# String Theory as a Theory of Quantum Gravity

## A Status Report

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# Quantum Gravity: the Big Divide

Is Quantum Gravity the Quantisation of Einstein Gravity?

- Hypothesis L: General Relativity captures correctly the microscopic (fundamental) degrees of freedom of the gravitational field
- Hypothesis S: General Relativity is only an effective (low energy, "emergent") phenomenon arising at large distances from a more fundamental theory with different degrees of freedom

There really appears to be no a priori way to know this with certainty. However, differences in consequences of believing either hypothesis L or hypothesis S, by personal prejudices, peer pressure, or divine inspiration, are dramatic and appear to have firmly divided the quantum gravity community into two camps!

# Introductory Comments

- Being quite resistent to peer pressure and lacking divine inspiration, I remain agnostic and try to keep an open mind regarding this issue.
- However, currently I find the case for hypothesis S, in particular for

  string theory as a general framework for a theory of quantum gravity

  very compelling, and talk will be about this aspect of string theory.
- Regrettably, some (in my opinion largely unscientific) anti-string feeling/attitude seems to be common in large parts of the quantum gravity community. However, as researchers interested in quantum gravity,

  we should look at the evidence and judge string theory solely by its ability to provide us with answers to questions that we feel any theory of quantum gravity worth its salt should provide us with,

  and not by, say, its failure to (so far?) provide specific predictions for BSM physics, or disgust with some of the hype and overblown claims regarding string theory (I may share your feelings . . . )

# Overview

In this talk I will try to lay before you a critical evaluation of the currently available evidence, in roughly historical order:

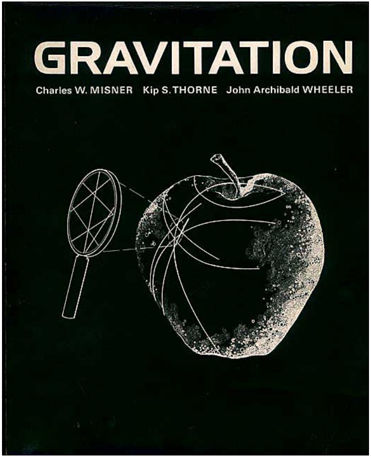
- The Past: String Theory and Perturbative Quantum Gravity
- The Present: Non-Perturbative String Theory and Gravity
  - Matrix (String) Theory
  - D-Branes and Black Hole Microstates
  - AdS / CFT Correspondence

  (each of these would merit a separate talk at this conference)
- The Future: Conceptual Challenges and Technical Problems

Caveats/Disclaimer:

- Will necessarily be a bit of a tour de force / lightning overview
- But this will not be a propaganda talk: I will try to give a balanced account both of the achievements and of the shortcomings and open problems. (a personal assessment perhaps not shared universally by other reserarchers in the field).

[Based to a large extent on an article with Stefan Theisen that appeared in the GRG Memorical Volume dedicated to John Archibald Wheeler († April 13 2008) the person who single-handedly kept Quantum Gravity research alive in the mid-20th century.]



# String Theory and Perturbative Quantum Gravity: Basics

String Theory provides a unifying framework for all elementary particles and their interactions (this much is undeniable, whether one likes it or not)

- gauge forces arise from massless excitations of open or closed strings
- inevitably and automatically includes gravity (through massless second-rank tensor excitations of the closed string)

However, identification of this excitation with the graviton is somewhat indirect (wordsheet correlators $\Rightarrow$ S-matrix of an effective space-time supergravity theory, or worldsheet $\beta$-function $\Rightarrow$ Einstein equations)

- This is inevitable and should not be held against string theory. After all, gravity is emergent in string theory, like the other forces, so this is a feature not a bug!

[Note: I may repeatedly use loaded terms like emergence or background (in-)dependence in the following without trying to define them precisely. This I consider to be counterproductive at this point.]

# String Theory and Perturbative Quantum Gravity: Achievements

- String theory provides a (presumably order by order finite) consistent perturbative quantisation of quantum gravity, avoiding the perturbative non-renormalisability of the field theory approach, and with correct low-energy limit
- Theories with such properties do not grow on trees (indeed, as far as I am aware, string theory is the only known approach to accomplish this!)
- $\Rightarrow$ accept additional structures introduced by string theory ("extra dimensions", infinite towers of massive fields, supersymmetry) even though not clear if or why required for quantum gravity.

