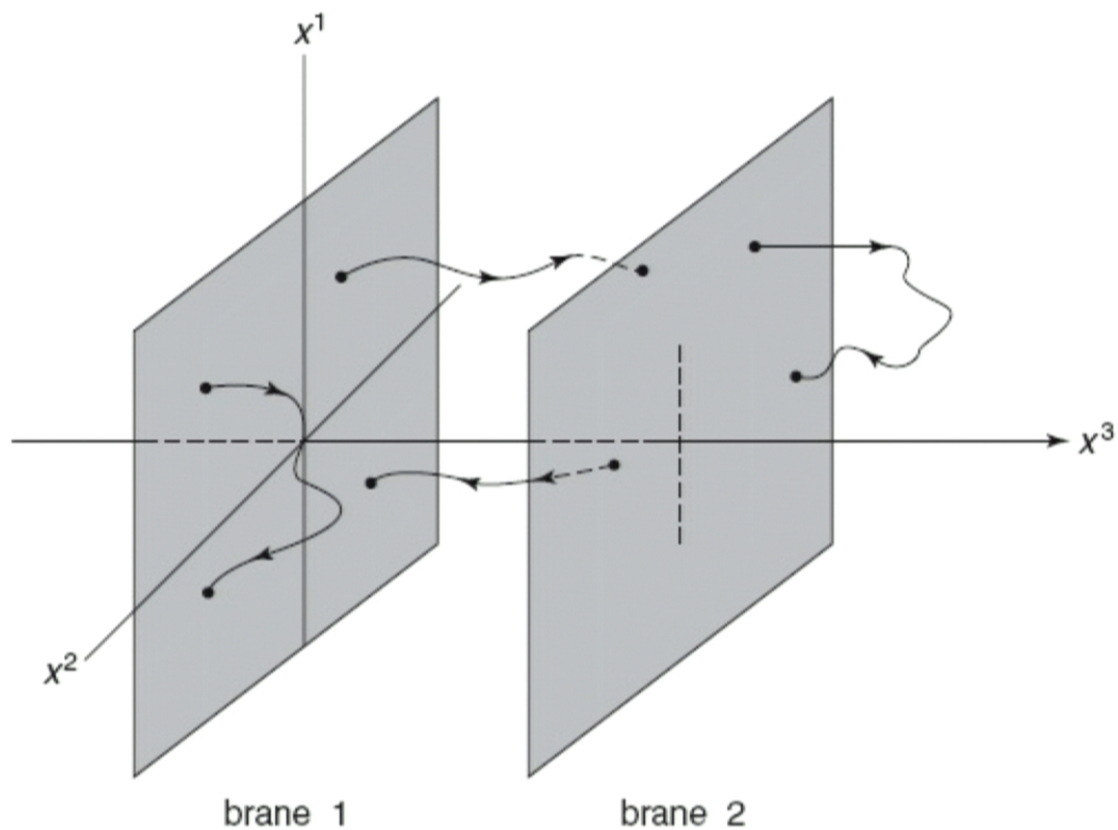
where

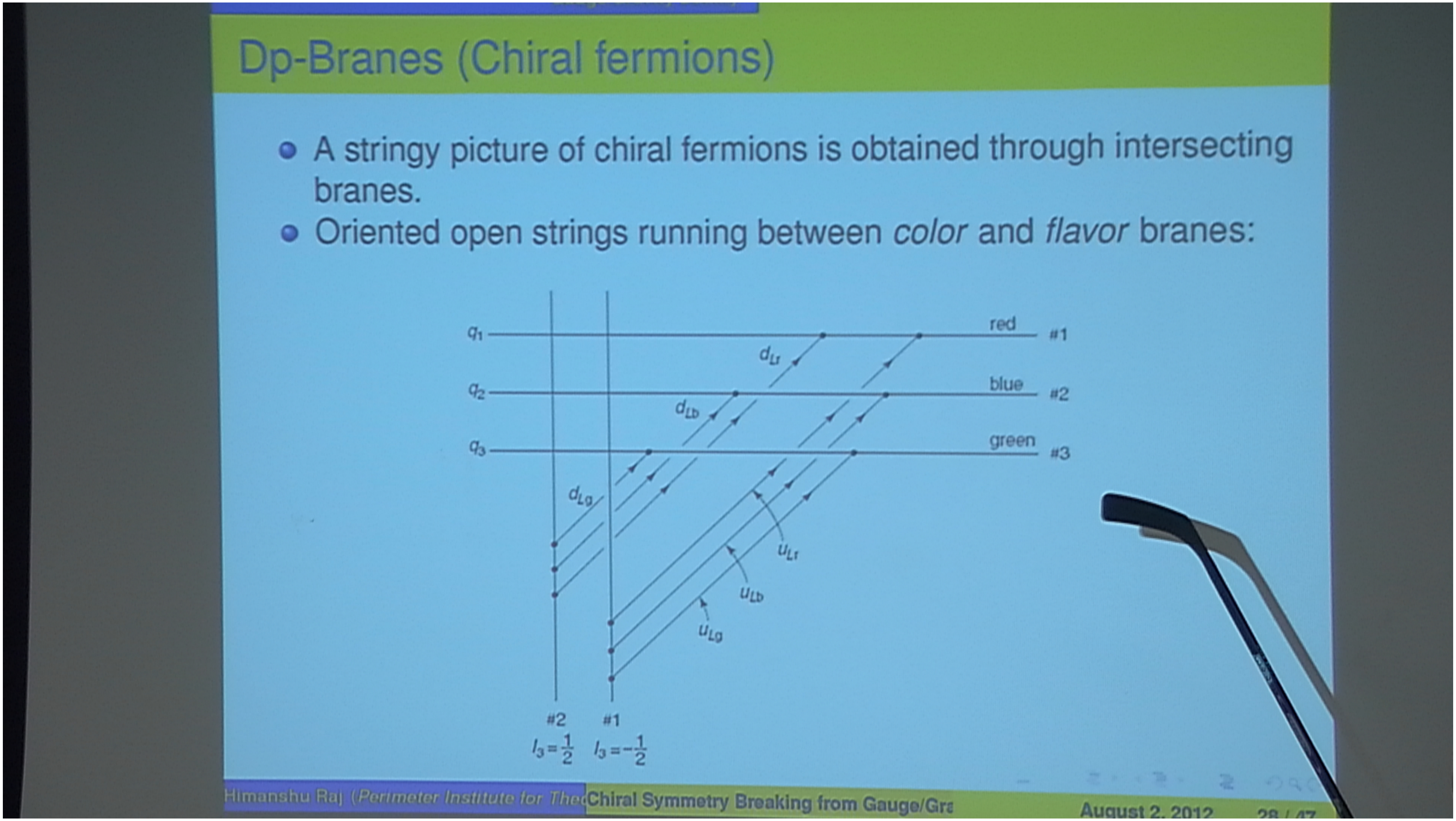
$$\tilde{F}_3 = F_3 - C_0\wedge H_3,$$

$$\tilde{F}_5 = F_5 - \frac{1}{2}C_2\wedge H_3 + \frac{1}{2}B_2\wedge F_3$$

A little p-Brane physics

- These are extended objects that span p-spatial dimensions, that sweep a (p+1) dimensional world volume in d+1 dimensional spacetime.
- Dp-branes were originally introduced for conserving momentum at string end points satisfying Dirichlet boundary conditions.
- Quantize open strings on a single D-brane:
  - at massless level the spectrum contains a Maxwell gauge field having $p-1$ polarization states
  - and $d-p$ massless scalars for each transverse directions.
- If there are N-coincident Dp-branes then there are N^2 ground states.
- $U(N)$ Yang-Mills theory lives on the world volume of N coincident Dp-Branes.


x^1
x^2
x^3
brane 1
brane 2


Dp-Branes (Chiral fermions)
A stringy picture of chiral fermions is obtained through intersecting branes.
