Concluding Remarks

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Strings 2004, Paris

Six Questions

of Strings 2004

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I. WHAT CAN WE TELL TO EXPERIMENTERISTS ?

No SUSY at LHC ?

Douglas described a statistical approach to study the space of string vacua.

He estimates that the distribution of cosmological constant is independent of M_{SUSY} and that the prior distribution of M_{SUSY} prefers high scale SUSY breaking.

- More analysis of correlations
- Microscopic basis for the statistical approach
- Proton decay ?

KKLT PROPOSAL

(1) THE TREE LEVEL SUPERPOTENTIAL STABILIZES COMPLEX STRUCTURE MODULI AND DILATON.

DOUGLAS CONJECTURED $N_{VAC} = L^{b_3} \int det(-R-\omega)$

KACHRU TESTED IT WITH AN EXPLICIT EXAMPLE AND FOUND AN EXCELLENT AGREEMENT.

(2) NONPERTURBATIVE CORRECTIONS MAY STABILIZE KÄHLER MODULI

DOUGLAS : D3 BRANE INSTANTONS

TRIVEDI : NONPERTURBATIVE GAUGE DYNAMICS ON D7 BRANES

(3) SUSY BREAKING

TRIVEDI ARGUED THAT AN INFLATON POTENTIAL SATISFYING THE SLOW ROLL CONDITION AND THE 60 e-FOLDING CAN BE GENERATED.

STRINGS IN THE SKY

JONES POINTED OUT THAT NETWORKS OF STRINGS CAN BE
GENERATED AT THE END OF BRANE INFLATIONS,

NOT DILUTED
AWAY

BUT NO MONOPOLES / DOMAIN WALLS.

MYERS SHOWED THAT CERTAIN STRING NETWORKS CAN BE
STABLE IN THE $K^2 L M^2 T$ MODEL. THE STRING TENSION T
IS ESTIMATED AS $G_4 T \sim 10^{-10}$, NOT EXCLUDED
BY THE CURRENT CMB OBSERVATION, BUT LIGO/LISA
WILL BE SENSITIVE TO GRAVITATIONAL WAVES FROM
THEIR KINKS AND CUSPS.

JONES ESTIMATED THEIR RECONNECTION PROBABILITY,
WHICH SEEMS TO DISTINGUISH THEM FROM
FIELD THEORY EFFECTS IN COSMOLOGY.

II. DOES THE STANDARD MODEL

EXIST (IN STRING THEORY) ?

A REALISTIC MODEL REQUIRES (AMONG OTHERS)

- REALISTIC SPECTRUM

- SOFT SUSY BREAKING TERMS ← 4 TALKS

FLUX COMPACTIFICATIONS ON ORIENTIFOLDS NATURALLY GIVE RISE TO NO-SCALE SUPERGRAVITY MODELS.

FERRARA EXPLAINED HOW THE NO-SCALE STRUCTURE ORGANIZES THE LOW ENERGY EFFECTIVE ACTION.
$$V < 0, = 0, OR > 0$$

LOUIS STUDIED ORIENTIFOLDS WITH D3 BRANES AND DERIVED THEIR $N = 1$ EFFECTIVE ACTION.

WHEN SUSY IS BROKEN AND SOFT TERMS ARE GENERATED, HE FOUND THAT THE NO SCALE STRUCTURE IMPLIES UNIVERSAL SCALER MASS.

LINEAR MULTIPLET DESCRIPTION

CHIRAL FERMIONS CAN BE INTRODUCED
BY ADDING D7 BRANES.

$\downarrow$

almost MINIMAL SUPERSYMMETRIC STANDARD MODEL

LUEST : INTERSECTING D7

URANGA : D3 / D7 ON $\mathbb{C}^3/\mathbb{Z}_3$

LUEST FOUND THAT NO SCALE STRUCTURE IS
VIOLATED IN THE CHIRAL SECTOR.

———————— • ————————

GRANA DESCRIBED HOW THE CY GEOMETRY IS DEFORMED
BY BACKREACTIONS DUE TO FLUXES.

SHE PRESENTED A MATHEMATICAL FRAMEWORK

"TWISTED GENERALIZED CALABI-YAU."

