30 Years of Supergravity

Conference Summary

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Supergravity

1. Construction
2. Properties
3. Applications

1. Construction

One of the two first papers on supergravity was written in Paris.

Wess, who was mistaken for Scherk in Moscow, explained how superspace can be used to organize supersymmetric theories and their Feynman rules.

He also discussed non-commutative deformation of superspace.

Van Nieuwenhuizen showed how to derive N=1 supergravity action using a 30-year-hindsight, such as:

Factorization of $\delta \mathcal{L}$

"SUGRA has become as simple as gravity, but one needs to know a few tricks."

He also discussed boundary conditions for supergravity and ended with a nice review of the history of spinors.

Grisaru used the Superspace Approach to derive Lagrangians for:

N=1 supergravity coupled to matter

N=2 sigma-model for a generalized Kahler manifold with the NS-NS 2-form flux

Fre described the Rheonomic Approach.

For the 11d supergravity, FDA associated to the super-Poincare algebra automatically tells you that there are the 3 and 6 form potentials. The supergravity field equations follow from consistency conditions.

He discussed how to use the rhenomic approach to supergravity theories in various dimensions and ended with its application to flux compactifications.

Extended Supergravities

N=2 Supergravities:

de Wit described the construction of the Lagrangian in 4d using the superconformal multiplet calculus.

Life on the cone is simpler.

The off-shell formulation makes it possible to organize higher derivative terms, which are used to study quantum corrections to entropies of BPS black holes.

Gunaydin explained how the Jordan algebra controls the structure of N=2 Maxwell-Einstein theories in 5d when the scalar manifold is a symmetric space.

He discussed some examples that can be realized by string/M theory compactifications.

2. Properties

Double your particles, double your fun.

Dualities

Pope showed how to organize the scalar fields that appear in the reduction of 11d supergravity on n-dim torus into the coset G/H, where G= En. The G-action extends to the full sugergravity mutiplets.

He also discussed dualities relating different form fields.

Nicolai discussed symmetries G of maximally supersymmetric sugra's in various dimesions, not necessarily coming from reduction of higher dimensional theories.

There is a general pattern that bosons are in single valued rep's and fermions are in double valued rep's of the R-symmetry K(G).

Does this extend to G = E9 and E10?

Search for the fundamental symmetry

West pointed out that, just as scalar fields in the 11d sugra on n-dim torus transform non-linearly under En, the metric and the 3 form in the 11d sugra make non-linear realization of the algebra G11.

The smallest Kac-Moody algbra containing G11 is E11, suggesting that E11 plays a fundamental role in the 11d supergravity.

Julia showed that the U-duality groups can be enlarged into Borcherds algebras.

He noted a remakable correspondence between symmetry in string/M theory and geometric data about del Pezzo surfaces

Hull discussed which subgroups of supergravity dualities are quantum symmetries of string/M theory.

Quantization of BPS charges and compatibility with T-duality give strong constrains on possible quantum symmetries.

He asked whether there is a background independent way to understand duality symmetries.

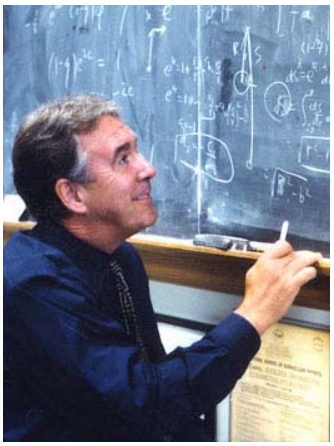
BPS Configurations

Gibbons described the history that has lead to the discovery of BPS black holes in supergravity and string theory, starting with Scherk's observation on anti-gravity.

Ferrara discussed the black hole attractor equation, which requires that the area of the horizon is minimized for a given set of chages and which determines values of relevant scalar fields at the black hole horizon.
For BPS black holes in N=2 theory, the conditions are:

$$\mathcal{D}_i Z = 0 \quad , \quad Z : \text{central charge}$$

The attractor conditions for non-BPS solutions were also discussed.



