# OPENING LECTURE

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# MY ASSIGNMENT:

## Give an overview of the status of the field

I agreed to this, even though it was obvious to me that I am incapable of doing justice to all that is happening.

After some agonizing, I have decided to survey some recent developments in two of the subjects not covered by review talks. First, I will make a few general remarks.

# WHAT IS "THE FIELD"?

Since the discovery of gauge/gravity duality and other developments, it has become clear that QFT and string theory/M-theory are NOT distinct subjects. String theory and M-theory can be viewed as important components of the logical completion of quantum field theory.

The boundaries of "the field" are not sharply defined. As our studies illuminate various aspects of particle physics and cosmology, and our techniques find new applications, more and more topics become appropriate for string theory conferences.

## IS STRING THEORY RADICAL?

String theory grew out of the S-matrix theory program, which was popular in the 1960s. For many years string theory appeared to be a radical alternative to quantum field theory.

It is now clear that string theory and M-theory are not radical at all. In fact, they are the most conservative and inevitable ways in which to formulate quantum theories of gravity. I think this deserves to be emphasized when speaking about string theory to non-experts.

# MY ASSESSMENT OF THE STATUS OF THE FIELD

- The field is thriving; it continues to attract extremely talented young people
- Impressive progress is being made on many fronts and there is much enthusiasm
- String theory *techniques* are stimulating progress in fundamental mathematics and other areas of physics

# THREE LESSONS

Before discussing specific topics, I would like to share some lessons that I have learned in the course of over 40 years of research in string theory and related subjects.

I wish that these had been emphasized to me when I was a student. It might have made a difference.

**Lesson #1: If a theory meant to solve problem A turns out to be better suited to solving problem B, modify your goal accordingly.**

Example: The original goal of string theory was a theory of hadrons, but it works better as a theory of quantum gravity and unification. The massless particles should be identified as gauge particles and a graviton rather than vector mesons and a Pomeron.

Yang and Mills (1954) originally identified SU(2) gauge fields with $\rho$ mesons. In the early days string theorists had been doing essentially the same thing!

**Lesson #2: Take "coincidences" seriously.**

Example 1: The massless states of type IIA superstring theory correspond to the lowest modes of 11d supergravity on a circle. This was known for many years before it was taken seriously.

Example 2: It was well known that the conformal group in $d$ dimensions is the same as the Anti de Sitter isometry group in $d+1$ dimensions many years before AdS/CFT duality was proposed.

**Lesson #3: When working on hard problems explore generalizations with additional parameters that can be varied.**

This lesson seems to be widely appreciated. There are many examples in the recent literature.

I will discuss a couple of examples later. They are the $\Omega$ background for $\mathcal{N} = 2$ gauge theories and the $\mathbb{Z}_k$ orbifold generalization of $AdS_4 \times S^7$.

## THERE WILL BE SEVEN REVIEW TALKS

I will defer to the respective speakers for discussion of these topics.

MON PM: Applications of holographic duality to QCD and condensed matter physics (Karch)

TUES AM: Higher-spin holography (Yin)

TUES PM: Multiloop methods for gauge and gravity scattering amplitudes (Carrasco)

WED AM: String phenomenology (Uranga)

THURS AM: Beyond the Standard Model in light of the LHC (Dimopoulos)

THURS PM: Alternative approaches to quantum gravity (Nicolai)

FRI AM: Topological strings and their applications (Vafa)

# OTHER TOPICS

Here are some other interesting topics that I considered discussing, but will only list:

- Integrability of certain large-$N$ gauge theories ($\mathcal{N} = 4$ SYM and ABJM) and their holographic dual world-sheet theories; tests of the corresponding dualities
- New examples of holographic dualities
- Dualities with Horava–Lifshitz scaling

- $c$ theorems, $a$ theorems, and $F$ theorems
- BPS degeneracies and wall-crossing formulas
- Microstates and black-hole entropy
- Black holes as fuzzballs
- Double field theory and U-dual generalizations
- Attempts to formulate (2,0) SCFTs in 6d
- String cosmology

# TWO SUBJECTS

For a few minutes each, I will discuss two subjects in which there has been significant progress in recent years:

**I. N = 2 Gauge Theories**

**II. BLG and ABJM Theories**

I will organize my remarks by emphasizing some of the key papers.