# String Theory and Perturbative Quantum Gravity: Comments

- Infinite Tower of Massive Fields: It is precisely the infinite tower of massive fields (or the extended nature of the string) that is responsible for the good UV behaviour of the theory
- Extra Dimensions: This is actually quite misleading, as this is just a simple geometric way of describing certain CFTs with a given central charge; in general no geometric interpretation and no extra dimensions, just some "worldsheet stuff" required by consistency. Real question to ask seems to be

  Why are there any large dimensions at all?
- Supersymmetry: Required for stability of string theory / allows controlled calculations - significance for quantum gravity in general beyond that? (but strongly coupled gauge theories without supersymmetry have regretful tendency to exhibit instabilities; and who knows what happens when one includes full set of standard model fields in other approaches to quantum gravity)

# String Theory and Perturbative Quantum Gravity: Shortcomings

This old (1980s) worldsheet picture of string theory is not completely satisfactory because it is

- inherently perturbative
  (in an expansion in Newton's or the string coupling constant)
- limited to a set of rules for computing on-shell scattering amplitudes in an on-shell background

If one wants to study situations where one expects quantum gravitational effects to become relevant (black holes, big bang), or if one wants to address conceptual issues of quantum gravity, this is a double handicap.
However, I will not dwell on this, because the situation has changed.
In the last 15 years important progress has been made in understanding some non-perturbative aspects of string theory! Nowadays there are much more compelling ways of seeing / understanding the emergence of gravity from string theory.

# Non-Perturbative String Theory: D-Branes, Dualities and AdS/CFT (1995 –)

- D-Branes: Non-perturbative sectors of closed string theory (gravity) described in terms of perturbative open string theory (gauge theory)!
- Weak-Strong Coupling Dualities:
  IIB S-duality ($g \to 1/g$), IIA $\leftrightarrow$ Heterotic, etc.
- M-Theory and Unification of Perturbative String Theories:
  Different known consistent string theories recognised as different perturbative expansions of one underlying theory
- Gauge Theory – Gravity Duality, in particular AdS/CFT:
  arising from the fact that D-branes can be equivalently described as gravitational objects in the (bulk) closed string theory, or in terms of their lower-dimensional worldvolume gauge theory (holography!)

# Non-Perturbative String Theory: D-Branes, Dualities and AdS/CFT (1995 –)

I will briefly discuss 3 developments pertinent for quantum gravity:

- Matrix Theory
- D-Branes and Black Hole Microstates
- AdS / CFT Correspondence

Common to or underlying all of them is an intriguing general

Gauge Theory / Geometry or Gravity Correspondence

exhibited by string theory, which encodes information about geometry in gauge theory terms and vice-versa. Has its origins in an

open string (gauge fields) / closed string (gravity) duality

of string theory, and hints at completely novel ways of addressing quantum gravity issues.

# Matrix Theory: Basics

- Matrix Theory = non-perturbative formulation of M-theory in 11d Minkowski space-time (can be derived via discretisation of 11d super-membrane action [de Wit, Hoppe, Nicolai (1988)] or via DLCQ of underlying theory [BFSS (1996)])
- From DLCQ perspective: worldline theory of $N$ D0-branes = dimensional reduction of $d = 9+1$ SYM to $d = 0+1$,

$$L \sim \mathrm{Tr}\, R^{-1}(\dot{X}^a)^2 + R[X^a, X^b]^2 + \text{superpartners}$$

($X^a \in \mathfrak{u}(N)$, $a = 1, \dots, 9$; $R, N \to \infty$ with $p_- = N/R$ fixed)

- There is no space, only time. $X^a$ play the role of non-Abelian (non-commutative) space-coordinates.
- Compactification on $T^p \Rightarrow (p+1)$-dimensional gauge theory.