WHICH CAN BE USEFUL FOR SYSTEMATIC STUDY

OF FLUX COMPACTIFICATION.

III. ARE THERE STILL THINGS

TO BE LEARNED FROM AdS/CFT ?

YES ! MORE THAN $1/3$ OF TALKS

$g_{YM}^2 N = 0$ (FREE $\mathcal{N} = 4$ SYM$_4$) $\Leftarrow$ 4 TALKS

THERE IS A SECTOR OF THIS FREE THEORY THAT IS
DUAL TO THE MASSLESS HIGHER SPIN THEORY IN AdS$_5$.

VASILIEV USED THE HIGHER SPIN SYMMETRY TO ORGANIZE
NONLINEAR TERMS IN THE EQUATIONS OF MOTION.
(THE FREE THEORY ON THE BOUNDARY CAN BE
DUAL TO THE INTERACTING THEORY IN THE BULK.)

BIANCHI DISCUSSED A PERTURBATION BY TURNING
ON $\lambda = g_{YM}^2 N$.
OTHER FIELDS GET COUPLED,
AND THE HIGHER SPIN SYMMETRY IS
SPONTANEOUSLY BROKEN.

La Grande Bouffe

GOPAKUMAR POINTED OUT THAT GAUGE THEORY AMPLITUDES

AT $g_{TM}^2 N = 0$ (FINITE N) CAN BE EXPRESSED

AS INTEGRALS OVER MODULI SPACE OF RIEMANN SURFACES.

THIS CAN BE A USEFUL STARTING POINT

TO PROVE THE AdS/CFT CORRESPONDENCE.

AHARONY SHOWED THAT THE FREE $N=4$ SYM$_4$

ON $\mathbb{R} \times S^3$ HAS A 1ST ORDER PHASE TRANSITION

AT $T_{DECONFINEMENT} = T_{HAGEDRON}$ FOR $N \to \infty$.

THE AdS$_5$ PREDICTION FOR $\lambda = g_{TM}^2 N \gg 1$ IS

$$T_{DECONFINEMENT} \sim 1/R$$
$$T_{HAGEDRON} \sim \lambda^{1/4}/R$$

$$(R : \text{RADIUS OF } S^3)$$

INTEGRABILITY WITH LARGE CHARGES

BEISERT, TSEYTLIN, ZAREMBO

$$N \to \infty \ , \quad \lambda' = \frac{\lambda}{J^2} \ : \ \text{FIXED}$$

QUANTITATIVE COMPARISON CAN BE MADE
WHEN SEVERAL CHARGES ARE LARGE.

$SYM_4 \Rightarrow$ SPIN CHAIN : INTEGRABLE

$\Rightarrow$ EFFECTIVE SIGMA-MODEL

SPINNING STRING $\Rightarrow$ THE WORLDSHEET THEORY IS *INTEGRABLE*

$\Rightarrow$ EFFECTIVE SIGMA-MODEL

COINCIDE TO $O(\lambda'^2)$

DISAGREEMENT AT $O(\lambda'^3)$

DUE TO DIFFERENCE IN ORDER OF LIMITS :

GAUGE THEORY : EXPAND IN λ, $J \to \infty$

STRING THEORY : $J \to \infty$, EXPAND IN $\lambda' = \frac{\lambda}{J^2}$

New Insights from Gauge Theory

Zamaklar studied decay of a D0 brane in AdS_5 using its dual description as a time dependent sphaleron configuration.

Intriligator reported a very promising progress toward a proof of the a-Theorem, a 4 dim generalization of Zamolodchikov's c-Theorem.

Dixon presented remarkable iterative identities for planar multi-loop amplitudes in $N=4$ SYM_4.

GREEN SHOWED THAT OPE OF THE OPERATOR

COUPLED TO g_{YM} WITH ANY OPERATOR IN $N=4\ SYM_4$

. IS DETERMINED BY THE WARD-TAKAHASHI IDENTITY.

$\Rightarrow$ ○ NON-RENORMALIZATION OF

2 . 3 POINT AMPLITUDES

○ DIFFERENTIAL EQUATION FOR CORRELATION

FUNCTION OF BPS OPERATORS,

ASSUMING TRUNCATION OF LONG OPERATORS.