# I. $N = 2$ GAUGE THEORIES

This subject developed rapidly following the 1994 classic papers of Seiberg and Witten. Further insight was provided by Witten's 1997 geometrical derivation based on lifting a type IIA brane configuration to a single M5-brane in M-theory.

I will now sketch some more recent developments.

## Seiberg-Witten Prepotential from Instanton Counting

N. A. Nekrasov [hep-th/0206161]

- Introduced a two-parameter generalization $(\epsilon_1, \epsilon_2)$ of $\mathcal{N} = 2$ gauge theories (called the "$\Omega$ background") and hence of the SW prepotential $\mathcal{F}(a, \epsilon_1, \epsilon_2; \Lambda)$. The usual prepotential is given by $\epsilon_1, \epsilon_2 \to 0$.
- Computed the instanton partition function in the $\Omega$ background, $Z = \exp(\mathcal{F}^{\text{inst}}/\epsilon_1\epsilon_2)$, using the localization method introduced by Losev, Nekrasov, Shatashvili [hep-th/9711108, hep-th/9801061].

# N = 2 Dualities

D. Gaiotto [arXiv:0904.2715]

- A large class of $\mathcal{N} = 2$ SCFTs is defined by wrapping M5-branes on a Riemann surface with marked punctures (obeying certain rules).
- Generalization of S-duality: Various dual *generalized quiver theories* correspond to different pants decompositions of the Riemann surface.
- A family of strongly interacting (non-lagrangian) SCFTs provide basic ingredients.

## The Gravity Duals of N = 2 Superconformal Field Theories

D. Gaiotto and J. Maldacena [arXiv:0904.4466]

- This paper studies the holographic dual of the large-$N$ limit of a certain class of $\mathcal{N} = 2$ SCFTs.
- Using results of Lin, Lunin, Maldacena [hep-th/0409174], it constructs the dual M-theory description (with $AdS_5 \times M_6$ geometry). A function appearing in the $M_6$ metric is a solution of a 3d Toda equation.

## Liouville Correlation Functions from Four-dimensional Gauge Theories

L. F. Alday, D. Gaiotto and Y. Tachikawa

[arXiv:0906.3219 [hep-th]]

- Relates 2d Liouville/Toda theory conformal blocks and correlation functions to the Nekrasov partition function of the corresponding 4d $\mathcal{N} = 2$ SCFT.
- Remark: I suspect that the 3d Toda system in the M-theory dual corresponds to the large-$N$ limit of these 2d Toda theories. This suggests that one of the M-theory dimensions is discrete for finite $N$.

## Quantization of Integrable Systems and Four Dimensional Gauge Theories

N. A. Nekrasov and S. L. Shatashvili [arXiv:0908.4052]

- An $\mathcal{N} = 2$ gauge theory in an $\Omega$ background (with $\epsilon = \epsilon_1$, $\epsilon_2 = 0$) provides the quantization of the classical integrable system underlying the moduli space of vacua.

- The $\epsilon$ parameter is identified with $\hbar$; the twisted chiral ring maps to quantum Hamiltonians; supersymmetric vacua correspond to Bethe states.

## The Omega Deformation, Branes, Integrability, and Liouville Theory

N. A. Nekrasov and E. Witten [arXiv:1002.0888]

- Reformulates the $\Omega$ deformation of 4d gauge theory in a way that is valid away from the fixed points.
- Uses this reformulation to explain the relation between $\Omega$ deformation and integrable Hamiltonian systems as well as AGT duality.

## The Omega Deformation from String and M-Theory

S. Hellerman, D. Orlando and S. Reffert [arXiv:1204.4192]

- This paper (and previous ones by the same authors) gives a string theory construction of $\Omega$ deformation. It is given by a *fluxtrap* background, which is T-dual to a *fluxbrane* or Melvin background.

- Lifting to M-theory corresponds to wrapping an M5-brane on a Riemann surface with self-dual flux. A "9-11 flip" allows them to reinterpret the $\Omega$ deformation in terms of non-commutative geometry.

