1999 Summer Student Lecture Programme

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Dreams of a Finite Theory

Lecture Notes

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(or why would have been good for the US to build the SSC)

DREAMS

OF A FINAL THEORY

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Author of The First Three Minutes

PANTHEON BOOKS, NEW YORK (1992)
Dreams of a Finite Theory

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Outline

- Who cares about gravity?
- The problem of infinities
- Classical points/strings
- Quantum string magic
- Large extra dimensions?
- An entirely new cosmology?
- Conclusions

Who cares about gravity?

- The Standard Model (SM) of non-gravitational phenomena works very well.
- Not just as a Classical Field Theory.
- Experiments at CERN, DESY, FermiLab, etc. have fully confirmed the validity/necessity of a Quantum-FT description, which includes radiative corrections
- What about Gravity, the 1st force known to humankind?
- Superficially, gravity and electromagnetism, being the two long-range forces, look very similar... however...
There are essential differences

1. In natural units (c=\(h=G_N=1\)):

\[ F_N = -\frac{m_1 m_2}{r^2}, \quad F_C = \frac{q_1 q_2}{r^2} \]

For the e-p system:

\[ \frac{F_N}{F_C} = \frac{m_1 m_2}{q_1 q_2} \sim 10^{-40} \]

⇒ This is why gravity is always neglected in the study of the hydrogen atom or of other microscopic systems.

So, why care about gravity?

2. Gravity always adds up

⇒ becomes strong for large bodies while EM forces cancel out for neutral systems (for earth-moon system EM forces are negligible)

⇒ relevance in Astrophysics

3. Gravity actually depends on (relativistic) energy, not just on rest mass (Cf. deflection of light by the sun, microlensing etc.)

⇒ \( F_N, F_C \) become comparable at energies around \( 10^{17}-10^{18} \) GeV

i.e. not far from the presumed scale of Grand Unification...

⇒ relevance in (early) Cosmology

What then if we do care about gravity?
At first sight, no problem. We do have a very elegant and successful theory of gravitational phenomena. It dates from 1916, and is Einstein’s General Relativity (GR).

Like the standard model of non-gravitational phenomena, GR has now been tested to high accuracy, last but not least through (indirect) evidence for the emission of gravitational waves by binary pulsar PS1913+16 in full accordance with GR’s expectations.

Many competitive theories of gravity have been ruled out, as it is the case for most alternatives to the SM.

Furthermore, both the SM and GR are deeply rooted in similar physical principles:
1. Gauge-Invariance for the SM
2. Equivalence Principle for GR

The mathematical analogy is actually so strong that Kaluza (1921) and Klein (1926) (KK) succeeded in reformulating electromagnetism + gravity as just GR in a space containing one extra spatial dimension.

In KK theory the extra dimension of space is a circle of radius $R$. 
Basic KK Theory: \[ D=4 \Rightarrow D=5 \]

\[ Q = \frac{p_5/c}{\Lambda_{\text{Pl}}} = n \frac{\ell_p}{R}, \quad n=0, \pm 1, \pm 2 \ldots \]

\[ F_c \sim F_N \quad \text{at} \quad E = \frac{hc}{R} = M_c c^2 \]

\[ M_c = \text{mass of typical KK excitations} \]
The beautiful outcome of the KK approach is that charge is naturally quantized (as observed). The basic unit of electric charge gets identified with the ratio $l_p/R$, where $l_p \sim 10^{-33}$ cm. is the fundamental (Planck) length that can be constructed out of $c$, $h$ and $G_N$. But what fixes $R$ itself?

Charge is quantized because it gets reinterpreted as the 5th component of momentum, and because momentum on a circle of radius $R$, is quantized in units of $h/R$. This is also the scale of KK energy levels.

Hence, quantum mechanics is very central to the KK idea.

The problem of infinities

Unfortunately, the same quantum mechanics which is at the basis of the KK idea kills it. Why?

Ultraviolet divergences in QFT: Virtual processes in which very energetic quanta are emitted and reabsorbed are not sufficiently suppressed in QFT and give infinitely large contributions to physical observables such as masses, couplings.