# Non-Perturbative String Theory and Quantum Gravity
# Matrix Theory: Selected Achievements

- Space is Emergent! When $X^a$ diagonal $\Rightarrow$ interpretation as ordinary space-time coordinates of $N$ D0-branes. For these "flat directions" of the potential to be preserved by quantum corrections, supersymmetry is essential!
- Gravity is Emergent / Induced! Perturbative calculation $X^a =$ (diagonal) $+$ small perturbation, integrate out perturbation $\Rightarrow$ one generates leading term in classical gravitational interaction between two gravitons in $d = 10 + 1$ lightfront supergravity:
  Classical Gravity = Quantum (1-loop) Effect in Gauge Theory
  (again supersymmetry is essential, and $d = 10 + 1$ is essential)
- Matrix String Theory: $d = 1 + 1$ SYM, non-perturbative description of IIA string theory via DLCQ: String Theory is Emergent!
- Hints of Quantum Geometry: Non-geometric non-Abelian degrees of freedom dominate strong string (weak gauge) coupling dynamics!

# Non-Perturbative String Theory and Quantum Gravity
## Matrix Theory: Shortcomings

- At present, Matrix Theory is far too background dependent (whatever definition of background independence one prefers)
- Construction of Matrix (String) Theory for non-trivial backgrounds extremely complicated and not well understood (with the exception of certain plane-wave backgrounds - see talk by Ben Craps next week).
- Large $N$-limit extremely complicated and not well understood.
- Compactification on $T^p$ for $p > 5$ (in particular to 4 dimensions): resulting theory not well defined, not decoupled from quantum gravity $\Rightarrow$ does not give a definition of the theory.

For very recent proposal for how to deal with (some of) these issues, see

T. Banks, Fuzzy Geometry via the Spinor Bundle, with Applications to Holographic Space-time and Matrix Theory, `arXiv:1106.1179`

(and then please explain it to me . . . )

# Non-Perturbative String Theory and Quantum Gravity
## D-Branes and Black Hole Microstates: Achievements

Black Hole Microstates: Successful microscopic explanation of the Bekenstein-Hawking black hole entropy for a wide variety of extremal and near-extremal black holes in various dimensions in terms of completely explicit counting of black hole (D-brane) microstates,

- including precise numerical factors
- with correct higher derivative corrections (Wald entropy)
- as well as Hawking radiation with precise greybody factors from D-brane gauge theory calculations

(hard to believe that all this is a big fluke/conspiracy/coincidence)

Fuzzballs: Identification of large classes of horizonless geometries that may give rise to the black hole solutions after coarse-graining:

- may be capable of explaining thermodynamic properties of black holes
- offers a possible resolution of the information paradox
- supported by considerations from AdS / CFT

# D-Branes and Black Hole Microstates: Open Issues

- Successes are for the moment limited to (near) extremal black holes: (but Kerr/CFT?) - Schwarzschild is the hardest case (no useful expansion parameter, unstable quantum system)
- No fundamental or a priori explanation why $S_{BH} \sim A$: Given charges (quantum numbers) $Q_a$ of the black hole, calculate separately $S_{BH} = S_{BH}(Q_a)$ and $A = A(Q_a)$ and then find that each and every time $S_{BH} \sim A$. This is ridiculous, and both a blessing and a problem:
  - Blessing because shows that one is not inputting $S \sim A$ into the calculations (unlike in certain other approaches where horison is a priori treated as a boundary on which conditions need to be imposed)
  - Problem because it clearly means that we are missing something!
- de Sitter entropy: de Sitter has oberver-dependent event horizon - de Sitter entropy also equal to $A/4 \Rightarrow$ there should be common explanation. But what microstates? Living where? Very weird . . .

# AdS/CFT Correspondence: General Remarks

- Proposed equivalence (deduced from string theory) between string theory in certain backgrounds and a lower-dimensional conventional gauge theory or CFT.
- In particular, non-perturbative and holographic description of quantum gravity on asymptotically AdS space-times via gauge theory on conformal boundary (e.g. $\mathrm{AAdS}_5$ and $\mathcal{N} = 4$ $SU(N)$ $\mathrm{SYM}_4$)
- Role of extra dimension played by energy scale of the gauge theory.
- Precise mapping between bulk (AdS, gravitational) fields and boundary (CFT, gauge theory) operators.
- Mostly used to gain insight into strongly coupled gauge theories via classical gravity, but is currently also the most powerful and popular tool we have to study quantum gravity questions within the context of string theory.