$\Rightarrow$ AGREE WITH SUPERGRAVITY RESULTS.

New Insights from Bulk Geometry

Klebanov presented convincing evidences for the earlier claim that the cascading $SU(N+M) \times SU(N)$ gauge theory is *in the baryonic branch*.

- Bulk mode corresponding to the pseudo Goldstone boson for spontaneous breaking of $U(1)_B$.

- D-strings at the bottom of the bulk geometry = axionic strings

Maoz found Euclidean solutions (with non-zero Yang-Mills fields) with more than one disconnected boundaries. Some are stable.

Holographic interpretation ?

Approaches to Black Hole Puzzles

Mathur pointed out that, for a 2-charge black hole, there is a unique geometry inside of the horizon for each state of the black hole.

He argued that the black hole horizon is a boundary of a region with fuzzy geometry.

Shenker discussed black hole singularity from the holographic point of view.

He found that the phase transition in 't Hooft loops expectation values observed earlier in the bulk has an analogue in the weakly coupled SYM_4.

He reported progress at finite temperature SYM_4 computation.

MANY YEARS BEFORE THE AdS/CFT CORRESPONDENCE WAS DISCOVERED, POLYAKOV HAD SUGGESTED THAT STRING THEORY DUAL TO A GAUGE THEORY SHOULD BE *IN HIGHER DIMENSIONS* (EXTRA DIM. = *LIOUVILLE*).

ALONG THIS *LINE OF THOUGHT*, HE DISCUSSED SIGMA-MODELS FOR *NON-CRITICAL STRING WORLDSHEET* USING SUPERCOSETS, *WITH NONTRIVIAL FIXED POINTS* FOR AdS GEOMETRIES WITH RR FLUXES.

HE SPECULATED THAT THEY ARE DUAL TO NONSUPERSYMMETRIC GAUGE THEORIES.

IV. NEW PHENOMENA IN STRING THEORY ?

Two-Dimensional Theories

Matrix model for 2d string theory has infinitely many conserved charges.

Sen identified the corresponding charges in the continuum formulation of the theory.

For a black hole, they all vanish except for the one that corresponds to its mass.

He conjectured that the black hole in Matrix model is made of a large number of fermion/hole excitations, each with very small energy.

Maldacena studied the entropy of 2d black hole described by the KKK matrix model.

He found that each fixed representation carries no entropy.

The formula

$$e^S \sim \frac{1}{n!}$$

does not count the number of microstates, but is the multiplicity of the representation with the biggest contribution.

MINIMAL STRING THEORY

SEIBERG COMPUTED DISK AMPLITUDES FOR BRANES IN THE (p, q) MINIMAL CFT + 2d GRAVITY. HE FOUND THAT A RIEMANN SURFACE EMERGES NATURALLY AS A MODULI SPACE OF BRANES.

THIS FITS NICELY WITH TOPOLOGICAL STRING RESULTS, WHERE THE CORRESPONDING MATRIX MODEL IS LARGE N DUAL TO CLOSED STRING ON CY_3 ASSOCIATED TO THE RIEMANN SURFACE.

LIOUVILLE

MATRIX MODEL

TOPOLOGICAL CLOSED STRING
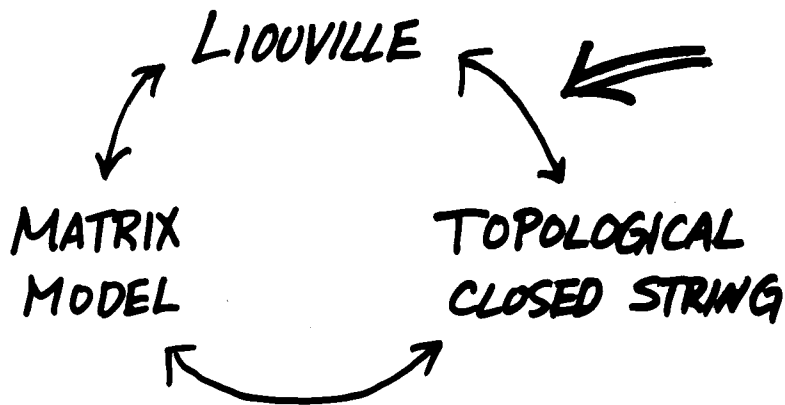
SATISFYING UNIFIED PICTURE

RASTELLI POINTED OUT THAT OPEN STRING THEORY
ON N FZZT BRANES IN THE $(2,1)$ MINIMAL STRING
IS THE KONTSEVICH MODEL.