The recommended therapy for such a disease is called renormalization, but it saves the patient only if he/she is not too sick.....
A PARADOXICAL SITUATION

1. Classically, gauge and gravitational interactions look very similar

2. Semi-classically, they can be unified a la KK ($D = 3+1 \rightarrow 4+1$)
   but

While gauge theories can be promoted to the level of a full quantum theory, the SM, GR cannot.

3. If we insist on the KK idea of a 5th dimension, then even gauge theories cannot be quantized, since $q \sim p_5$ can take arbitrarily large values.

⇒ Unification of gravitational and non-gravitational interactions at the full quantum level appears to require a

FINITE THEORY

- gauge theories like those of the SM are OK, i.e. all infinities can be lumped into a finite number of observables.

⇒ One obtains a renormalized QFT containing a finite number of uncalculable parameters which have to be taken from experiments. The rest is predictable (⇒ precision tests of the SM).

- Since gravity couples to energy, UV-divergences are more severe in GR than they are in the SM.

⇒ For GR, UV infinities cannot be lumped into a finite set of observables and predictivity is lost.
IS IT SUPERSTRINGS?

- For about 30 years particle theorists have played with strings.
- Since 1984 they have been taking (super)strings as a serious candidate theory of all interactions.
- What's the basis of this faith?

CLASSICAL POINTS/STRINGS

- In many respects, the concept of string-like particles appears to be a harmless/boring extension of the concept of point-like particles.
- Theorists like to describe dynamical systems by assigning to them an action $S$.
- Let's compare $S$ for points and for strings:
\[ S_{\text{Points}} = \sum_i m_i c \ell_i + \text{interactions} \]

- 0-dimensional
- Free action geometric, unique \( \Rightarrow \) free
  particles move along geodesics
- Interaction part non-geometric, non-unique

\[ S_{\text{String}} = T \cdot A \cdot \text{(where are the interactions?)} \]

- 1-dimensional
- Classical string motion minimizes area swept (geodesic surface)
Describing Interactions in String Theory

Example → time

= 3-loop diagram of QFT!
Quantum String Magic

- Two major miracles:

1. Upon quantization strings acquire a finite, minimal size (Cf. har. osc.)
   \[ \Delta X \cdot (h/T)^{1/2} = \lambda_s \]

2. The classical inequality between J and M gets corrected (Cf. har. osc.)
   \[ J \dot{\mathcal{S}} M^2/2\pi T + a_0 h \]
   \[ a_0 = 1/2, 1, 3/2, 2. \]

→ These two properties of quantum strings make them candidates for a finite theory of all known interactions. The 1st provides an UV cutoff, the 2nd gives carriers of all fundamental forces, incl. gravity.

- Depending on the way it vibrates a string can have non-zero mass M and angular momentum J, which, classically, take continuous values.

- Since there cannot be J without a finite size, and finite size implies finite M, an inequality holds:
  \[ J \dot{\mathcal{S}} M^2/2\pi T \]

→ Massless spinning strings are classically forbidden.
Allowed and forbidden $J, M^2$ values

CLASSICAL

$J$ vs $M^2/(2\pi T)$

QUANTUM (no loops)

$J/k$ vs $M^2/(2\pi T)$

- allowed boson
- allowed fermion
Two minor miracles:

1. Strings like $D>4$. Extra dimensions allow for a KK-type unification in which $R$ is $O(\lambda_s)$.
   ⇒ From observed value of electric charge we deduce:
   \[
   \lambda_s \sim 10 \ l_p \sim 10^{-32} \text{ cm}
   \]
   At this scale ($10^{17}$-$10^{18} \text{ GeV}$) gravity and gauge interactions are of comparable strength.

2. The arbitrary parameters of QFT are replaced by VEV's of fields, e.g.
   \[
   \alpha \sim G_N \ T \sim \exp(<\phi>)
   \]
   where $\phi$ is a scalar field, the dilaton. Today the dilaton must be frozen at the bottom of its potential.