Oriented open strings running between *color* and *flavor* branes:
q_1
q_2
q_3
red #1
blue #2
green #3
d_{Lr}
d_{Lb}
d_{Lg}
u_{Lr}
u_{Lb}
u_{Lg}
#2 #1
$I_3 = \frac{1}{2}$ $I_3 = -\frac{1}{2}$
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Dp-Brane action

- In the background of Type IIB supergravity the action of the D-Branes takes the form (in the Einstein frame) :

$$S_{\text{p-Brane}} = -T_{D_p}\int d^{p+1}x\, e^{\frac{p-3}{4}\Phi}\sqrt{-\text{Det}\left(\underbrace{G_{AB}+B_{AB}}_{M_{AB}}+2\pi\alpha' F_{AB}+(2\pi\alpha')^2\partial_A\Phi^i\partial_B\Phi^i\right)}$$

$$\pm T_{D_p}\int \text{P}\left[\sum_n C_n\wedge e^{B_2+2\pi\alpha' F_2}\right]$$

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- On expanding in α'

$$S_{\text{DBI}} = T_{D_p} \int d^{p+1}x\, e^{\frac{p-3}{4}\Phi} \sqrt{-\text{Det} M_{AB}} \left(\frac{1}{4} \text{tr} A^2 \right), \quad A = 2\pi\alpha' M^{-1}$$

- Compare with the Yang-Mills action.