→ PHYSICS PROOF OF OPEN/CLOSED STRING DUALITY
IN THIS CASE.

HE ALSO SHOWED THAT TOPOLOGICAL STRING
ON $AdS_3 \times S^3$ WITH k UNITS OF NS-NS FLUX
IS EQUIVALENT TO THE $(k,1)$ MINIMAL STRING.

AdS RADIUS = LIOUVILLE

D BRANES IN $\mathcal{N} = 2$ SCFT

WALCHER DISCUSSED D BRANES IN THE LANDAU-GINZBURG MODEL

MATRIX FACTORIZATION

$$Q^2 = W \cdot id$$

$\quad \llcorner$ LG potential

$$Q = \begin{pmatrix} 0 & f \\ g & 0 \end{pmatrix}$$

f, g : TACHYON CONFIGURATION IN $D\bar{D}$.

HE STUDIED MODULI SPACE OF D BRANES IN THIS FORMALISM.

EGUCHI EXPLAINED THAT THE MODULAR BOOTSTRAP GIVES A SIMPLER DERIVATION OF THE ZZ AND $FZZT$ BRANES IN THE LIOUVILLE MODEL.

$$\chi_0(\tau) = \langle ZZ | e^{i\pi\tau H} | ZZ \rangle$$

APPLYING IT TO THE $\mathcal{N} = 2$ LIOUVILLE MODEL, HE CLASSIFIED BRANES IN THE MODEL.

$\quad \cdots$ BRANE ON CONIFOLD, 2d BLACK HOLE, etc.

ANOMALIES ··· 20 YEARS AFTER
THE FIRST REVOLUTION

MOORE DISCUSSED TOPOLOGICAL ISSUES IN 11d SUGRA.

· HE POINTED OUT THAT A NAIVE CLASSIFICATION
OF ELECTRIC / MAGNETIC FLUXES BY $H^4 \oplus H^7$
IS NOT APPROPRIATE AND NEEDS TO BE REPLACED
BY A NON-ABELIAN GROUP :
  ELECTRIC FLUXES (PAGE CHARGES) DO NOT COMMUTE.

HENNINGSON DISCUSSED THE (2,0) THEORY IN 6 DIMENSIONS
WITH TENSOR MULTIPLETS AND SELF-DUAL STRINGS.
HE SHOWED THAT ANOMALY CANCELLATION CONDITIONS
LEAD TO ITS ADE CLASSIFICATION.

SUPERTUBES

CYLINDRICAL D2 BRANES SUPPORTED
AGAINST COLLAPSE BY ANGULAR MOMENTUM

TOWNSEND DESCRIBED THEM AS SOLITONS
OF GAUGE THEORIES ON BRANES.

HORAVA POINTED OUT THAT THE GOEDEL UNIVERSE

AND THE OVER-ROTATING BLACK HOLE GEOMETRY

CAN BE GLUED TOGETHER AT A SUPERTUBE,

REMOVING CAUSALITY VIOLATING REGIONS OF BOTH GEOMETRIE

HE SPECULATED THAT THEY MAY BE AT

CENTERS OF GALAXIES.

BAKAS STUDIED THE RICCI FLOW ($\sim$ RG FLOW)

FOR 2d TARGET SPACE.

. HE FOUND THAT THE EQUATION IS EXACTLY

SOLVABLE BY THE BÄCKLUND TRANSFORMATION.

FERRARI DISCUSSED A SMOOTH PROCESS IN A GAUGE THEORY

WHERE A D BRANE-LIKE OBJECT (TENSION $\sim 1/g$)

TURNS INTO A SOLITONIC OBJECT (TENSION $\sim 1/g^2$).

AT A CRITICAL POINT, THERE IS AN EXOTIC OBJECT

WITH TENSION $\sim 1/\sqrt{g}$.

