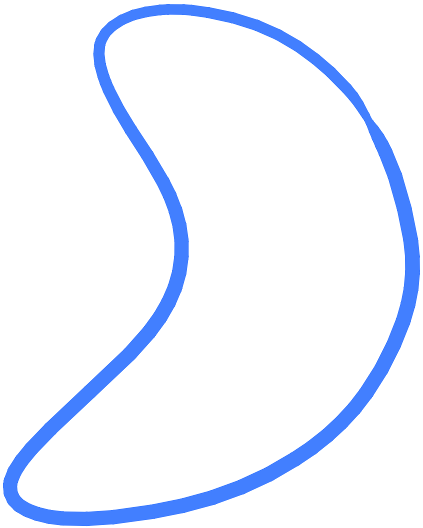
Conference Summary

Strings 2008

Hirosi Ooguri

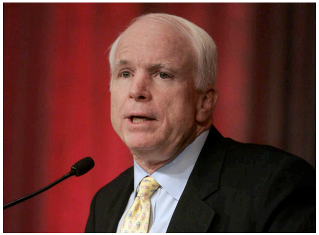
California Institute of Technology & IPMU

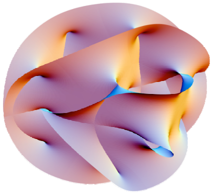
Why String Theory?



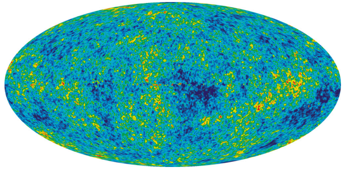
String theory is

(1) a candidate

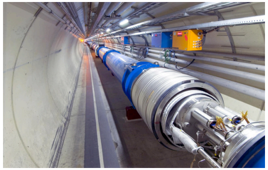




$10^{-9} \times 10^{-9} \times 10^{-9} \times 10^{-9}\,m$



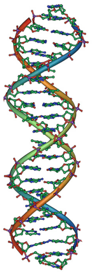
$10^{9} \times 10^{9} \times 10^{9}\,m$



$10^{-9} \times 10^{-9}\,m$

to govern everything.

$10^{9} \times 10^{9}\,m$



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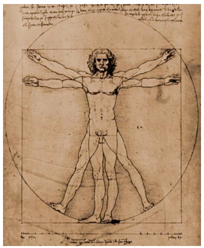
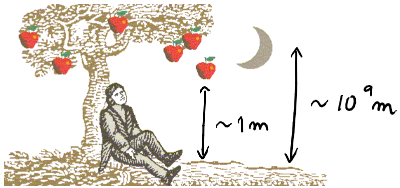


$1\,m$



$10^{9}\,m$

String theory is

(2) a model

String theory is already a good approximation to our world.

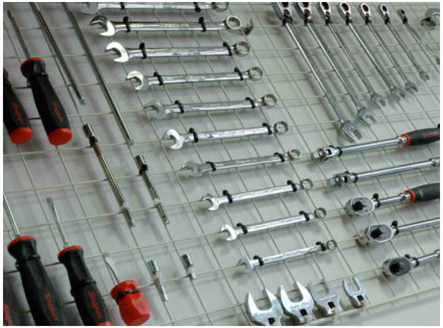
Four Large Dimensions, Gravity, Chiral Fermions, Gauge Interactions, Symmetry Breaking, ...

It teaches us what are possible in a consistent theory of quantum gravity.

e.g., It explained how Hawking's seemingly robust argument for information loss by black holes can go wrong.

String theory is

(3) a tool



Numerous applications to study strongly interacting systems:

Quark-Gluon Plasma

Hadron Physics

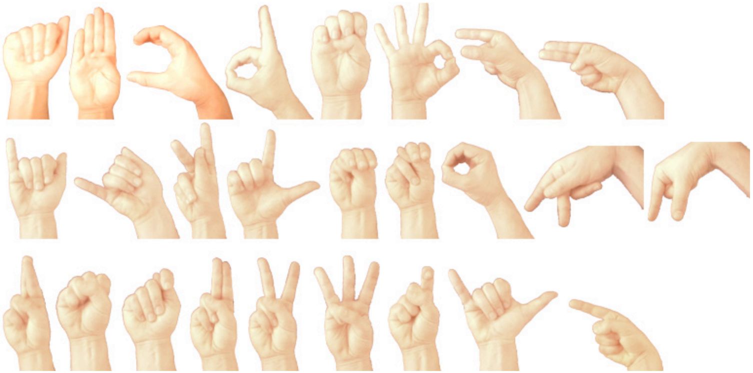
Quantum Phase Transitions in CMP

Cold Atoms

... via the AdS/CFT correspondence.

String theory is

(4) a language



Quantum Gravity:
Spacetime does not exist beyond the Planck scale, and they **should emerge from more fundamental structure**. We need a new language to talk about it.

Quantum Field Theory:
Recently discoveries suggest that traditional Feynman diagrams may not be the best words **even in perturbation theory**.