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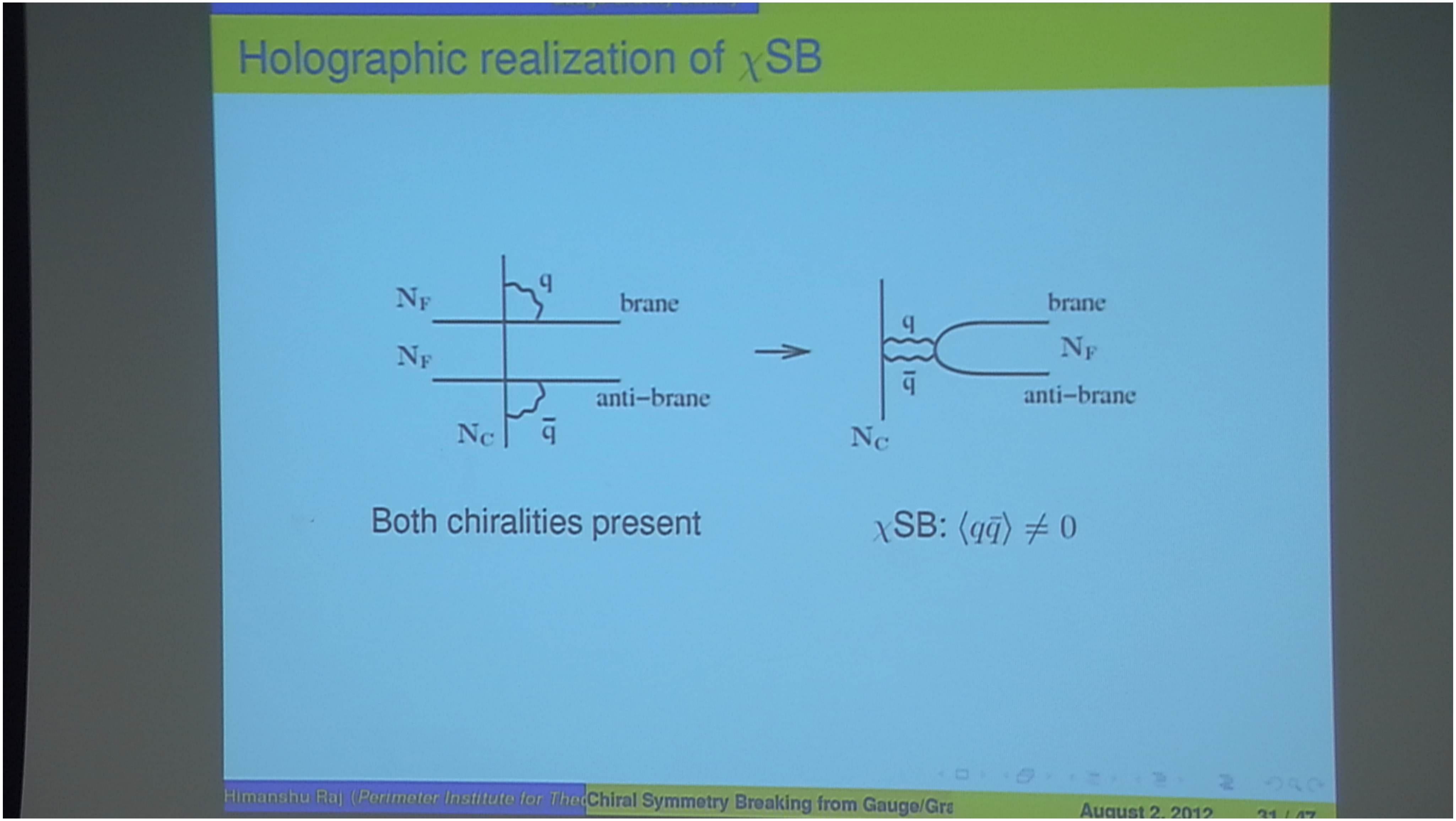
Holographic realization of χSB
N_F
q
brane
N_F
anti−brane
N_C
$\bar{q}$
brane
q
N_F
$\bar{q}$
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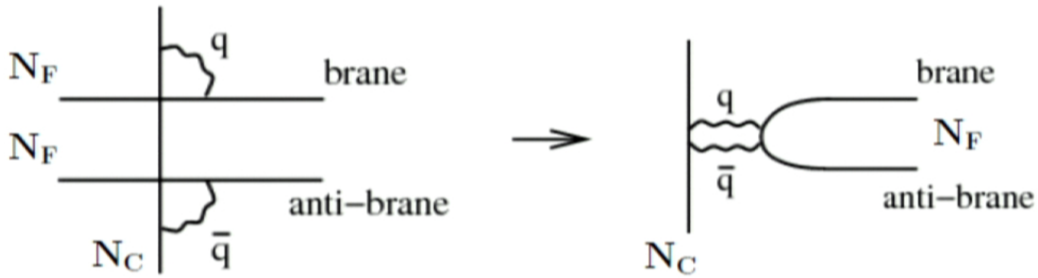
Both chiralities present
χSB: $\langle q\bar{q}\rangle \neq 0$
Himanshu Raj (Perimeter Institute for The
Chiral Symmetry Breaking from Gauge/Gra
August 2, 2012
31 / 47

Holographic realization of χSB



Both chiralities present χSB: $\langle q\bar{q}\rangle \neq 0$

- We interpret this mechanism as the holographic manifestation of the spontaneous breaking of chiral symmetry.

