String Theory Appetizer

Motivation :

The standard Model provides a remarkably precise description of particle physics at energies up to several TeV (currently 8 TeV) however it is far from satisfactory on many counts

- involves hugely different scales and coupling constants

  $m_\nu \ll m_{e^-} \ll m_t$, $\theta_{QCD} \ll 10^{-10}$, Yukawas, ...

  10^{-12} GeV 10^{-4} GeV [0.5 MeV] 10^{2} GeV [173 GeV whereas $m_{u,d,s} \simeq 10^{-3}$ GeV, $m_s \sim 100$ MeV]

  → esthetically unappealing

- incompatible with cosmological observations :

  5% of total energy carried by SM fields (baryonic matter)

  23% cold dark matter

  72% vacuum energy density , $\sim (10^{-3}\ eV)^4 = \Lambda$

  while $(100\ GeV)^4$ scale of electroweak symmetry breaking would be 'natural'

- First and foremost, the SM model says nothing about gravitational interactions, which are treated classically. Any attempt of quantizing gravity by standard perturbative methods stumbles on the fact that GR is unrenormalizable:

* This is a bit oversimplified: consistent string theories only exist in 10 dimensions, and their spectrum includes, beyond the 10D-graviton, other fields of spin < 2 : scalar (dilaton),
fermions (for superstrings)
gauge fields (for het strings, or open strings)
gravitinos (superstrings)

To describe D=4 physics, one must concentrate on vacua of the form $\mathbb{R}^{3,1} \times X_6$
(or AdS, or dS, or FRW)

where X_6 is some compact 6 manifold of size R
4D spectrum and interactions depend on the details of X_6; include Kaluza Klein spectrum + other stringy states winding around X_6

* Even though string theory is formulated perturbatively around a given background, quantum fluctuations are expected to relate all possible vacua. A manifestly background indep[t], non-perturbative formulation is still missing, but there are hints from semi-classical analysis:

D-branes, 11D SUGRA, etc

* Historically string theory started as a model of strong interactions. With advent of AdS/CFT correspondence, it is now again a useful tool (QGP, CMT), irrespective on its ambition as a unified theory of all interactions

Starting from Einstein-Hilbert action

$$S_{EH} = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g}\, R$$

and expanding $\quad g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_p^2} h_{\mu\nu}$

where $\quad M_p = \sqrt{\frac{\hbar c}{G_N}} \sim 10^{19}$ GeV, $\quad 2.10^{-8}$ kg

10^{-35} m, $\quad 10^{-44}$ s

such that the graviton field $h_{\mu\nu}$ is canonically normalized, one finds an infinite series of interactions

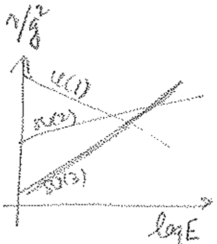
$$S_{EH} = \int d^4x\, (\partial h)^2 + \frac{1}{M_p^2} h(\partial h)^2 + \frac{1}{M_p^4} h^2(\partial h)^2 + \dots$$

which must be fine tuned to cancel ∞ number of divergences

This is acceptable as an effective theory of quantum gravity, but the perturbative expansion breaks down as $\left(E/M_{pl}\right) \sim 1$. As in Fermi theory, suggests new particles around that scale

Why should we worry about such ridiculously high energies (short distances)?

* expected to be reached near Big Bang or black hole singularities



* the logarithmic running of gauge couplings suggests unification around 10^{16} GeV, especially in MSSM

* the Planck scale seems to be related to

$\begin{pmatrix} 0 & M_W \\ M_W & M_U \end{pmatrix}$

- neutrino physics : 'see saw' $\quad \frac{(100\text{ GeV})^2}{10^{18}\text{ GeV}} = 10^{-12}$ GeV

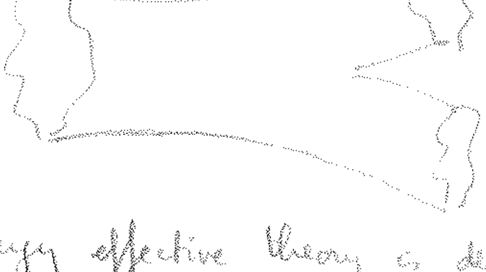
- cosmological constant : $\quad (10^{19})^2 . (10^{-42})^2 = (10^{-11,5}\text{ GeV})^4$

$H_0 \sim 1,5.10^{-42}$ GeV Hubble constant

* At a fundamental level, it is inconsistent to treat gravity classically and gauge interactions quantum mechanically, as it would lead to violation of uncertainty principle.

* Since the graviton is a fluctuation of space time geometry, it is expected that the usual notions of geometry break down at Planckian energies.
Some approaches to quantum gravity (eg. loops and foams, dynamical triangulations, etc) have taken this radical point of view, but have so far not been able to recover ordinary Newtonian / Einstein gravity at long distances.

* String theory is, in a way, a more conservative approach, which resolves the UV divergences of perturbative quantum gravity, by including an infinite number of new degrees of freedom with mass > M_p analogue to Z/W bosons.
These cancellations are ensured by viewing all these new states as excitations of relativistic closed strings interacting by splitting and joining interactions:



- UV divergences cured by non locality
- only 1 coupling constant! + 1 scale: the string tension

The low energy effective theory is described by S_{EH} + infinite number of higher derivative interactions with fixed, finite coefficients