Large extra dimensions?

- Although strings love extra dim's only gravity needs to propagate in all of them, gauge interactions could be confined to a lower-dimensional subspace (a "brane") e.g. to $D=4$.

- This opens up the amusing possibility that extra dimensions be large.. within known exp. limits, of course.

- E.g. If gravity lives in two extra dimensions of millimetric size, it becomes strong at $1 \text{ TeV}$. ...

- In this case the UV cutoff of string theory has to be lowered to $1 \text{ TeV}$ and plenty of new phenomena (e.g. black hole formation, KK grav. emission..) expected at LHC energies.....
An entirely new cosmology?

- Did the Universe always live in the (constant-dilaton) phase where it is now? If not, a new cosmology is possible.

- Recall one of Einstein’s cosmological equations (for spatially-flat U):
  \[ 3H^2 = 8\pi G_N \rho \]
  As the Universe expands, \( \rho \) decreases (for conventional matter) and same is true for \( H \) ...

- SCM' problems (see A. Cohen)

- In string cosmology \( G_N \sim \exp < \phi > \) can grow in the very early \( U \) making \( H \) grow....

- New kind of inflation is possible

THE PRE-BIG BANG SCENARIO

1. The universe started off in a very cold, empty and weakly coupled state ("asymptotic triviality").

2. It inflated (with a growing \( H \)) as it became more and more strongly coupled (dilaton-driven inflation)

3. Inflation lasted until a moment of maximal \( H, T, \rho \), was reached: this moment is to be identified with the usual Big Bang. The BB singularity was avoided thanks to the minimal length of string theory, i.e. by QM.

4. Ordinary, non-inflationary cosmology followed while \( \phi \) relaxed to its present value.
SOME CONSEQUENCES

1 A stochastic background of gravitational waves, much in excess of the one predicted by ordinary inflation, and possibly detectable within the next decade.

2 A unique mechanism to generate seeds for the observed (\(\mu\)-Gauss) cosmic magnetic fields on galactic scales.

3 An interesting spectrum of axions, strongly dependent on the evolution of the extra dimensions during inflation- which may have seeded CMB anisotropies

=> Future data on those (MAP, PLANCK) may thus provide window on the pre-bangian Universe......

CONCLUSIONS

- Superstring theories do have an enormous theoretical appeal.
- Only available framework to bring about a truly unified quantum description of all physical processes
- The challenge: convert a beautiful theoretical/mathematical framework into something predictive ... and testable.
- At least bring our understanding of gravity to the same level at which we understand non-gravitational physics
Many unresolved puzzles in gravitation and cosmology (big bang, black holes, \( \Lambda_{\text{cosm}} \)) probably do need a consistent way to combine GR and QM (E. Witten, The New Republic, Dec. 1997)

Insisting on theoretical consistency has paid off enormously towards understanding EW and Strong interactions..but it took some 50 years of hard experimental & theoretical work to produce the SM.

Insisting on the finiteness of Quantum Gravity will probably pay as much, if we are able to spot the right theoretical and experimental ideas

A dream that may remain just that for a while...
"...Proving that SUSY is correct would also give a huge boost to an even more ambitious theory, known as string theory, which aims at unify QM and GR,...This may sound like something about which only specialists could care, but it actually is the key to answering some of the questions that people who are not scientists most often ask."
The process of what the universe is today, as we know it, is an explosion, often called the Big Bang. But contemplation of the Big Bang raises some obvious questions like: What happened before the Big Bang? What was the beginning of time? Because QM and gravity were both important near the Big Bang, the answer to questions such as these depend on combining QM and GR to an understanding of the quantum nature of space and time.”
Further Readings suggested

- On the quest of a T. O. E.
  Brian Greene: The elegant Universe
  (Norton & Co / N.Y. - London '99)

- On classical & quantum strings
  G. V: “Quantum Strings & the constants of Nature” in “The challenging questions”
  Erice '83 (Plenum Press, N.Y. 1990)

- On string cosmology

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