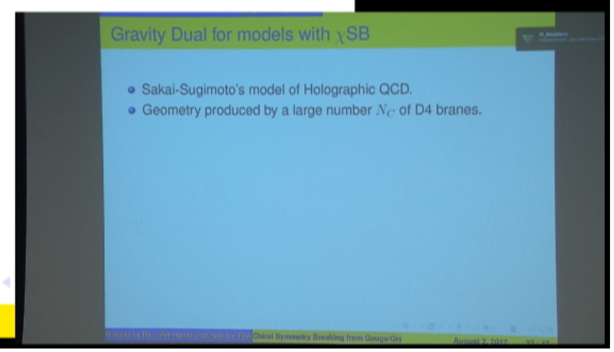
Gravity Dual for models with χSB

- Sakai-Sugimoto's model of Holographic QCD.

Gravity Dual for models with χSB

PI_Resident
Connection Established

- Sakai-Sugimoto's model of Holographic QCD.
- Geometry produced by a large number N_C of D4 branes.



Gravity Dual for models with χSB

- Sakai-Sugimoto's model of Holographic QCD.
- Geometry produced by a large number N_C of D4 branes.
- Embed the flavor $D8$, $\overline{D8}$ as probes.
- This system of $D4$-$D8$-$\overline{D8}$ intersecting branes give chiral fermions.
- The D-branes extend over the following directions:

	0	1	2	3	4(τ)	5	6	7	8	9(U)
$D4$	•	•	•	•	•					
$D8$-$\overline{D8}$	•	•	•	•		•	•	•	•	•

Sakai Sugimoto model

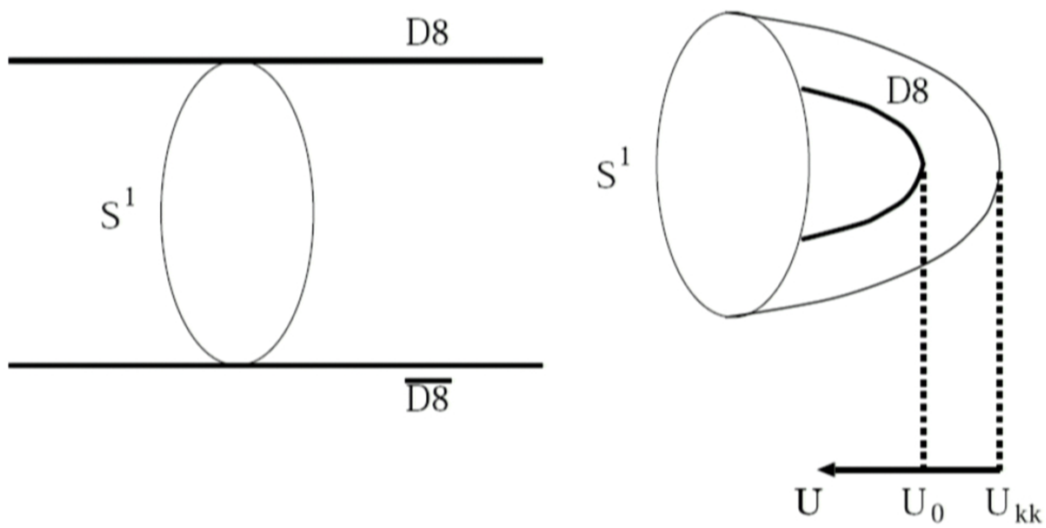


Figure: $D4$-$D8$-$\overline{D8}$ configuration

The U-shaped embedding of $D8$-$\overline{D8}$ brane is a holographic realization of χSB

String dual for Walking gauge theories

String dual for Walking gauge theories

- Construction using wrapped branes (MN solution)
- Consider N_C D5-branes in Type IIB SUGRA.
- The background (in the Einstein frame) is:

$$ds^2 = e^{\Phi/2}\left(dx_{1,5}^2 + \alpha' g_s N_c \left(dr^2 + \frac{1}{4}\sum_{i=1}^{3}\tilde{\omega}_i^2\right)\right)$$

$$F_3 = \frac{N_c}{4}\tilde{\omega}_1 \wedge \tilde{\omega}_2 \wedge \tilde{\omega}_3$$

- To get an effective 4D effective theory we need to wrap the N_C D5-branes on a small 2-sphere.

Gravity dual for Walking gauge theories

- A particular deformation of the MN solution gives the following background (in the Einstein frame):
  [Nunez, Papadimitriou and Piai (2008)]

$$
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ds^2 &= e^{\Phi(\rho)/2}(dx_\mu dx^\mu + ds_6^2) \\
ds_6^2 &= e^{2k(\rho)}d\rho^2 + e^{2h(\rho)}d\rho^2(d\theta^2 + \sin^2\theta d\phi^2) \\
&+ \frac{e^{2g(\rho)}}{4}\left((\tilde{\omega}_1 + a(\rho)d\theta)^2 + (\tilde{\omega}_2 - a(\rho)\sin\theta d\phi)^2\right) + \frac{e^{2k(\rho)}}{4}(\tilde{\omega}_3 + \cos\theta d\phi)^2 \\
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- AND should solve a set of first order BPS equations to preserve 4 supercharges.