Duff pointed out that the entropy of BPS black hole in the N=2 STU model can be expressed in terms of Cayley's hyper-determinant, which is related to 3-tangle measuring quantum entanglement of 3 qubits.

Similarly, the entropy in the N=8 supergravity can be expressed in terms of Cartan's quartic E7 invariant, which has an interpretation as a tripartite entanglement of 7 qubits.

Stelle studied supergravity solutions that correspond to branes saturating the BPS bound.

-- M2 and M5 branes in the 11d supergravity
-- pp waves and NUTS solutions
-- intersecting branes,
-- Horava-Witten and Randall-Sundrum

Papadopoulos classified configurations with 32 susy's in type II and M theories. Locally they are flat, AdSxS, or plane waves.

He also classified maximally supersymmetric configurations in IIB theory for each stability subgroup of Killing spinors.

There are no configurations with 31 susy's in IIA or IIB.

Quantization

Townsend reviewed various proofs of non-renormalization theorems in the WZ model and SYM.

WZ model: described the proof by superfield

Is the holomorphy argument complete?

SYM: No go theorem for N=4 perturbation.
But the N=2 perturbation is suffice.

The anomaly puzzle and its resolution.
Finiteness is decided at one loop.

Bilal used the holomorphy argument to discuss non-perturbative non-renormalization theorems for F-terms in SYM coupled to matters.

He also derived various exact results on N=2 theories.

Townsend also discussed non-renormalization theorems for non-renormalizable theories.

Is the 4d N=8 supergravity finite?

asked by **Green** and **Nicolai**.

Facts:

N=4 perturbation theory: 3 loop counterterm
N=8 perturbation theory: 7 loop counterterm

Bern, et al used the Kawai-Lewellen-Tye relation to show that first potential divergence will be at least at 5 loop.

String worldsheet:

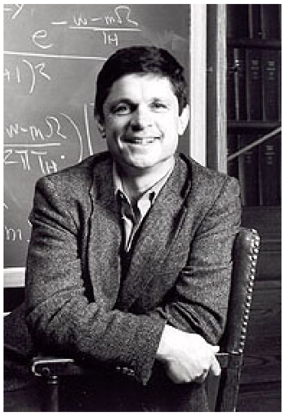
In the NSR formalism, it is described by the 2d supergravity coupled to matter.

It is the birthplace of supersymmetry (in the western world).

Topological string theory:

Topologically twisted 2d supergravity coupled to the sigma-model for CY3.

$\Rightarrow$ Gromov-Witten invariants



Strominger presented a proof of the OSV conjecture, which relates the topological string partition function to counting of microstates of BPS black holes in 4 dim.

How about higher dimensions?

In general, one needs to embed supergravity in string theory.

But, certain computations are independent of UV completion.

For example, geometric quantization of 1/2 BPS configuraitons found by Lin, Lunin, Maldacena reproduces the counting of BPS states in the corresponding gauge theory.

In this case, quantization of supergravity phase space gives the correct answer.

I think that Mathur's conjecture should also be understood in a similarl fashion.

Green discussed higher derivative terms in the M theory and IIB effective actions:

$$D^{2h} R^4 , \quad h = 0, 1, 2, \cdots$$

Supersymmetry implies that their coefficients are solutions to the Poisson equations in the moduli space and are uniquely determined by demanding duality invariance.

It the type II limit, this reproduces tree and one-loop 4 gravition ampiltudes correctly.

It also implies a series of non-renormalization theorems, some of which have been verified by string perturbation theory.

3. Applications

Elegant theories often
find unintended uses.

Supergravities as collective coordinates of large N theories

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 mode

He discussed sigma-models for non-critical string worldsheet, with non-trivial fixed points.

Freedman reviewed AdS/CFT correspondence.

Correlation functions in type IIB supergravity in AdS5 x S5 are computed and compared to those in N=4 SYM. This has lead to the unexpected discovery of non-renormalization of 3-point functions.