# AdS/CFT Correspondence: Achievements

- Powerful and concrete, unexpected and still surprising realisation of the holographic principle which on various grounds had been suspected to play a role in quantum gravity ['t Hooft, Susskind]
- Is an example of emergent gravity, of emergent space-time and of emergent general covariance
- Is even an example of emergent string theory (completely explicit mapping between gauge theory operators and massive string states in Penrose/BMN-limit, again anticipated by ['t Hooft] long time ago)
- Provides natural explanation for thermal properties of black holes, since they give dual description of finite temperature field theories
- May provide the controlled and sufficiently mild form of non-locality that appears to be required to resolve issues arising in relation with information loss paradox and/or trans-Planckian scattering.
- ...

(wow! difficult not to be impressed by this)

# AdS/CFT Correspondence: Open Issues

- No question that there are deep relations between gauge theory and gravity, and boundary and bulk theories, but precise statement? Complete equivalence? possible that gauge theory is faithfully encoded in bulk but not vice-versa (some kind of coarse-graining)?
- How general is such a correspondence? appears not to be limited to situations where bulk theory is a string theory (but microscopic dual gauge theory so far only understood (derivable) via string / D-brane realisations).
- In principle dual CFT should contain all information about formation, collision and evaporation of black holes. In practice any process localised in the bulk will be encoded in complicated non-local way in the boundary theory - code not yet completely deciphered.
- Convincing resolution of information loss problem?
- Other boundary conditions (asymptocially flat, de Sitter)?

# Synopsis

Accounting for black hole entropy and understanding the presumably holographic nature of quantum gravity are cornerstones of research in quantum gravity

accomplishments within string theory are quite remarkable, far-reaching and encouraging and represent significant progress

Nevertheless, current status of string theory as a theory of quantum gravity is still somewhat unsatisfactory, and in addition to the rather immediate problems and open questions mentioned before there still remain a number of other and perhaps more basic open conceptual and technical issues.

# The Future: Technical Problems

(or will they turn out to be conceptual?)

Currently available technology seems to be not well suited to study non-supersymmetric (time-dependent, or de Sitter) backgrounds (in particular also spacelike cosmological singularities)

Time-dependence gives rise to some rather basic problems:

- absence of Lightcone Gauge and No-ghost theorems,
- limited validity of Euclidean formulation
- little is known / understood about CFTs with non-compact target spaces (Liouville theory notable exception)
- questionable usefulness of standard on-shell S-Matrix formulation of string theory in a cosmological setting
- perturbative and non-perturbative instabilities of non-susy backgrounds

Promising approaches rely on non-perturbative formulations of string theory: AdS/CFT, M(atrix) Theory (cf. talk by Ben Craps)

# The Future: Conceptual and Foundational Issues

Ideally, like in GR, we would like to enunciate some basic principles like the equivalence principle and general covariance from which the entire structure of string theory follows. At the moment we have no such thing:

- What are the fundamental symmetries of string theory?
  (All the infinite duality symmetries that have been uncovered so far may be only the tip of the iceberg)
- What is string or quantum geometry?
  (When most string backgrounds do not have a classical geometric interpretation at all)
- Is there a useful notion of background independence in string theory?
  (In particular for emergent space-times)

Obviously these are rather profound and complicated interrelated issues, and I will just add a few remarks to clarify why the situation in string theory is so different (and so much more challenging) than in other approaches or settings.

# The Future: Conceptual and Foundational Issues

## Quantum Geometry

- Already at perturbative level, string geometry and classical geometry are not the same thing (observed geometry depends on whether it is probed by particles, string, branes). Examples: orbifold singularities.
- Perturbatively and non-perturbatively, space-time geometry and diffeomorphism invariance are emergent semi-classical phenomena.
- Perturbative and non-perturbative dualities can also mix gravitational with other degrees of freedom.

Even when we can talk about a classical geometry, there is a high redundancy in description of observable quantities, but as long as the symmetries of string theory are not completely understood it is difficult to disentangle observables and gauge symmetries, describe uniquely physical states in string theory etc. (and describing quantum geometry for non-geometric backgrounds is left as an exercise . . . )

# The Future: Conceptual and Foundational Issues

## Background Independence

- In principle, string theory is background-independent (different backgrounds are different solutions of the same theory) But in practice background independence is not manifest, as one needs a background before one can expand around it to move to another solution. This background-dependent realisation of background-independence is clumsy and unsatisfactory.
- More fundamentally, traditional notions of background-independence appear to be inappropriate (and/or show a distinct lack of imagination): in string theory a space-time will never ever emerge as a naked topological space (without some extra structure) but always in conjunction with a whole host of other geometrical and non-geometrical fields. Thus the usual notions with respect to which GR is background-independent do simply not apply.
  This does not make the theory background-dependent!