BPS equations

- For this particular background the BPS equations automatically solve the equations of motion!
- These equations are written down conveniently in terms of a new set of variables $P(\rho),\ Q(\rho),\ Y(\rho), \tau(\rho),\ \sigma(\rho)$ defined as:

$$4e^{2h} = \frac{P^2 - Q^2}{P\cosh\tau - Q},\quad e^{2g} = P\cosh\tau - Q,\quad e^{2k} = 4Y,\quad a = \frac{P\sinh\tau}{P\cosh\tau - Q},\quad b = \frac{\sigma}{N_c}$$

and the BPS conditions are:

$$\sinh\tau(\rho) = \frac{1}{\sinh(2\rho - 2\rho_0)},\quad \cosh\tau(\rho) = \coth(2\rho - 2\rho_0)$$

$$Q(\rho) = (Q_0 + N_c)\cosh\tau + N_c(2\rho\cosh\tau - 1)$$

$$Y(\rho) = \frac{P'}{8},\quad e^{4\Phi(\rho)} = \frac{e^{4\Phi_0}\cosh^2 2\rho_0}{(P^2 - Q^2)Y\ \sinh^2\tau}$$

$$\sigma(\rho) = (Q + N_c)\tanh\tau = \frac{2N_c\rho + Q_0 + N_c}{\sinh(2\rho - 2\rho_0)}$$

$$P'' + P'\left(\frac{P' + Q'}{P - Q} + \frac{P' - Q'}{P + Q} - 4\coth(2\rho - 2\rho_0)\right) = 0.$$

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Approximate solution to the BPS equation

$$P \approx c(\cos^3\alpha + \sin^3\alpha(\sinh(4\rho) - 4\rho))^{1/3}$$

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$$e^{4(\phi-\phi_0)} = \frac{3}{c^3 \sin^3\alpha}$$

- For the solution to be well defined it turns out that

$$1 \ll \cot\alpha \leq \exp\left(\frac{2^{4/3}}{3}\frac{c}{N_c}\right)$$

Reading off the gauge coupling

$$\frac{g_4^2 N_C}{8\pi^2} = \frac{N_C \coth(\rho)}{P(\rho)}$$

Dp-Brane action

- In the background of Type IIB supergravity the action of the D-Branes takes the form (in the Einstein frame) :

$$S_{\text{p-Brane}} = -T_{D_p} \int d^{p+1}x \; e^{\frac{p-3}{4}\Phi} \sqrt{-\text{Det}\left(\underbrace{G_{\text{AB}} + B_{\text{AB}}}_{M_{\text{AB}}} + 2\pi\alpha' F_{\text{AB}} + (2\pi\alpha')^2 \partial_{\text{A}}\Phi^i \partial_{\text{B}}\Phi^i \right)}$$

$$\pm T_{D_p} \int \text{P}\left[\sum_n C_n \wedge e^{B_2 + 2\pi\alpha' F_2} \right]$$

- On expanding in α'

$$S_{\text{DBI}} = T_{D_p} \int d^{p+1}x \; e^{\frac{p-3}{4}\Phi} \sqrt{-\text{Det} M_{\text{AB}}} \left(\frac{1}{4} \text{tr} A^2 \right), \quad A = 2\pi\alpha' M^{-1} F$$

