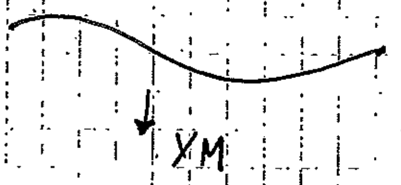
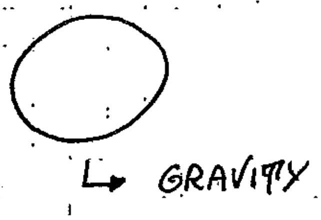
STRING THEORY IN BULLET POINTS

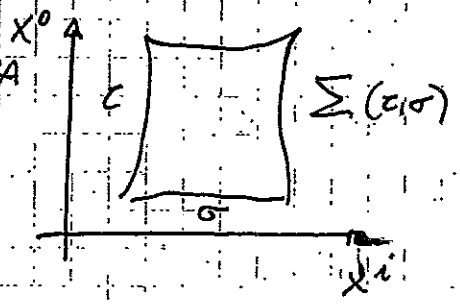
→ NEW POSTULATE: the fundamental constituents of Nature are 1-dimensional.

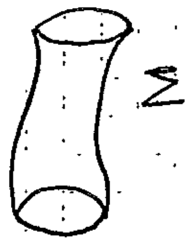




→ UNIFICATION OF FORCES (→ FROM QFT $M_{GUT} \simeq 10^{16}$ GeV)

→ QFA





$\boxed{\text{2D QFT}}$

→ MODES OF THE STRINGS: FIELDS

→ ONLY ONE FREE PARAMETER: $l_s = 2\pi\sqrt{\alpha'}$ = length.

$M_s = \frac{1}{\sqrt{\alpha'}}$

→ BUT: COUPLINGS ARE DETERMINED BY VEVS, CURRENT UNDERSTANDING IS THAT THERE IS A LANDSCAPE OF $\gtrsim 10^{500}$ VACUA OF THE THEORY

→ INTERACTIONS ARE DETERMINED BY THE PROPERTIES OF THE WORLDSHEET.

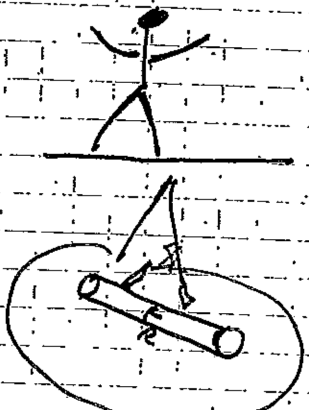
→ SMEARING OF INTERACTIONS IS SUCH THAT ST MIGHT HAVE ONLY UV-FINITE AMPLITUDES (CURR. PROV. AT 2-LOOPS)

→ CONSISTENCY OF THE QUANTUM THEORY ON THE WS REQUIRES $d = 10$ DIMENSIONS FOR SUPERSTRING THEORY → 10D THEORY IS SUPERSYMMETRIC.
(BOSONIC AND FERMIONIC D.O.F.s ARE RELATED BY SYMM. TRANSF.)

→ ~~WE SEE~~ IF WE WANT TO STICK WITH THIS THEORY, WE NEED TO MAKE THE FOLLOWING ASSUMPTION

EXTRA-DIM. (6) ARE COMPACTIFIED AT SOME SMALL ENOUGH "RADIUS"

⟹ DYNAMICS AT DISTANCES $> R$ DOES NOT NOTICE THE EXTRA COMPACT DIRECTIONS
(ARTHUR'S EXAMPLE)

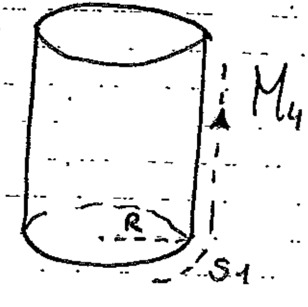


→ STRING COMPACTIF. PRESERVING SOME SUSY ARE DONE ON CALABI-YAU MANIFOLDS.

→ TO UNDERSTAND WHAT WE GET IN 4D, ~~LET US MAKE~~ LET US HAVE A LOOK AT THE EASIEST EX. OF

KALUZA-KLEIN DECOMPOSITION

→ 5D spacetime compactified on $M_4 \times S_1$



→ Field are periodic in the 5th dim.

E.G. $\phi(x, x_5) = \phi(x, x_5 + 2\pi R)$

→ At low energies $E \lesssim \frac{1}{R}$ it is most adequate to have a 4D description:

$$\phi(x, x_5) = \sum_{n=-\infty}^{+\infty} \phi_n(x)\, e^{\frac{i n x_5}{R}}$$

→ Each mode is a different 4D field!