He also discussed holographic RG flows.

Applications to quasi-equilibrium processes
in finite temperature gauge theories:

shear viscosity coefficients, etc.

$\Leftarrow$ related to the computation of $\langle T_{\mu\nu} T_{\rho\sigma} \rangle$
by the Kubo formula

graviton propagator
in the bulk.

Application to non-supersymmetric QCD:

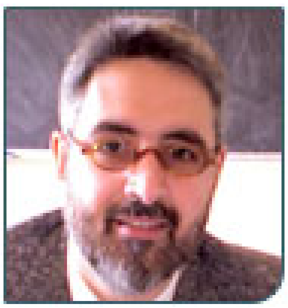
confinement, glueball mass spectrum,
chiral symmetry breaking,
meson mass spectrum, chiral lagrangian, ...

The unreasonable effectiveness
of the supergravity approximation
requires an explanation.

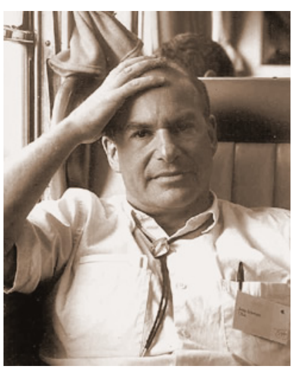
Challenge: estimate theoretical errors.

Supergravities as low energy limits of superstring theory

Olive described the collaborative scientific atomosphere of CERN in the early 70's, which had lead in 1976 to the discovery of the GSO projection and spacetime supersymmetry in string theory.



Angelantonj reviewed the GOS and orientifold projections for superstring in 10 and lower dimenwsions.



Schwarz discussed structures of 11d supergravity and 10d type IIA/IIB theories.

The duality between the M theory on 2d torus and the type IIB theory on a circle relates the SL(2,Z) S-duality of IIB to the modular invariance of the 2d torus in the M theory side.

Narain reviewed orbifold compactifications of the heterotic and type II string theories.

The moduli space of the type IIA string on K3 and the heterotic string on T4 coincide, suggesting the string-string duality. He discussed further evidences for this duality based on BPS state counting and gauge symmetry enhancements.

Kiritsis discussed BPS mass spectra in various string compactifications. The mass formulae can be used to test string-string duality conjectures.

He also discussed BPS mass formulae in the context of the Scherk-Schwarz compactification.

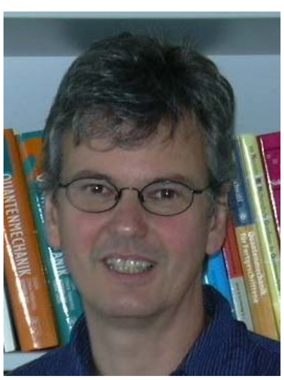
String Compactifications

Candelas discussed aspects of Calabi-Yau geometry for N=1 compactifications of the heterotic string theory.

Special geometry of the moduli space:

$$R_{i\bar{j}k\bar{l}} = g_{i\bar{j}}\, g_{k\bar{l}} + g_{i\bar{l}}\, g_{k\bar{j}} + C_{ikm}\, \bar{C}_{\bar{j}\bar{l}\bar{n}}\, e^{2K} g^{m\bar{n}}$$

Mirror symmetry: relates stringy effects to classical geometry.



Louis described type II string compactified on a manifold with SU(3)xSU(3) structure, which is a generalization of CY3 with fluxes. He studied the 4d action, and discussed mirror symmetry and string-string duality in the presence of fluxes.

Derendinger discussed N=4 supergravity and its gauging as an effective description of string compactifications with fluxes.

The dictionary between fluxes and structure constants in the low energy effective theory is clarified.

Van Proeyen pointed out that, to use supergravity for string cosmology, it is important to understand consistency between the FI and superpotential terms.

He showed how this can be resolved for type IIB string on CY orientifold with D3, D7 and fluxes.

Which supergravity theories are realized as low energy limits of superstring theory?