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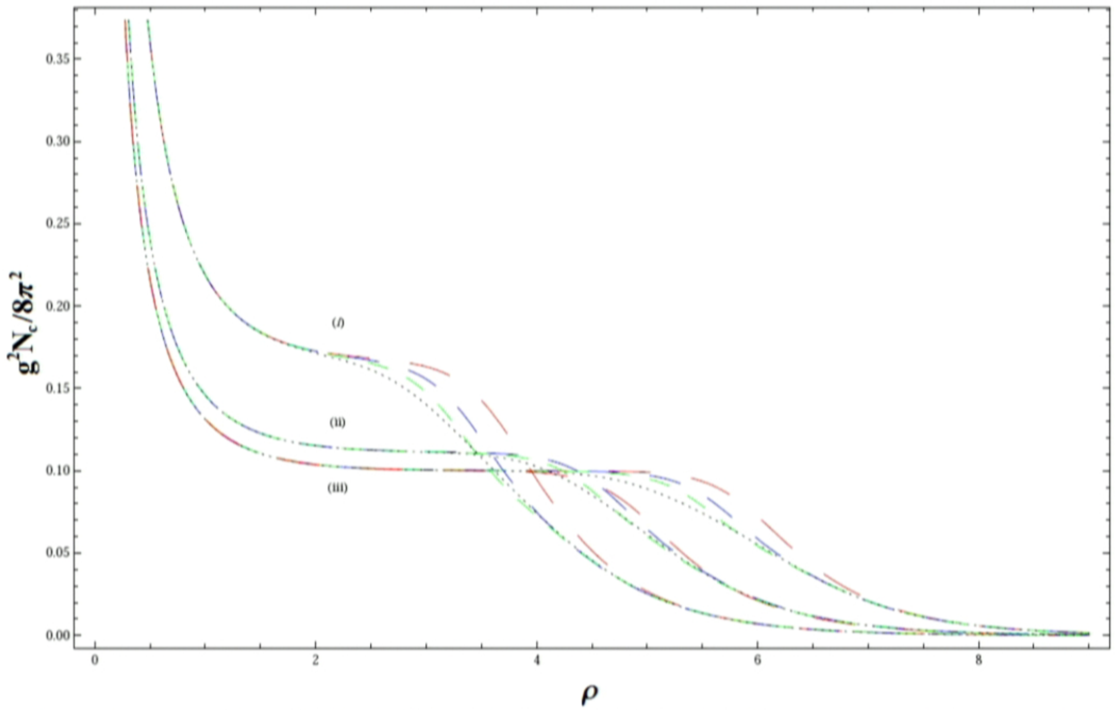

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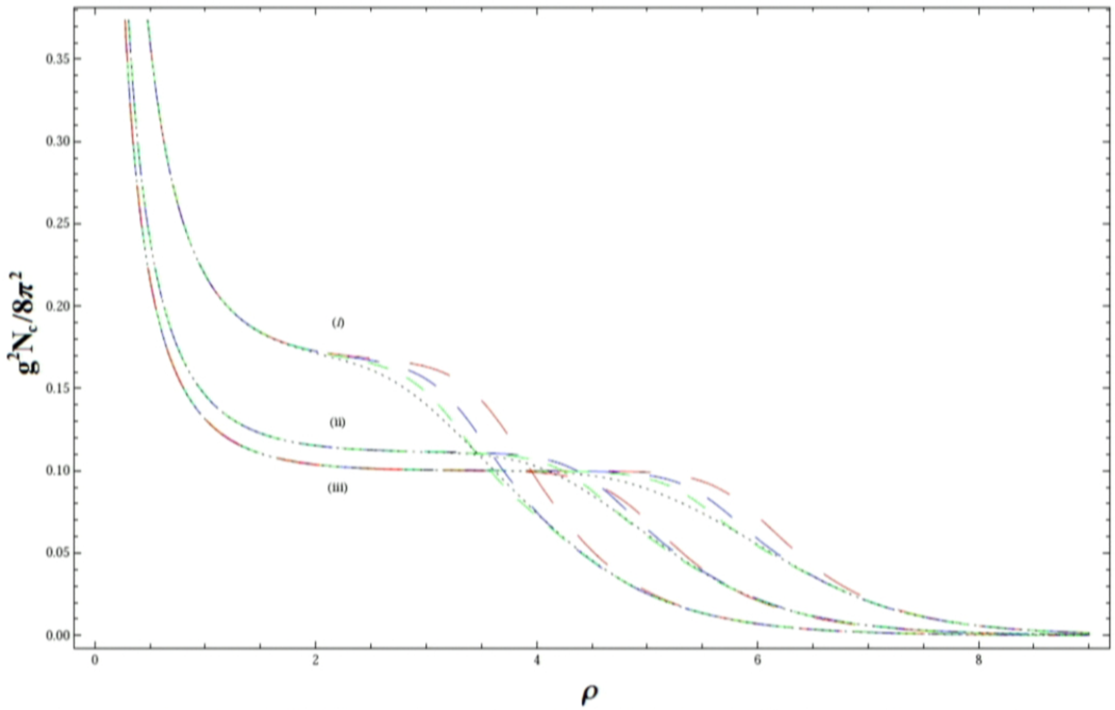


$D5$-$D7$-$\overline{D7}$ system

- We now add flavor D7-branes to this background as probes $N_f \ll N_C$ [L.Anguelova (2010)]

	0	1	2	3	4(θ)	5(ϕ)	6$\tilde{\theta}$	7$\tilde{\phi}$	8ψ	9 (ρ)
$D5$	•	•	•	•	•	•				
$D7$-$\overline{D7}$	•	•	•	•			•	•	•	•