Quantum Gravity:
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Recently discoveries suggest that traditional Feynman diagrams may not be the best words **even in perturbation theory**.

They may be related by the gauge/gravity duality.

String theory is

(1) a candidate
(2) a model
(3) a tool
(4) a language

Exciting progress has been reported at this conference in each of the 4 categories.

Caveat:
An important work often plays more than one roles.

e.g., ***studies of extremal black holes*** *have taught us important lessons on quantum gravity (2), led to useful tools (3), and uncovered beautiful mathematical structure (4).*

(1) string theory as a candidate

Attempts to derive realistic models
from string theory may lead to:

(a) a proof that string theory can be a unified theory of all particles and their interactions.

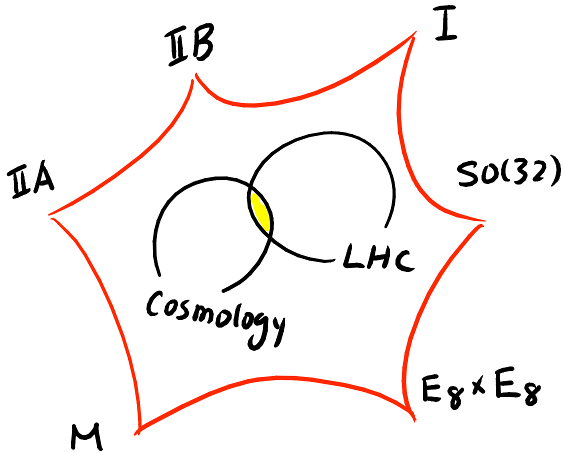
(b) new mechanisms to solve phenomenological problems.

(c) testable predictions if very few classes of compactifications fit all the known data.

Ibanez reviewed the current status of the MSSM landscape:
heterotic, type IIA/B orientifolds, and F-theory.

He pointed out that **phenomenologically desired couplings** (*neutrino masses, mu-terms, Yukawa couplings, moduli fixing*) are **often prohibited in perturbation theory**, and one needs to evaluate stringy instanton effects. **Weigand** discussed techniques to evaluate these effects for type II orientifolds.

Ibanez noted that, in the gravity mediation scenario, sparticle masses are sensitive to ultraviolet physics and may give information on string vacua.



Heterotic String

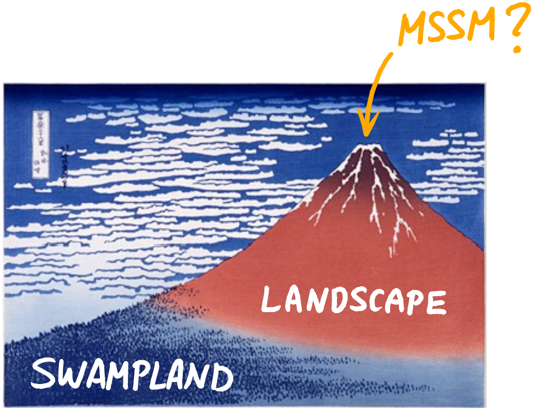
The *E8* x *E8* heterotic string on *R4* x *smooth CY3* with gauge instanton *V* is the classic example (CHSW) of string compactification.

Donagi presented an explicit example with:

> *MSSM gauge group SU(3)* x *SU(2)* x *U(1) with no extra U(1), precise MSSM spectrum with no exotic (but with moduli), semi-realistic coupling, R-parity, mu-terms.*

Satisfying the **anomaly cancellation condition** and the **stability condition** of *V* simultanenously turns out to be highly non-trivial.

Only one satisfactory example, so far.



F-theory

The **F-theory construction** combines the advantages of local models (flexibility and control of model building) and the heterotic construction (gauge unification).

Vafa argued that, if one assumes that gravity decouples from gauge dynamics (motivated by asymptotic freedom of typical GUT models), there is an **almost unique F-theory construction that satisfies all the phenomenological requirements**:

top quark mass, mu-terms, doublet-triplet splitting, weak scale supersymmetry breaking ...

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Is there any problem that is left unsolved?

Supersymmetry Breaking

General Gauge Mediation:

Shih gave a general definition of **gauge mediation** of supersymmetry breaking and presented a framework to compute soft terms in the MSSM.

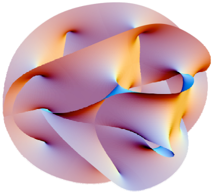
He discussed **general predications** of this framework.

Holographic Gauge Mediation:

H. Verlinde applied this framework to the case when the hidden sector is the Klebanov-Strassler geometry with anti-D3 branes and the supersymmetry breaking effect is mediated by D7 brane probes.

... stringy realization of **warped gaugino mediation**.