--- Swampland Question

From general principles:

Anomaly cancellations,

discussed by **Alvarez-Gaumé**

Absence of continuous global symmetry

From specific string theory constructions:

Limit on the size of gauge groups

More recently other criteria have been proposed:

Limit on the strength of U(1) gauge coupling

$$\underbrace{m}_{\text{new scale}} < \underbrace{e}_{U(1)\text{ coupling}}\, m_{Planck}$$

(Arkani-Hamed, Motl, Nicolis, Vafa)

Scalar moduli space has infinite diameter.

New light particles appear in the infinite directions.

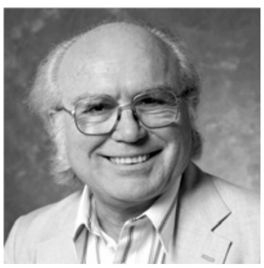
The fundamental group is trivial.

(Vafa + H.O.)

Models for High Energy Physics Phenomenology

Fayet described the construction of the supersymmetric standard model from the historical perspective.
He explained why we need:

-- new particles as superpartners
-- R-parity
-- a second Higgs doublet



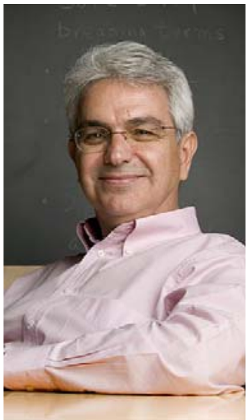
Zumino reviewed the current status of MSSM.

Success: Unification, Dark matter candidate

Issues: Little hierarchy problem
Hidden sector (*somewhat artificial*)

At LHC, it may be difficult to distinguish SUSY from alternative solutions to the hierarchy problem such as large extra dimensions.

He also let us know clearly what he thinks about the Anthropic Principle.



Dimopoulos described the evolution of SUSY phenomenology since the 70's. He explained the motivation for soft terms as parametrization of SUSY breaking.

Split Supersymmetry:

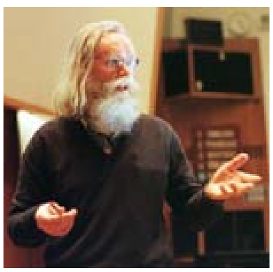
One can preserve the sucesses of SUSY and remove its shortcumings by keeping masses of fermion superpartners to be of the order of 1 TeV while lifting scalar masses to be much higher.

This does not solve the hierarchy problem. One has to learn to live with fine tunings of the Higgs mass as well as the cosmological constant. These may be explained by the entropic principle.

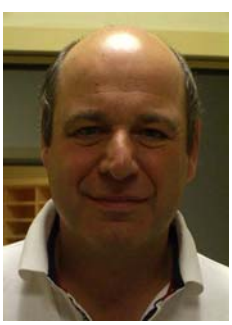
Once supersymmetry is discovered in Nature, supergravity is inevitable.

In some scenarios, supergravity has more direct roles in high energy physics phenomenology.

Nilles discussed benefits of the gravity mediated SUSY breaking. He pointed out that this mechanism can be naturally realized in the perturbative heterotic string theory and the heterotic M theory.



Ellis and **Zwirner** argued that no-scale supergravities are desirable since they can break SUSY while keeping the cosmological constant to be zero. They may also contain a good candidate for the inflaton.



Zwirner also discussed how no-scale models can be realized in string theory.

Journée Joël Scherk

18 October 2006

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Brink, **Neveu**, **Van Nieuwenhuizen**, **Zuber** shared personal stories, which were moving.

His important contributions to physics have been discussed throughout the meeting.

dual models, supergravities, ...

So many of what we take granted have been due to him!

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In rare occasions when speakers touched on subjects I am familiar with, I was reminded of Coleman's observation that you can never underestimate the pleasure one can derive by listening to things you already know when they are presented well.

Thank you,

Costas, Eugène, Laurent

and

the distinguished speakers of the conference,

for the opportunity to listen to the progress of supergravity in the last 30 years.

On to the next 30 years!