→ $\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}(\partial_5 \phi)^2 = \frac{1}{2} \sum_n \left[-|\partial_\mu \phi_n|^2 + \frac{n^2}{R^2} |\phi_n|^2 \right]$

⇒ MASSLESS 5D SCALAR BECOMES A TOWER OF MASSIVE SCALARS $m_n = \frac{n}{R}$

→ At energy E only the modes $n \lesssim ER$ are accessible.
⇒ if $E \lesssim \frac{1}{R}$ only ϕ_0 (massless)!

→ Symmetries: $G = P_4 \times \underbrace{U(1)}$ ↳ translations along S^1.
KK modes are reps of G. n is the charge under $U(1)$
→ n_i summed over incoming and outgoing particles in a collision is conserved.

→ Now let's see what happens with gravity.

$$S_{5DG} = 2 M_5^3 \int_{M_4 \times S_1} \sqrt{-g}\, R(g)$$

5D Metric tensor: $g_{MN}(x, x_5)$

→ Let us linearize around 5D Minkowski.

$$g_{MN} = \eta_{MN} + h_{MN}.$$

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & g_{\mu 5} \\ g_{5\mu} & g_{55} \end{pmatrix} = \begin{pmatrix} \eta_{\mu\nu} + h_{\mu\nu} & h_{\mu 5} \\ h_{\mu 5} & 1 + h_{55} \end{pmatrix}$$

→ h_{MN} has redundant d.o.f. Indeed, being a spin 2 field, it should have $(2s+1) = 5$ d.o.f.s in 4D, but we have 10!

→ GAUGE FREEDOM : $x^M \to x^M + \epsilon^M(x, x^5)$

$$h_{MN} \to h_{MN} + \partial_N \epsilon_M + \partial_M \epsilon_N \qquad \underbrace{\epsilon^M}_{\to\ 5\ \text{gauge params}}$$

→ we choose to eliminate h_{55} and $h_{\mu 5}$

$$h_{55} \to 2\partial_5 \epsilon_5$$

Expanding in Fourier modes we get:

$$h_{55} \to h_{55} + \delta h_{55}$$

$$\delta h_{55}^{(n)} = 2in\, \epsilon_5^{(n)}$$

→ So we cannot gauge away $h_{55}^{(0)}$!

(corresponding to $\oint_{S_1 \to \text{COMP.}} \partial_5 \epsilon_5 = 0$)

→ Similarly for $h_{\mu 5}$:

$$\delta h_{\mu 5}^{(n)} = \partial_\mu \epsilon_5^{(n)} + in\, \epsilon_\mu^{(n)}$$

So only the zero modes survive and they give:

$$h_{55}(x, x_5) \equiv \phi(x) \qquad h_{\mu 5}(x, x_5) \equiv A_\mu(x)$$

with the ~~g~~ residual gauge freedom:

$$A_\mu \to A_\mu + \partial_\mu \epsilon^{(0)} \qquad h^{(0)}_{\mu\nu} \to h^{(0)}_{\mu\nu} - \partial_\mu \epsilon^{(0)}_\nu - \partial_\nu \epsilon^{(0)}_\mu$$

→ Our 4D theory has a massless scalar ϕ (RADION), coming from fluctuations in the length of the compact.

$$\delta L = \oint h_{55}/_2 = \pi R \phi$$

This is a MODULUS

→ Expanding $h_{\mu\nu}$ in Fourier modes, one can now find the effective 4d Planck scale.

$$M_4^2 = M_5^3 2\pi R \quad (\text{depends on } R)$$

→ VEVs of MODULI fix the value of the couplings of the 4D theory.

→ one of the main goals of string phenomenology:

MODULI STABILIZATION

(~~we come~~

→ In 4D, the graviton is identified with $h^{(0)}_{\mu\nu}$. ~~which~~
~~After~~ After Weyl rescaling~~s g~~:

$$h^{(0)}_{\mu\nu} = \bar{h}_{\mu\nu} - \frac{1}{2} \phi \eta_{\mu\nu}$$

we get a diagonal kinetic term for $\bar{h}_{\mu\nu}$ → CAN. KIN. TERM OF GRAVITONS
and a self kinetic term for ϕ.

$$\sim \phi \Box \phi$$

→ How does this 4D theory look compared to GR?

$h_{\mu\nu}^{(0)}$ couples to matter.