Cosmology



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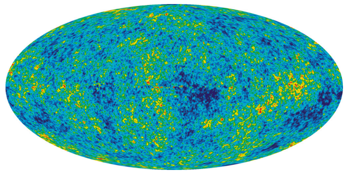

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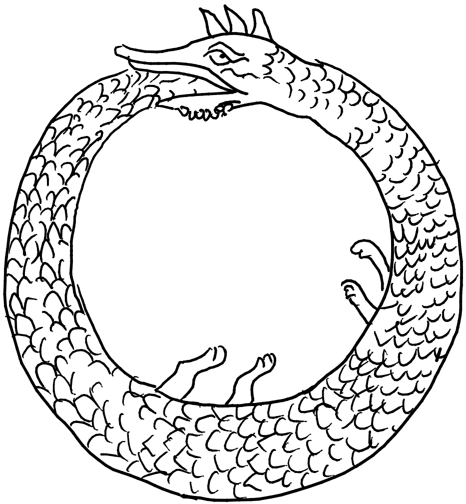
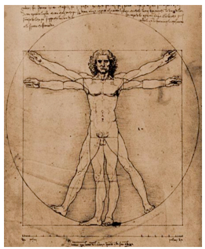


Gravity and **Quantum Mechanics** become important



$1\, m$

at the two extreme ends of scales.

Kallosh reviewed **near-future tests of string theory** with B-mode polarization, spectral index, non-gaussianity, and cosmic string.

She discussed how current studies of stringy inflation models, including the D3/D7 hybrid inflation and the KKLMMT inflation, compare with cosmological data.

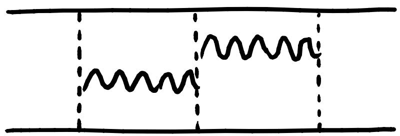
The recent proposal by Silverstein and Westphal may help circumvent the difficulty in realizing $\Delta\phi > M_P$, necessary for chaotic inflation.

(2) string theory as a model

Trans-Planckian Energy Collisions provide important **gedanken experiments** for string theory.

Veneziano showed how results of classical General Relativity are reproduced from small angle elastic scattering (leading eikonal). In inelastic scattering, **stringy effects**, such as tidal force on strings and string formations, can be seen.

To understand scatterings with small impact parameter, he formulated an **effective *2d* field theory** and showed that its critical behavior matches well with the criterion for **generation of closed trapped surfaces** .



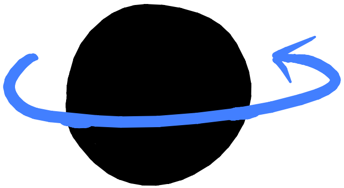
This description may help us understand the **unitarity of S-matrix** for black hole formation and evaporation and lead to a resolution of the **information paradox**.

Gravity in three dimensions:

There are **chiral conformal field theories** in two dimensions, where the right-moving sector is trivial.

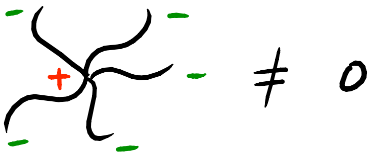
Strominger proposed that the pure Einstein gravity with negative cosmological constant with a fine-tuned Chern-Simons term is dual to such a conformal field theory.

He also conjectured that the near horizon limit of an extremal Kerr black hole is described by such a conformal field theory.



Understanding **quantum gravity in de Sitter space** is important.

Polyakov explained, in a *2d* example, that **particle production screens the cosmological constant in de Sitter space**, in analogy with the Schwinger mechanism for magnetic field.
In higher dimensions, he formulated stability conditions of curved space and argued that **de Sitter space fails the eternity test**.



He conjectured that the **gauge theory dual of de Sitter space** is given by tuning the gauge coupling constant to a complex value, where **Feynman diagrams become dense**, as in the case of the double-scaled matrix model and unlike the AdS/CFT correspondence.

The role of time in string theory is not well-understood.

Hellerman described novel time-dependent solutions that are exact in alpha':

Bosonic String => Nothing

Dimensions-Changing Transition

Type 0 => Type II

Type 0 => Bosonic (via the Berkovits-Vafa embedding)

A word on Hellerman's affiliation...

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

wpi World Premier International Research Center Initiative

IPMU was established as **one of five WPI's** by the Japanese Government to discover fundamental laws of nature and to solve deepest mysteries of the Universe by **integrating mathematics, experimental and theoretical physics, and astronomy**.

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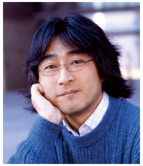
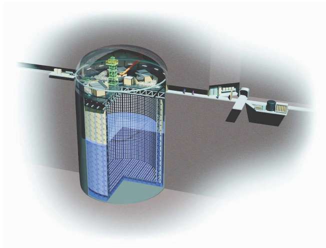


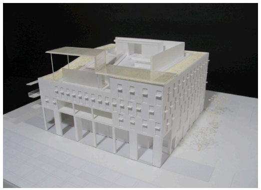
Hitoshi Murayama
Founding Director

International group of scientists



New experiments at Subaru and Kamioka to study dark matter and dark energy.

$150 - 200 M
for the next
10 years.