HE ALSO DISCUSSED OPEN/CLOSED TOPOLOGICAL STRING

DUALITY FOR A LARGE CLASS OF MULTI-MATRIX MODELS.

∇. IS THERE A BETTER FORMULATION
OF THE THEORY ?

Pure Spinor Formalism

- Manifestly Super Poincaré invariant in 10 dimensions

- Known to reproduce tree level amplitudes correctly.

- Higher loop generalization had been difficult due to the lack of "b".

Berkovits constructed an analogue of "b" and used the formalism to prove vanishing of multiloop N point amplitudes for $N < 4$, implying finiteness of amplitudes to all order in genus expansion. The R^4 conjecture of IIB also proven.

Fermion zero modes

TOPOLOGICAL STRING THEORY

o MAY HAVE A *NONPERTURBATIVE FORMULATION*.

o UNIFIES MANY IDEAS

   IN INTEGRABLE MODELS AND TOPOLOGICAL THEORIES

   IN DIVERSE DIMENSIONS.

o IS CLOSELY *RELATED*

   TO PHYSICAL SUPERSTRING ON $\mathbb{R}^4 \times CY_3$.

VAFA SHOWED THAT, FOR A NON-COMPACT TORIC CY_3, THE TOPOLOGICAL STRING PARTITION FUNCTION Z_{TOP} IS COMPUTABLE TO ALL ORDER IN PERTURBATION USING THE TOPOLOGICAL VERTEX.

Z_{TOP} IS ALSO EXPRESSED AS A SUM OVER BLOW-UPS OF THE TORIC GEOMETRY, WHICH CAN BE INTERPRETED AS QUANTUM FOAMS.

HE NOTED THAT THE RELATION

$$Z_{BH} = |Z_{TOP}|^2 \qquad \text{(EXPLAINED BY STROMINGER)}$$

SUGGESTS THAT Z_{TOP} ITSELF DOES NOT HAVE A NONPERTURBATIVE COMPLETION, BUT $|Z_{TOP}|^2$ DOES.

HE DEMONSTRATED THIS EXPLICITLY IN THE CASE WHEN Z_{BH} IS COMPUTABLE AS THE PARTITION FUNCTION OF $2d$ QCD ON T^2.

NEKRASOV SHOWED THAT THE A AND B MODELS
ARE S-DUAL :

$$Z_A^{PERT.} = Z_B^{D \; INSTANTONS} \qquad g_A = 1/g_B$$
$${}_B \qquad\qquad {}_A$$

DIJKGRAAF AND NEKRASOV PROPOSED

7-DIMENSIONAL ACTIONS (IN DUAL VARIABLES)

WHICH REDUCE ON $CY_3 \times S_R^1$

WITH $g_7 \to 0$, $R \to 0$; $g_{TOP}^2 = \dfrac{g_7^2}{R}$ FIXED

TO :

THE KÄHLER GRAVITY (A-MODEL)
+
THE KODAIRA - SPENCER THEORY (B-MODEL)
+
THEIR MIXING

ON TO 8 DIMENSIONS !

$\mathcal{S}$TROMINGER CONJECTURED :

$$Z_{BH} = |Z_{TOP}|^2,$$

WHERE

$$Z_{BH}(p, \phi) = \sum_{q} \Omega(p, q) \, e^{-\pi \phi \cdot q}$$

Ω = INDEX OF BLACK HOLE STATES

p, q : MAGNETIC / ELECTRIC CHARGES

$Z_{TOP}(X)$, $X = p + i\phi$: CY MODULI

$\mathcal{W}$ H Y ?

VI. What will Witten tell us?

- Healty return to phenomenology with new ideas.

  Landscape, Cosmic Strings, ...

- Deeper insights into formal structure.

  AdS/CFT, Topological String, ...

Santa Barbara Workshop

"Mathematical Structure
in String Theory"

August - December, 2005

ORGANIZED BY:

R. Dijkgraaf, M. Douglas, M. Kontsevich,
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FINE TUNING

BY THE ORGANIZERS.

Thank you,

Costas, Eugene,

Paul,

and many other friends in Paris.

ENJOY YOUR VACATIONS.