## II. BLG and ABJM Theories

- These are superconformal Chern–Simons theories in three dimensions. They have two Chern–Simons terms with levels $\pm k$.
- The BLG Lagrangian has $OSp(8|4)$ superconformal symmetry and $SU(2)_k \times SU(2)_{-k}$ gauge symmetry with eight real bifundamental matter multiplets.
- The ABJM Lagrangian has $OSp(6|4)$ superconformal symmetry and $U(N)_k \times U(N)_{-k}$ gauge symmetry with four complex bifundamental matter multiplets.

## Modeling Multiple M2's

J. Bagger and N. Lambert [hep-th/0611108]

## Algebraic Structures on Parallel M2-branes

A. Gustavsson [arXiv:0709.1260]

## Gauge Symmetry and Supersymmetry of Multiple M2-branes

J. Bagger and N. Lambert [arXiv:0711.0955]

# BLG from gauged supergravity

$\mathcal{N} = 8$ supergravity in 3d coupled to $n$ free supermultiplets has global $SO(8,n)$ symmetry. It is possible to gauge $SO(4)$ subgroups by including suitable Chern–Simons terms, as was shown in

**N=8 Matter Coupled AdS(3) Supergravities**

H. Nicolai and H. Samtleben [hep-th/0106153]

In particular, one can gauge an $SO(4)$ subgroup of the $SO(8,4)$ supergravity theory, leaving unbroken $SO(8)$ R-symmetry. If one then turns off the gravity ($m_p \to \infty$), this leaves the BLG theory, as was shown in

**Multiple Membranes from Gauged Supergravity**

E. A. Bergshoeff, M. de Roo, O. Hohm and D. Roest

[arXiv:0806.2584]

## $\mathcal{N} = 6$ Superconformal Chern-Simons-Matter Theories, M2-branes and Their Gravity Duals

O. Aharony, O. Bergman, D. L. Jafferis and J. Maldacena

[arXiv:0806.1218]

- At large $N$, fixed $k$, the ABJM theory is dual to M-theory on $AdS_4 \times S^7/\mathbb{Z}_k$.
- At large $N$, fixed $\lambda = N/k$, it is dual to type IIA superstring theory on $AdS_4 \times CP^3$.
- Quantum effects enhance $OSp(6|4)$ to $OSp(8|4)$ for $k = 1, 2$. (Opposite of an anomaly!)

## Nonperturbative Tests of Three-Dimensional Dualities

A. Kapustin, B. Willett and I. Yaakov [arXiv:1003.5694]

This paper tests several conjectured dualities between 3d SCFTs by using localization methods to compute their exact partition functions as functions of Fayet-Iliopoulos and mass parameters. (Adding parameters!)

In particular, the exact partition function of the $k = 1$ ABJM theory on $S^3$ agrees with that of $\mathcal{N} = 8$ super Yang–Mills theory. This is a nonperturbative test of their conjectured equivalence in the conformal limit.

## ABJM Theory as a Fermi Gas

M. Marino and P. Putrov [arXiv:1110.4066]

- Building on previous work by themselves and others, this paper derives the $N^{3/2}$ large $N$, fixed $k$ behavior of the free energy of the ABJM theory (and other 3d CSM theories) – including the coefficient.
- Localization is used to reduce the partition function on $S^3$ to a matrix model, which is reformulated as the partition function of an ideal Fermi gas. The full series of $1/N$ corrections is determined by the next-to-leading semiclassical approximation.

## CONCLUDING REMARKS CONCERNING STRING THEORY AND THE REAL WORLD

String theory has many possible vacua. It is unclear how much of particle physics and cosmology can be derived and how much is environmental. Some features undoubtedly are environmental (or "anthropic"), but this does not mean that all of them are.

There may be principles that can greatly narrow the range of possibilities (e.g. contractibility of the 4-cycle wrapped by 7-branes in F-theory). My guess is that many quantities will be computable.

Crucial information required for correctly extending the standard model to much higher energies might not be experimentally accessible. The scale and mechanism of supersymmetry breaking might be examples. Without this information it will be difficult to bridge the gap between the TeV scale and the Planck scale.

Despite this concern, I remain an optimist. The LHC is working magnificently, and the experimentalists are doing a great job. I expect that the Higgs boson is only the first of many experimental discoveries in this decade.

I am looking forward to an exciting conference.

**Thank you for your attention.**