New building
by fall 2009

(3) string theory as a tool

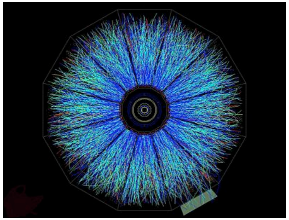
(3) string theory as a tool

Applied String Theory

Quark Gluon Plasma (reviewed by **Gubser** and **Starinets**):

Computation of the transport coefficients in *N=4* SYM at finite temperature is almost complete.

Shear/Bulk Viscosity, Conductivity, etc



Effects of hard probes, such as **drag force** and **jet splitting/quenching**, have also been computed using the AdS/CFT correspondence.

Gubser reviewed their applications to QCD at finite temperature. They provide a new theoretical window into strongly coupled thermal plasma.

How to quantify theoretical errors?

Minwalla showed:

{ regular long-wave length solutions to the Einstein equation with negative cosmological constant in the bulk }

= { solutions to a *generalized* Navier-Stokes equation }

Starinets presented computation of the specific heat and charge density current of SU(Nc) *N=4* SYM coupled to Nf *N=2* hypermultiplets using its holographic dual.

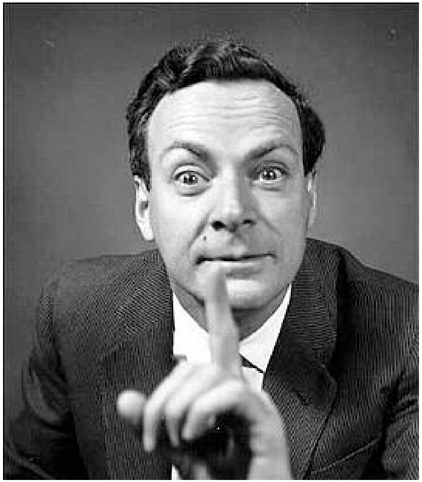
$C_V \sim T^6$ c.f. T^3 : Bose gas
T : Fermi gas

But with a zero sound mode!

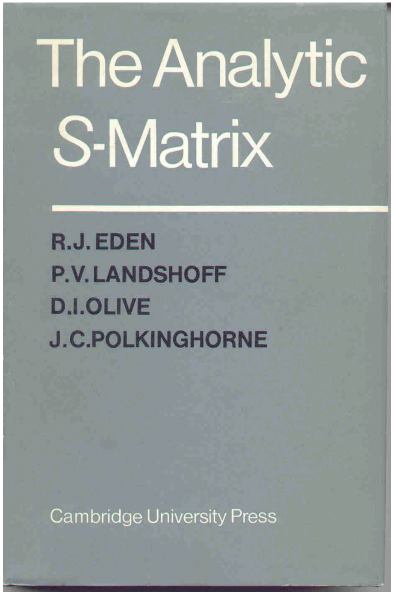
New type of strongly correlated quantum liquid?

(4) string theory as a language

Magic in Perturbation



The S-Matrix Theory Strikes Back



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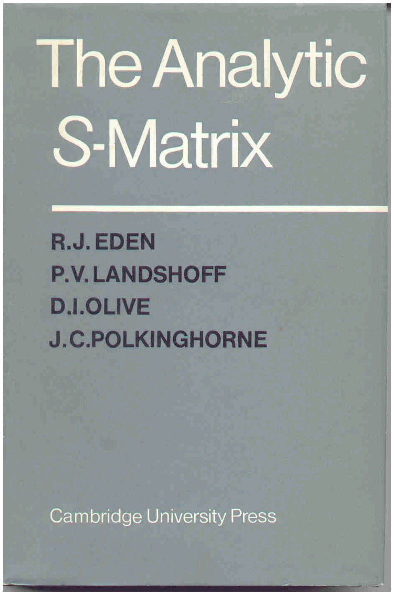
Julian Schwinger,
in "Particles, Sources, and Fields"

The S-Matrix Theory Strikes Back



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Twistor Space

Dixon reviewed **new perturbative techniques** to exploit **factorization** and **unitarity** in the **spinor helicity formalism**.

Combined with insights from string theory such as the **AdS/CFT correspondence** and the **KLT relation**, these techniques uncovered structures of perturbative amplitudes in gauge theory and gravity that are not apparent in Feynman diagrams.

Exponentiation of Finite Terms
Dual Superconformal Invariance
T-duality of MHV Amplitudes and Wilson Lines

T-duality and Dual Superconformal Invariance:

Berkovits showed that a combination of bosonic and fermionic T-dualities maps AdS5 x S5 to itself.

This exchanges ***N=4*** **SYM amplitudes** with **Wilson lines**, and **superconformal symmetry** with **another non-local symmetry**.

Sokatchev explained how this works explicitly in the planar gauge theory computation for **small 't Hooft coupling**.

Alday did the same for **large 't Hooft coupling** using the AdS/CFT correspondence.

The exponentiation phenomenon is also discussed in the two limits.
(In fact, a consequence of dual conformal symmetry)

String theory and quantum field theory are making progress hand in hand.