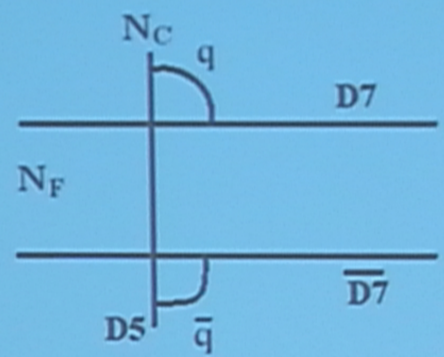
- The embedding function of these branes are now determined by the functions $\theta(\rho)$ and $\phi(\rho)$ which are found to be:

$$\theta(\rho) = \frac{\pi}{2}$$

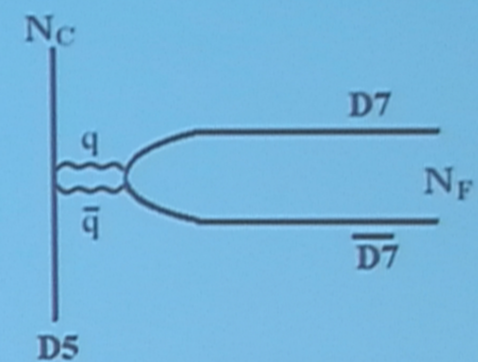
$$\tanh\left(\frac{\phi(\rho)}{\sqrt{B}e^{2\rho_0}}\right) = \pm\sqrt{1 - \frac{e^{4\rho_0}}{e^{4\rho}}},$$

where $B = \tan^3 \alpha/3$

Geometry of the $D7$ branes



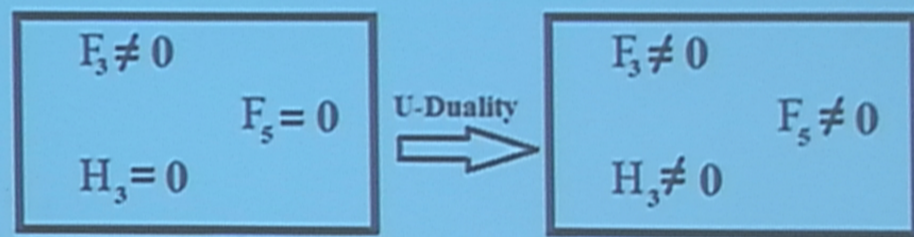
both-chiralities are present



χSB (condensate formation)

Current Project

Deform the background further



New Type IIB background with fluxes[1]

[1] Maldacena and Martelli

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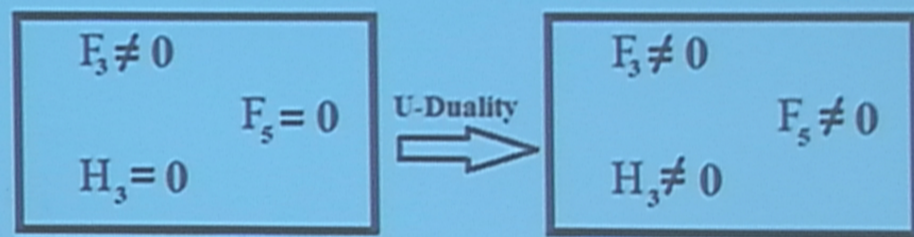

New Type IIB background with fluxes[1]

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New Background: (through U-Duality)

The new solution obtained after taking U-duality of the previous one is presented below:

$$ds^2 = \sum_{i=1}^{10} (e^i)^2$$

$$F_3 = \frac{e^{-\frac{3\phi}{4}}}{\hat{h}^{3/4}} \left[f_1 e^{123} + f_2 e^{\theta\phi 3} - f_3(e^{\phi 13} + e^{\theta 23}) + f_4(e^{\rho 1\theta} + e^{\rho\phi 2}) \right]$$

$$H_3 = -k_2 \frac{e^{\frac{5\phi}{4}}}{\hat{h}^{3/4}} \left[-f_1 e^{\theta\phi\rho} - f_2 e^{12\rho} + f_3(e^{\theta 2\rho} + e^{\phi 1\rho}) - f_4(e^{\theta 13} - e^{\phi 23}) \right]$$

$$F_5 = k_2 \frac{d}{d\rho} \left(\frac{e^{2\Phi}}{\hat{h}} \right) \hat{h}^{3/4} e^{-k-\frac{5\Phi}{4}} \left[-e^{t x_1 x_2 x_3 \rho} + e^{\theta\phi 123} \right]$$

The background fluxes are controlled by the parameter $k_2 \in [0, e^{-\Phi(\infty)}]$.

New Background

- We calculate the embedding function of the flavor branes in the new background.
- The result is consistent with the previous background in the limit $k_2 \to 0$

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- We calculate the embedding function of the flavor branes in the new background.
- The result is consistent with the previous background in the limit $k_2 \to 0$
- However there is not much change!
- The Chern-Simon term in the brane action now becomes important.