# Conclusions

- String theory is a successful and promising framework for a consistent theory of quantum gravity, and I see no reason to reject/dismiss it on scientific grounds (but can't argue with or against divine inspiration).
- However, it seems to me that in many respects we still appear to be at a rather preliminary stage of our understanding of this theory.
- In particular a non-perturbative formulation of the theory and uncovering its symmetries are important open issues.

Far-reaching statements on either side of the string theory debate, proclaiming

- either the imminent demise of string theory
- or the ultimate unavoidability (and virtue) of some potentially pseudo-scientific anthropic/multiverse scenario,

appear to be pre- (and quite im-) mature,

- and should not distract one from trying to better understand profound quantum gravitational issues to which string theory may hold the clue.

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[...] the challenges of quantum gravity are profound. While string theory has certainly provided new ideas about how to address some of these problems, it seems clear that it still has a fair ways to go if it is to resolve them all.

(Steven Giddings, Is string theory a theory of quantum gravity? `arXiv:1105.6359`)

We have our work cut out for us

(Andy Strominger, Five Problems in Quantum Gravity, `arXiv:0906.1313`)

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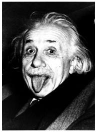

Thank You for Your Attention!

Extra Slides

# Visiting Camp L

If you believe L, then

- your belief is shared by most quantum gravity researchers with a classical GR background
- you will attempt to find a theory of quantum gravity via a non-perturbative quantisation of GR
- your reaction to the failure of perturbative quantisation of GR will be I told you so! It makes no sense split a metric into a "background" and a "fluctuation". There is no background!
- You will quote Penrose:
  *If we remove life from Einstein's beautiful theory by steam-rollering it first to flatness and linearity, then we shall learn nothing from attempting to wave the magic wand of quantum theory over the resulting corpse!*
- You will most likely end up working in Loop Quantum Gravity ($=$ non-perturbative canonical quantisation of GR)

# Visiting Camp S

If you believe S, then

- your belief is shared by most quantum gravity researchers with a QFT background
- you are convinced that it is meaningless to quantise Einstein gravity directly (analogy: thermodynamics, collective phenomena in condensed matter or solid state physics)
- your reaction to the failure of perturbative quantisation of GR will be I told you so! GR is only an effective theory, valid only below a certain energy scale, and should not be quantised as such!
- You will not quote anybody but start learning about CFT, SUSY, Algebraic Geometry, etc etc instead
- You will most likely end up working in String Theory

# String Theory and Perturbative Quantum Gravity: Basics

Method I:

- associate to each string mode a worldsheet (vertex) operator and calculate their 2d string worldsheet correlation functions
- interpret the results as on-shell S-matrix elements of an effective field theory (when expanded around Minkowski space)
- This effective field theory turns out to be the

  Effective Action = Einstein-Hilbert + Matter (Super-)Gravity Action

  (plus computable higher order stringy ($\alpha' = \ell_s^2$) and quantum ($g_s^2 \sim G_N$) corrections).
- Typical feature of string theory: Coupling constant $g_s$ arises as the expectation value of a massless scalar field, the dilaton.
- Calculations done in free worldsheet CFT $\sim$ string propagating in Minkowski space. Quantum consistency then requires $d = 10$.

# String Theory and Perturbative Quantum Gravity: Basics

Method II:

- couple worldsheet theory to space-time metric,

$$S \sim \int d\tau\, d\sigma [\eta^{ab} \partial_a X^\alpha(\tau,\sigma) \partial_b X^\beta(\tau,\sigma) g_{\alpha\beta}(X(\tau,\sigma)) + \ldots$$

  (thus metric plays role of infinite number of coupling constants), and possibly also to fields corresponding to other massless modes of the closed string (dilaton, Kalb-Ramond 2-form)

- require conformal invariance: equation for $g_{\alpha\beta}$ from vanishing of its $\beta$-function = equation derived from effective action:

$$\beta\text{-function equation} = \text{Einstein - Matter equation}$$

  (plus computable & identical higher order corrections)