Expression for all planar amplitudes in all values of 't Hooft coupling

Cachazo discussed **remarkably convergent behavior of *N=8* supergravity** amplitudes at **infinite complex momentum** due to maximum supersymmetry and enhanced spin symmetry.

The tree-level S-matrix is determined by 3-particle S-matrix.
The one-loop S-matrix is determined by the leading singularity.

The moduli space and E7(7) symmetry can be found from single and double soft emissions.

Green showed that maximum supersymmetry and duality symmetry impose **powerful constraints on higher derivative terms** in the low energy effective action of string theory, determining their perturbative and non-perturbative coefficients.

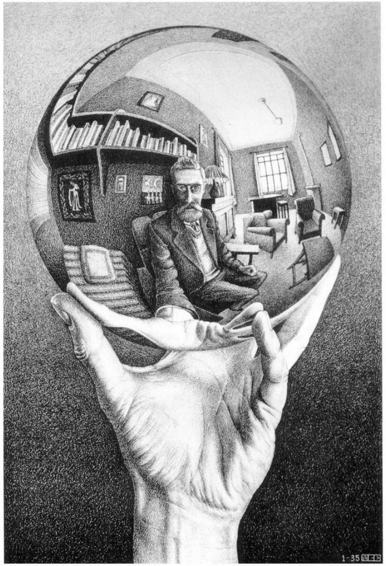
Is N=*8* supergravity finite?

Superstring Amplitudes:

Stieberger pointed out that the **supersymmetry Ward-Takahashi identities** imply remarkable simplifications of tree-level open string amplitudes.

In the large extra-dimension scenario, where the string scale can be ~ TeV, stringy effects may appear in LHC as universal deviation from the Standard Model jet distribution.

Toward a Proof of the AdS/CFT Correspondence



What does it mean to prove the AdS/CFT correspondence?

Since type IIB string theory is defined only perturbatively in the string coupling constant, the proof must be for the equivalence between the perturbative string computation in AdS5 *x* S5 and the 't Hooft expansion of the Yang-Mills computation.

It is a question about the *2d* worldsheet.

Take the *2d* sigma-model for AdS5 *x* S5, expand its observables for large target space curvature, and find that the planar Yang-Mills expansion emerges.

The integrabilities have been very helpful, in both *2d* and *4d*.

Consider $\mathcal{O}_{L,M} = \mathrm{Tr}\,(D^L Z^M) + \cdots$

For large M with fixed L, there is a beautiful formula for the anomalous dimension,

$$\gamma = f(g) \log M + \cdots$$

which interpolates the string computation and the Yang-Mills computation. (*reported at Strings 2007*)
This was the **strongest dynamical evidence for the AdS/CFT correspondence**.

Staudacher considered a more general limit where $j = \frac{L}{\log M}$ is fixed.

$$\gamma = f(g, j) \log M + \cdots$$

Again, a remarkable interpolation between the weak coupling and the strong coupling expansion.

For the anomalous dimensions of the Konishi operator, at 4 loop, there has been a disagreement between the string worldsheet computation using the asymptotic Bethe ansatz and the Yang-Mills computation.

The discrepancy is due to finite size effects of the worldsheet.

Janik generalized Lüscher's method to evaluate finite size effects using S-matrix and **resolved the discrepancy**.

$$\Delta_{\mathrm{Bethe}} = 4 + 12 g^2 - 48 g^4 + 336 g^6 - (2820 + 288\,\zeta(3))\, g^8 + \cdots$$

$$\delta\Delta_{\text{finite size}} = (324 + 864\,\zeta(3) - 1440\,\zeta(5))\, g^8 + \cdots$$

A highly non-trivial test of the AdS/CFT correspondence!
(*the first example involving finite size effects*)

M2 Branes
mini-Revolution

Four years ago, John Schwarz suggested that the **low energy effective theory of multiple M2 branes** is described by the Chern-Simons gauge fields coupled to massless matter fields with $N=8$ superconformal symmetry.

An explicit construction of the $N=8$ Lagrangian was discovered last year by Bagger and **Lambert** and by Gustavsson.

The $N=8$ theory at level $k=2$ with $SU(2) \times SU(2)$ gauge group seems to describe two M2 branes on R^8/Z_2.
It is not clear what the theory describes for other values of k or how to construct Lagrangians for higher rank groups.

Higher rank gauge groups are possible if one relaxes the **positivity condition** on the 3-algebra.
Mukhi showed that the resulting theory is classically equivalent to the $N=8$ super Yang-Mills theory on D2 branes.

Another possibility is to **reduce supersymmetry to $N=6$**.
Maldacena discussed such a model with $U(N) \times U(N)$ gauge group with bifundamental matter fields.

The ***N=6* theory** of level *k* with *U(N)* x *U(N)* gauge group is proposed to be dual to M theory on AdS4 x S7/Z_k.