Summary

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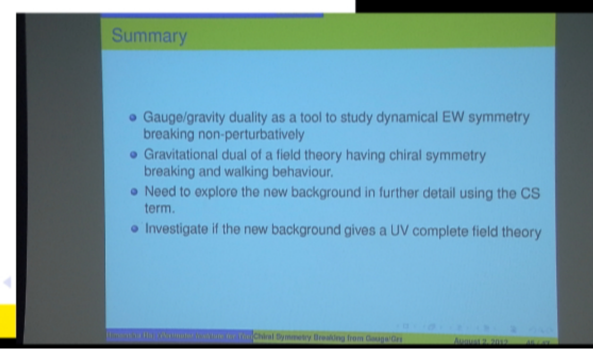

Acknowledgements

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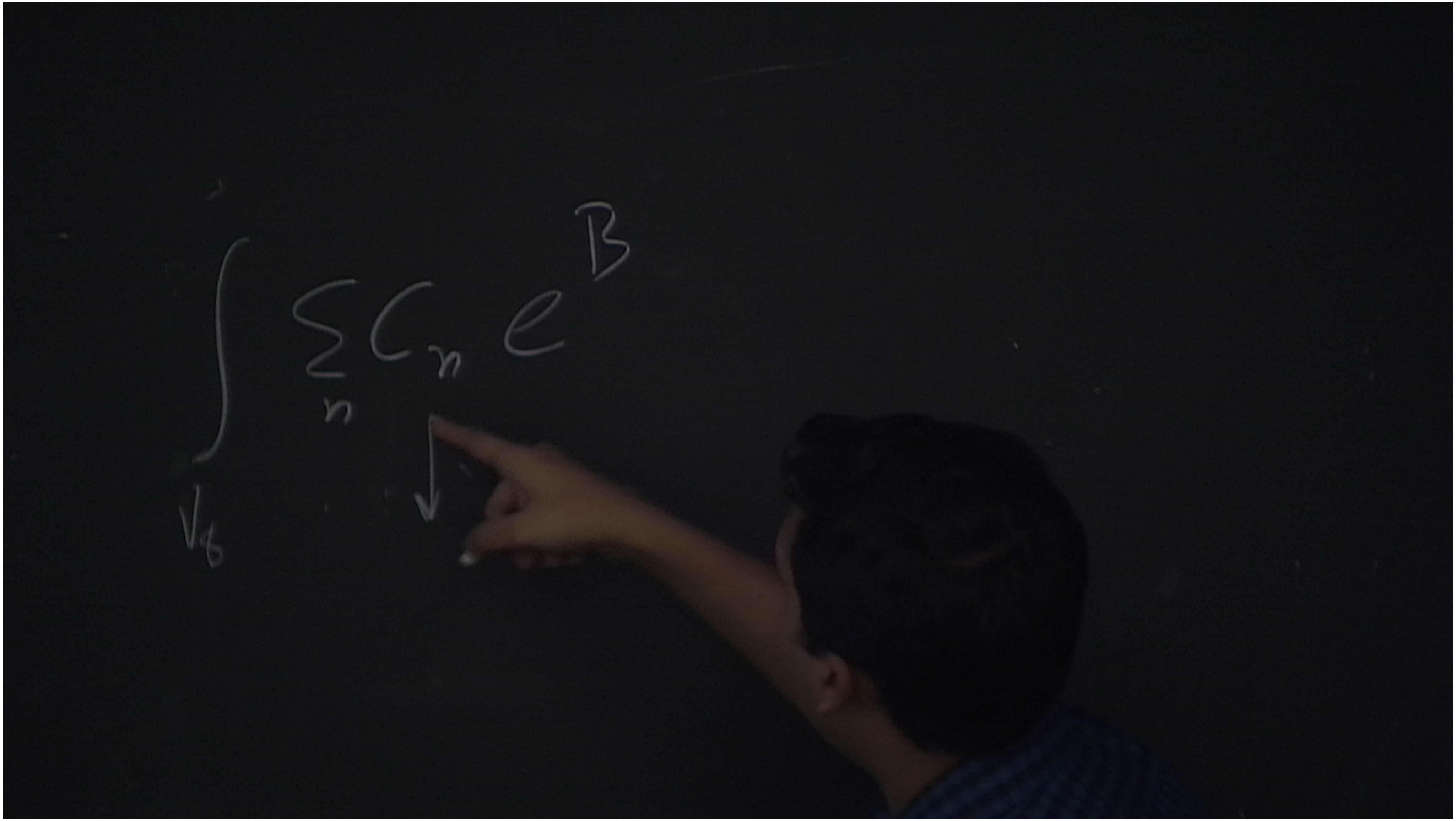

$$\int_{V_6} \sum_n C_n \left(1 + B + B \wedge B \right)$$

$$\downarrow$$

$$C_2 \neq 0 \quad \int C_2 \wedge B_2 \wedge B_2 \wedge B_2$$

Type IIB String theory

- The spectrum of type IIB superstring theory contains the following sector:

$$(NS+, NS+),\ (NS+, R-),\ (R-, NS+),\ (R-, R-)$$

- Here the $(NS+, NS+)$ and $(R-, R-)$ gives the bosonic contribution.
- The massless fields in the $(NS+, NS+)$ sector are:

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