Its propagator is given by:

$$\langle h_{\mu\nu}^{(0)} h_{\rho\sigma}^{(0)} \rangle = \langle \bar{h}_{\mu\nu} \bar{h}_{\rho\sigma} \rangle + \frac{1}{4} \langle \phi \phi \rangle$$

$$= \frac{1}{M_4^2} \left[GR + \underbrace{\frac{1}{6} \frac{\eta_{\mu\nu}\eta_{\rho\sigma}}{q^2}}_{\text{↳ due to the radion}} \right]$$

→ Newton constant (non relativistic regime).

Look at ~~graviton~~ $\langle h_{00}^{(0)} h_{00}^{(0)} \rangle$

$$32\pi G_N = \frac{2}{M_4^2}\left(\frac{1}{2} + \frac{1}{6}\right) = \frac{4}{3}\frac{1}{M_4^2}$$

→ In the relativistic regime ϕ does not couple to photons because they have a ~~vanishing~~ traceless $T_{\mu}^{\ \nu}$.

Radions do not contribute to deflection of light.

But then in terms of G_N the angle is only $\frac{3}{4}$ of the one which is predicted by GR.

$$\Delta\phi \sim \underset{\substack{\| \\ \frac{1}{M_4^2}}}{G_{NEW}} \sim \frac{3}{4} G_N \to \boxed{\text{INCOMPATIBLE WITH DATA}}$$

→ We need to give a mass to ϕ. Then its contribution to the potential decays as $\frac{e^{-m_\phi r}}{r}$

→ In other words, we need to stabilise R

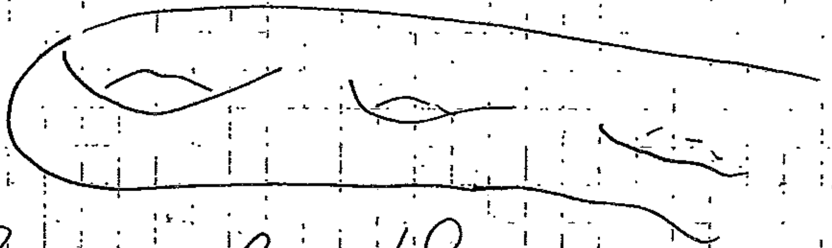
In this case one finds $m_\phi \gtrsim 10^{-3}\,\text{eV}$.

TAKE HOME MESSAGE (in ST)

Moduli are scalars which couple to the SM through operators that are Planck-suppressed.
The VEVs of these fields determine the value of some parameters of the SM.
→ They have to be stabilised.

→ ~~CY manifolds have a~~ Moduli reflect the geometry of the compact dimensions.

→ CYs have complicated geometries, with many holes.
(~10^4 of them)



⇒ large # of moduli in the 4D theory!

$\phi = a + ia$
↓ real part MODULUS
↳ axionic part

Radius → Volume of the CY

→ ~~Now let's go back to inflation String theory~~

COSMOLOGICAL MODULI PROBLEM(S)

1. (CMP) Moduli are generically long lived, as they couple through Planck-suppressed operators. ~~Then~~ They therefore dominate the energy density during inflation or contribute sign. to it after

inflation. In particular their late decay can affect BBN. We didn't talk about reheating, but if it is determ. by moduli decay, then:

$$T_{RH} \simeq \sqrt{\Gamma M_{P}}$$ ~~and~~ and by req. $T_{RH} \gtrsim O(MeV)$ we get

$$m_{mod} \gtrsim 50 \text{ TeV}$$

→ On the other hand moduli are naturally expected to have SUSY masses. If we want TeV scale SUSY, then there is tension with the bound above.

2. DARK RADIATION: moduli can decay to extra-SM matter or gauge fields.

Dark radiation contributes to $N_{eff}(T)$, which is constrained by experiments:

$$N_{eff} = 3.30^{+0.54}_{-0.51}$$ (95% cl, Planck + WP + high L + BAO)

e.g. $$\boxed{\Delta N_{eff} = \frac{\Gamma_{\phi \to \cancel{\text{extra-SM}}\, aa}}{\Gamma_{TOT}}}$$

→ This topic was the subject of our 1st paper.

DIGRESSION: MORE ON 10D → 4D AND SUPERGRAVITY

→ ~~The massless string spectrum in 10D enjoys~~

→ The theory of the massless spectrum ~~in~~ of Superstring theory in 10D is a SUPERGRAVITY THEORY, i.e. a theory with local supersymmetry.

→ After compactification on suitable manifolds (CY w/o orientifold planes) one gets a

4D theory ~~which~~ is, e.g.

→ $\mathcal{N}=2$ SUGRA

→ $\underline{\mathcal{N}=1 \text{ SUGRA}}$ → most interesting for phenomenology.