When *k* is large, it is dual to **type IIA string on AdS4 x CP3** with *k* units of 2-form flux and *N* units of 4 form flux.

The gauge coupling is *1/k*, and the 't Hooft couping is *N/k*.
The theory may be integrable in the 't Hooft limit.

Both AdS4 x S7/Z_k and AdS4 x *Squashed* S7/Z_k have dual Chern-Simons theories. In the type IIA picture, both are AdS4 x CP4 with different metrics.

Tomasiello showed that there is a family of string vacua interpolating the two, with non-zero Romans mass.

BPS Properties

BPS Black Holes and Topological String:

$$|\psi_{top}(p+i\phi)|^2 = \sum_q \Omega(p,q)\, e^{-q\cdot\phi}$$

Pioline reviewed mathematical structures that emerge in the microstates counting of BPS black holes in *N=2* in *4d*:

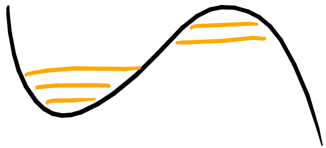
Split Attractor Flows,
Elliptic Genera of (0,4) MSW SCFT,
Donaldson-Thomas theory, etc.

Sen discussed **higher derivative corrections** to the entropy formula.

For BPS black holes, his result amounts to a **derivation of the OSV conjecture**, assuming the **AdS2/CFT1 correspondence** and that only F-terms contribute.

Progress in Topological String:

Marino described the mirror of the topological vertex construction in terms of a chiral boson on a Riemann surface (*the Kodaira-Spencer theory of gravity*). He proposed a method to evaluate **non-perturbative effects** by a sum over multi-instanton sectors, which corresponds to summing over all backgrounds.



Walcher generalized the BCOV **holomorphic anomaly equations** to open string and computed open Gromov-Witten invariants.

For **compact** Calabi-Yau manifolds, the use of topological string for counting of BPS states requires **tadpole cancellation conditions**.

Why?

Wall crossing in four dimensions:

The "number" of BPS states in *4d N=2* theory **can jump** across walls of marginal stabilities in the moduli space.

Moore consider the theory on $\mathbb{R}^3 \times S^1$, where the low energy theory is a *3d* sigma model whose target space metric depends on BPS states in *4d* as they appear as instanton in *3d*.

Requiring that the metric be smooth on the moduli space imposes conditions on the number of BPS states, which turn out to be the wall crossing formula of Kontsevich and Soibelman.

The metric is characterized by an analogue of **the *tt** equation** studied by Cecotti and Vafa for *2d* theories 15 years ago.

The S-duality should map boundary conditions of $N=4$ SYM into each other. In the U(1) theory, Neumann and Dirichelet conditions are exchanged.

The situation is more interesting in Non-Abelian cases.

Taking clues from intersecting brane configurations, **Gaiotto** constructed a large class of BPS boundary conditions, which map into each other under the S-duality.

Is this the complete classification?

The Parade of Beautiful Ideas

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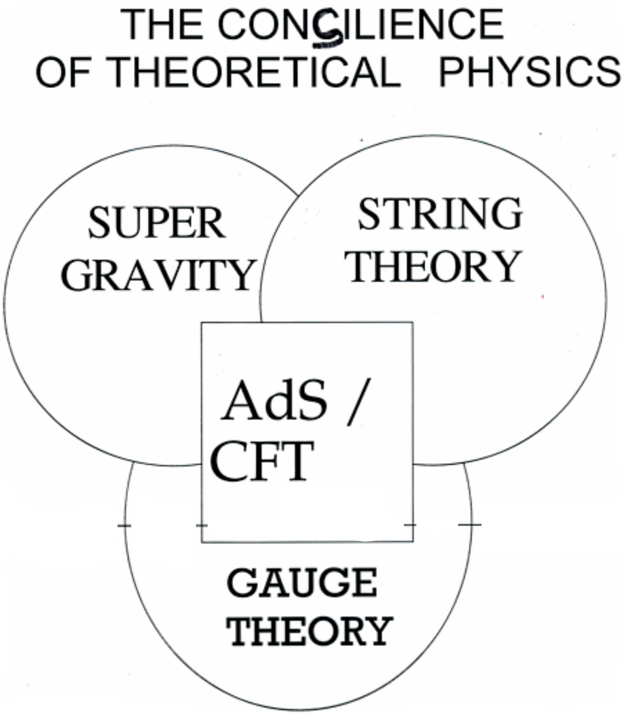
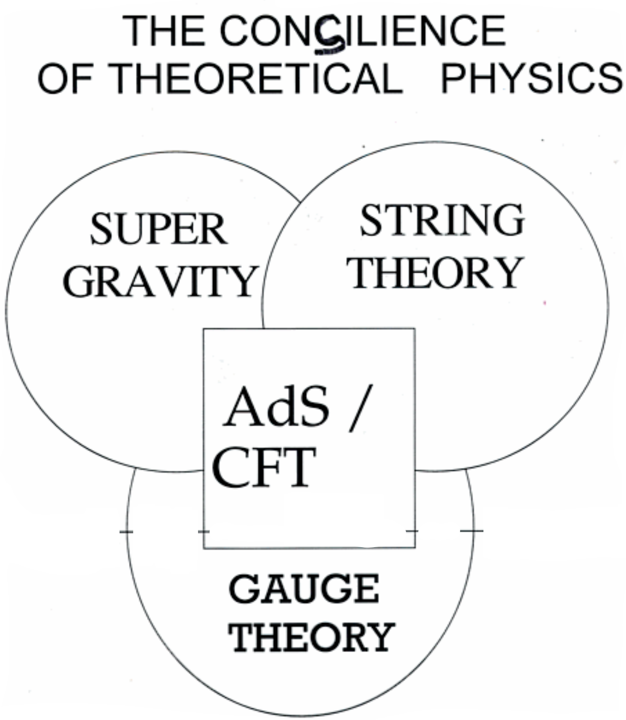
I hope Nature likes some of them.



