String theory Appetizer

- The Standard Model of Particle Physics is extraordinarily successful,

BUT:

- The Higgs boson has not been found yet (excluded by LEP below 114 GeV, between 140 and 600 GeV by Tevatron, hint of signal at 126 GeV at LHC in Dec)

- Involves hugely disparate scales and coupling constants

axions → $m_\nu \ll m_{e^-} \ll m_t$, $\theta_{QCD} < 10^{-10}$,

10^{-10} GeV 10^{-4} GeV 10^{2} GeV Yukawas, etc

- Cosmological observations show that SM fields can only account for ~ 4% total energy density leaving 21% cold dark matter
  75% vacuum energy density ~ $(2 \times 10^{-3}\ eV)^4$

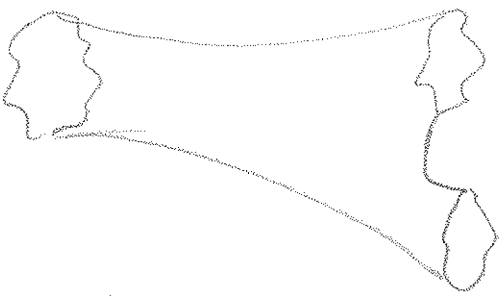
SUSY

- The running of gauge coupling suggests that $SU(3)\times SU(2)\times U(1)$ gauge interactions unify around $M_U \sim 10^{16}$ GeV but then the Higgs mass appears to be highly fine-tuned

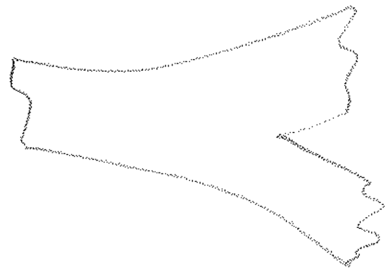
- First and foremost, quantum gravity effects must appear at $m_{Pl} = \sqrt{\frac{\hbar c}{G_N}} \sim 10^{19}$ GeV, 10^{-35} m, $2 \cdot 10^{-8}$ kg, 10^{-44} s

[e.g at the singularity inside black holes, or Big Bang] but Einstein's gravity is perturbatively non renormalizable with coupling constant growing at high energy

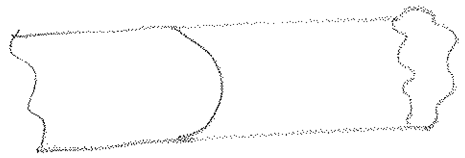
– String theory is an apparently consistent and essentially canonical framework for physics beyond the Standard model, unifying all interactions including gravity, as well as matter fields. String theory postulates that all particles are different excited states of elementary relativistic vibrating strings, which interact by splitting and joining interactions:



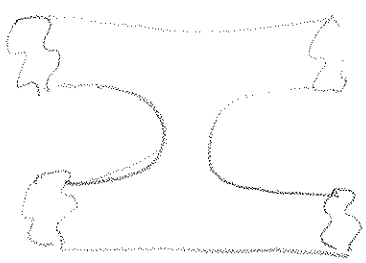
closed strings



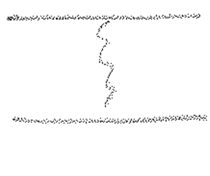
open strings



– String theory has only one dimensionful parameter, the string tension $T \sim \frac{1}{2\pi \ell_s^2} \sim m_{pl}^2$. Standard matter fields correspond (<u>+ more</u>: dilaton, axion, gravitino) to the lowest-lying vibration modes of the string, but they are accompanied by an infinite tower of heavy states, $M^2 \sim \frac{N}{\ell_s^2}$ which can be exchanged at high energy: <u>Regge excitations</u>



$\sim \sum_N$



which regulates the UV behavior of graviton scattering

(effectively, $\Lambda \sim \frac{1}{\ell_s}$ provides a UV cut-off)

- String theory is consistent only in <u>D=9+1</u> dimensions, although some of these dimensions can be highly curved, so that physics is effectively 3+1 - dimensional below $E \sim \frac{1}{R}$
  In particular, it incorporates <u>Kaluza-Klein</u> constructions, where gravity + gauge fields + scalars in 3+1 dim are unified in terms of higher dimensional gravitons

- In fact, the end-points of open strings can be constrained to lie on lower dimensional subspaces, known as <u>D-branes</u>, which incorporate <u>Brane-World scenarios</u>

- String theory requires (with some exceptions) that interactions at $E \gg \frac{1}{R}$ are effectively <u>supersymmetric</u>, described by 10D SUGRA. Whether SUSY is broken at low scale or not is another question.

→ *

- String theory is in principle background independent. It is usually <u>formulated perturbatively</u> in the vicinity of a fixed background (e.g $\mathbb{R}^{3,1} \times \mathcal{M}_6$), but quantum fluctuations interpolate between different backgrounds (even ≠ topologies). (Unfortunately, <u>string field theory</u> is only available for open strings at this point).

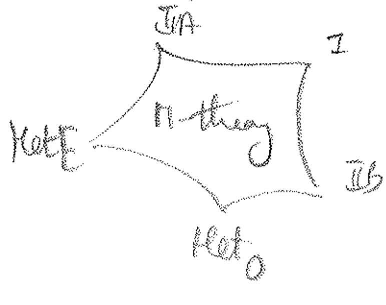
- In fact, string theory admits a plethora of static, stable solutions. Which is chosen depends on initial conditions (like in GR). Each of them has a different vacuum energy, one of which may hopefully be the one we live in.

- Historically, in the 60's, string theory started as a model of strong interactions. With the discovery of the fact that it contains a spin 2 massless excitation, it was then hailed as a unified theory of all interactions. With the advent of the AdS/CFT correspondence, it is now again a useful tool in studying strong interactions (e.g quark-gluon plasma), but also more generally strongly interacting field theories (eg: condensed matter)

- Other, less ambitious approaches to quantum gravity have been proposed:
  - Weinberg's proposal that gravity may have a non-trivial UV fixed point $\rightarrow$ hard to compute
  - Discretization of space-time, statistical approach $\rightsquigarrow$ hard to find a continuum limit
  - Loops and foams: focus on diffeo-invariant, background independent observables

    $\rightsquigarrow$ no evidence yet of Newton law at large distances

*: - While a non-perturbative formulation of ST is still lacking, there is evidence that it includes a regime where physics is 11 dim, and that different string theories arise in $\neq$ corners:



There also exist a 'bosonic version' in $D=25+1$, but it is unstable... Yet, it is the one we shall focus on.