→ ~~Scalar~~

V_F ↗

→ $\mathcal{N}=1$ SUGRA is characterised by the ~~three~~ following ~~objects:~~ action:

$$S^{(4)} = -\int \frac{1}{2} R * 1 + K_{I\bar{J}}\, DM^I \wedge * D\bar{M}^{\bar{J}} + \frac{1}{2}\,\mathrm{Re} f_{\kappa\lambda}\, F^{\kappa} \wedge * F^{\lambda} + \frac{1}{2}\,\mathrm{Im} f_{\kappa\lambda}\, F^{\kappa} \wedge F^{\lambda} + V * 1$$

where:

→ M^I denotes all complex scalars in the theory.

→ $K_{I\bar{J}}$ is the Kähler metric:

$$K_{I\bar{J}} = \partial_I \partial_{\bar{J}} \underline{K} \nearrow \cancel{K_a}$$

→ K is the Kähler potential, a real function of the fields, with dim. $[\text{mass}]^2$.

→ $$V = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2 \right) + \frac{1}{2} \left(\mathrm{Re} f\right)^{-1\,\kappa\lambda} D_\kappa D_\lambda$$

→ W is the superpotential: arbitrary holomorphic function of fields. It has dimensions $[\text{mass}]^3$.

→ f_{ab} : gauge kinetic function, holomorphic function of fields. Dimensionless.
~~for At tree level~~ Analoguous to the gauge coupling.

$$f_{ab} = \delta_{ab}\left(\frac{1}{g_a^2} - \frac{i\theta_a}{8\pi}\right)$$ for known. SUSY lagrangians

RK: in SUGRA there exists the superpartner of the spin 2 graviton
→ spin 3/2 gravitino.

INFLATION

→ Guided by the ETA PROBLEMS, we ~~see~~ look for fields which enjoy a shift symmetry in 4D.

→ In particular, moduli.

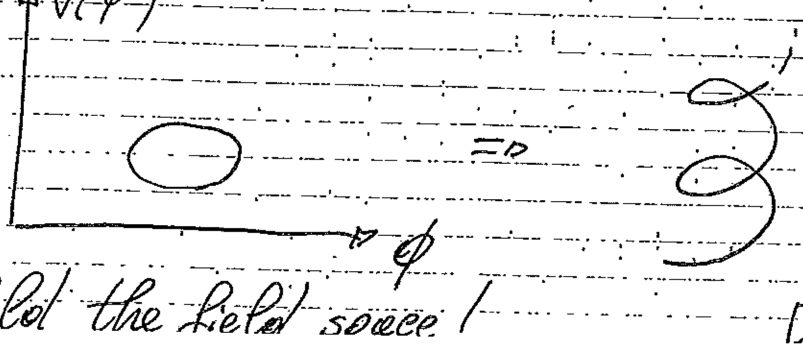
→ Suppose we want LARGE FIELD INFLATION: $\Delta\phi >> 1$ in Planck units.

→ By the KK construction, fields are periodic!

~~too~~ ~~$\phi \to \phi + \Delta$ [illegible]~~

→ Very tough to achieve large displacements!

→ Recent idea : Monodromy inflation SILV./WESTPH. '08



Pot. ~~Field space can be [illegible] unfolded [illegible]~~

→ Unfold the field space!

→ Our work : a realisation of large field inflation using a modulus as the inflaton, in a controlled setting (4D SUGRA). Specifically, the model is inspired by CHAOTIC INFLATION.

→ OUTLOOK FOR INFLATION IN OUR GROUP

Of course ~~much~~ a lot of work is left in various directions:

- → GEOMETRY: understanding what kind of geometries are needed to achieve LFI.
- → PHENO: reheating?

→ A very important question: is it possible to predict large or small field inflation ~~to~~ from string theory?

REFERENCES

- INFLATION : → NIMA ARKANI-HAMED,
  LECTURES AT TRIESTE SCHOOL
  ON SUPERSTRING THEORY
  users.ictp.it/~video/Conferences/
  /2577/2577.html.

  → BAUMANN, MCALLISTER
  "INFLATION AND STRING
  THEORY"

- EFT, EXTRA DIM. → RATTAZZI ~~R~~,
  "CARGESE LECTS ON EXTRA
  DIMENSIONS"
  hep-ph/0607055.

~~Remark on a mistake in the previous lecture:~~

~~$\frac{r}{\mu_S}$ indep. of N_e only for $V \sim \phi^p$~~

~~→ correct T_{RH} affects only mildly N_e.~~
~~So it's ok to have~~

- STRING THEORY → TIMO WEIGAND
  "INTRO TO STRING THEORY"