Opening Remarks
by David Gross

Strings '98



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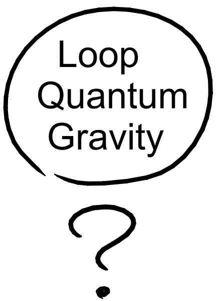

No Parallel Sessions

One of the strengths of string theory is its **power to identify surprising connections** between previously unrelated areas, e.g., the AdS/CFT correspondence.

The field is sufficiently small and tightly knit that any one theorist can attend all the talks of the Strings conference and understand them.

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(or pretend to, in my case...)

Therefore,

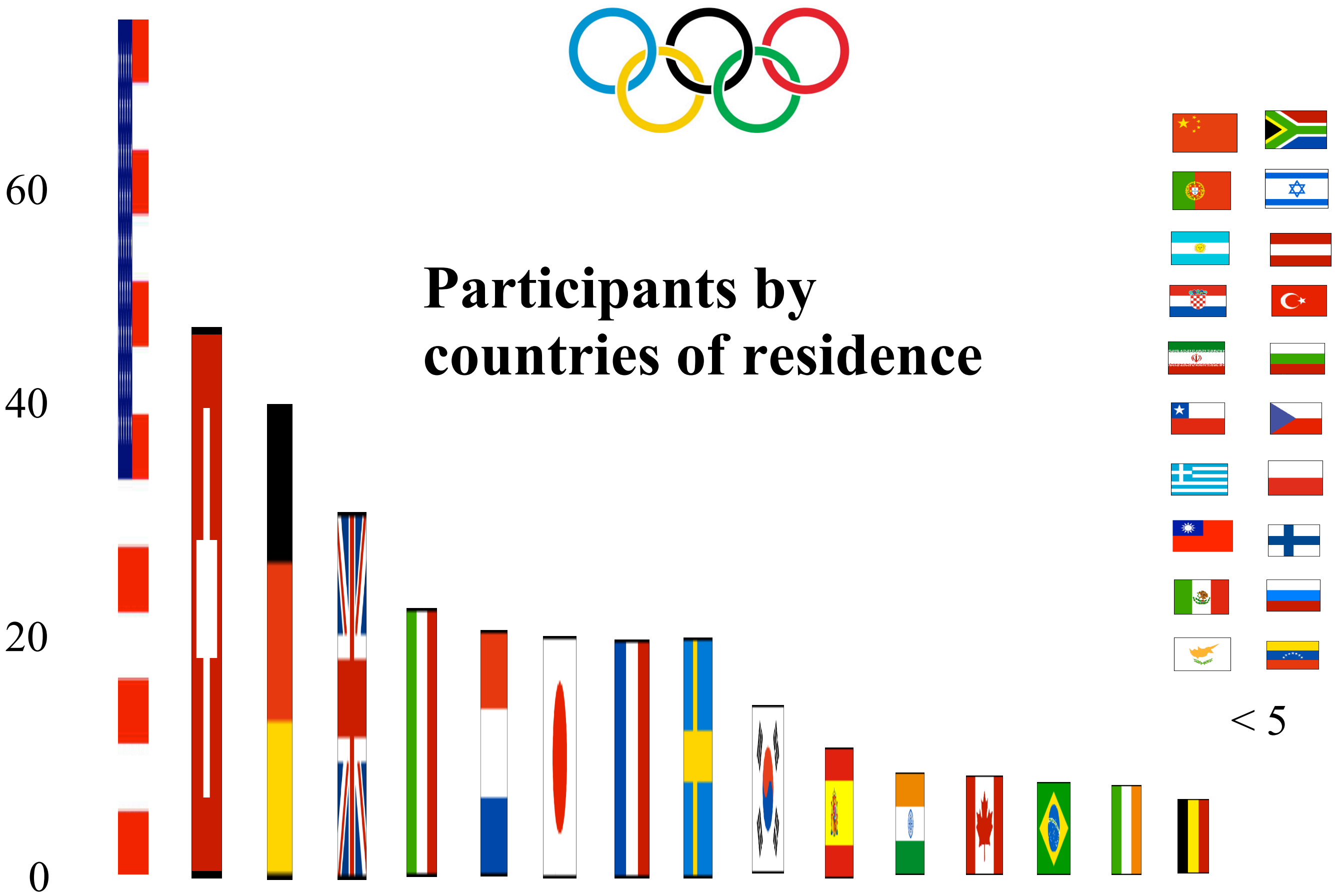
Aspen Center for Physics
2009 Summer Workshop

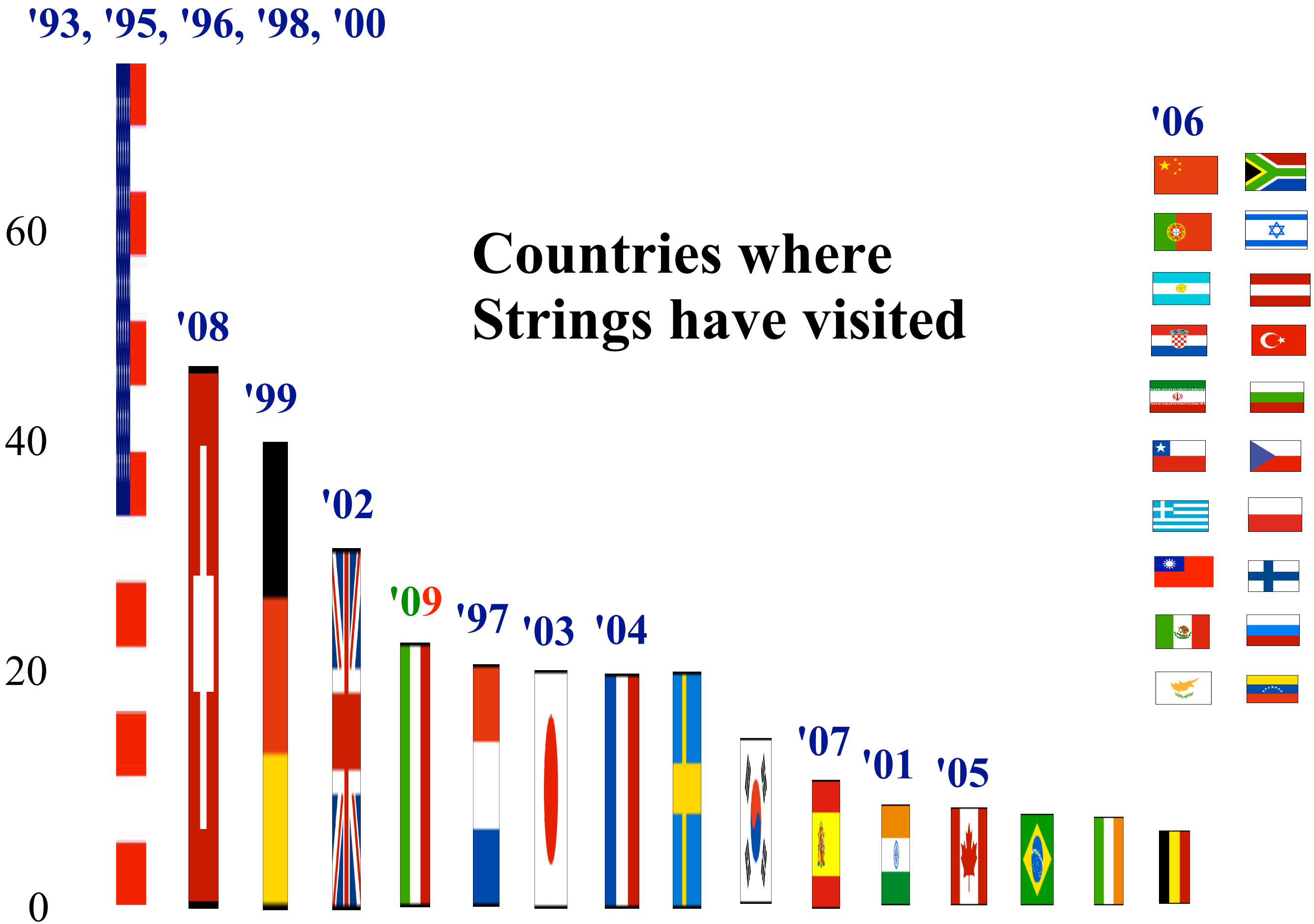
Unity of String Theory

July 27 - August 16, 2009

organized by A. Maloney, H. Liu, and H. Ooguri

403 Participants from 36 Countries


Participants by
countries of residence
60
40
20
0
< 5



'93, '95, '96, '98, '00
'06
60
Countries where
Strings have visited
'08
'99
40
'02
'09
'97
'03
'04
20
'07
'01
'05
0

Thank you, Elena, Nanie.

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Good luck with
your experiment.