Strings and the Cosmos

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String Theory as a Grand Unifying Theory

- *60’s: theory of strong interactions*
- *70’s: graviton, as well as gauge bosons in spectrum --> grand unification*
- *80’s: consistent as quantum theories, 5 supersymmetric string theories*
- *90’s: D-branes, dualities --> M-theory, AdS/CFT*
- *present: QCD, cosmology, particle physics ....*

Gravity--Gauge Theory Unification:

- *unification is built in*
- *massless excitations of strings:*

$$G_{\mu\nu}, B_{\mu\nu}, \phi,\ A_\mu; \quad \Psi$$

- *no UV divergences* $\Longrightarrow$ *physical amplitudes are finite.*
- *the only consistent quantum theory capable of describing graviton scattering at high energy*

Standard Model for Cosmology

Successes: inflationary models solve causality and flatness problems

- *Remaining problems:*
  - *initial conditions: a gravity theory valid beyond Planck scale*
  - *dark matter*
  - *cosmological constant/dark energy: extra dimensions, extra degrees of freedom*
  - *who is the inflaton? -- many light scalars in the low energy spectrum*

Inflation--highly successful phenomenology needing a fundamental theory

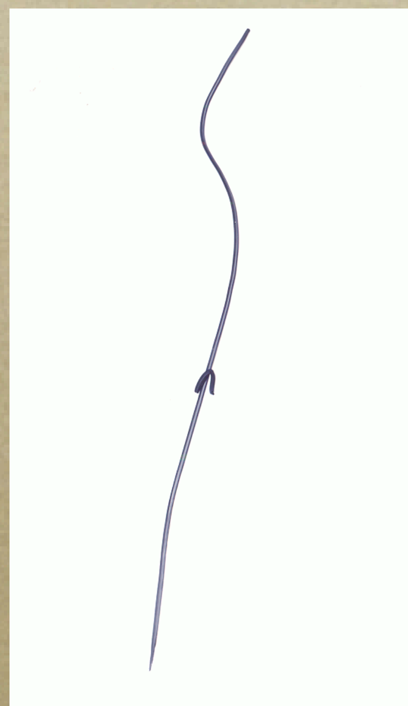
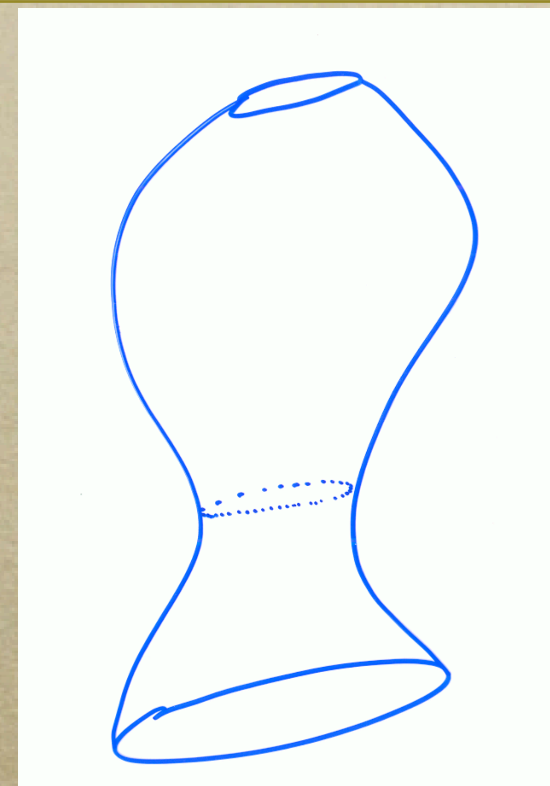
- CMB fluctuations confirm an inflationary universe at the early time.
- But it is hard to understand how it follows from any known microscopic physics.

String theory--a beautiful fundamental theory that provides a consistent description of gravity at high energy--looking for experimental confirmation

- The discovery of D-branes and progress in moduli-fixing $\longrightarrow$ models.
- String theory dramatically modifies our notion of spacetime and may improve the understanding of the early universe where quantum/high energy effects are crucial, where extra dimensions, if any, will come into play.

Outline

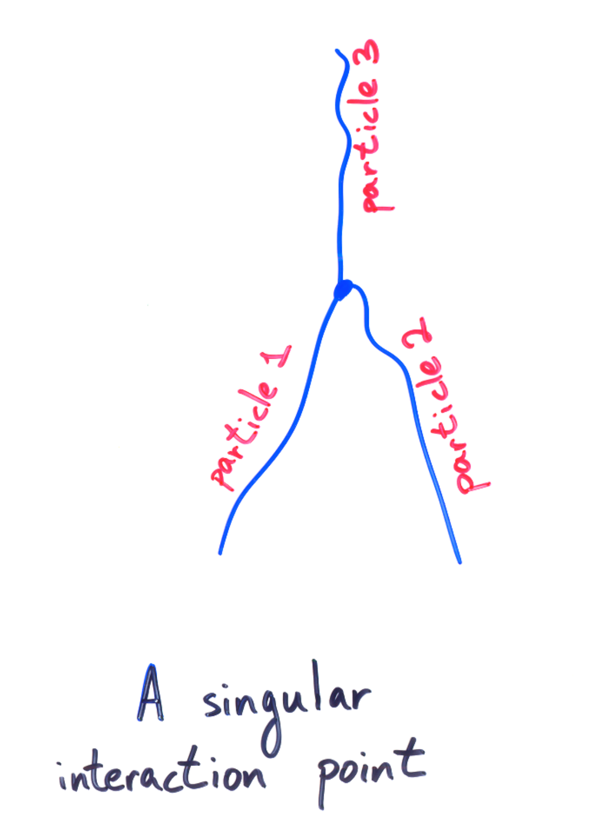
- *String theory as a GUT*
- *basic notions of string theory*
- *flux stabilization: a touch of reality*
- *T-duality: a lesson from string*
- *strings in fluxes: going beyond weak gravity*
- *conclusion*

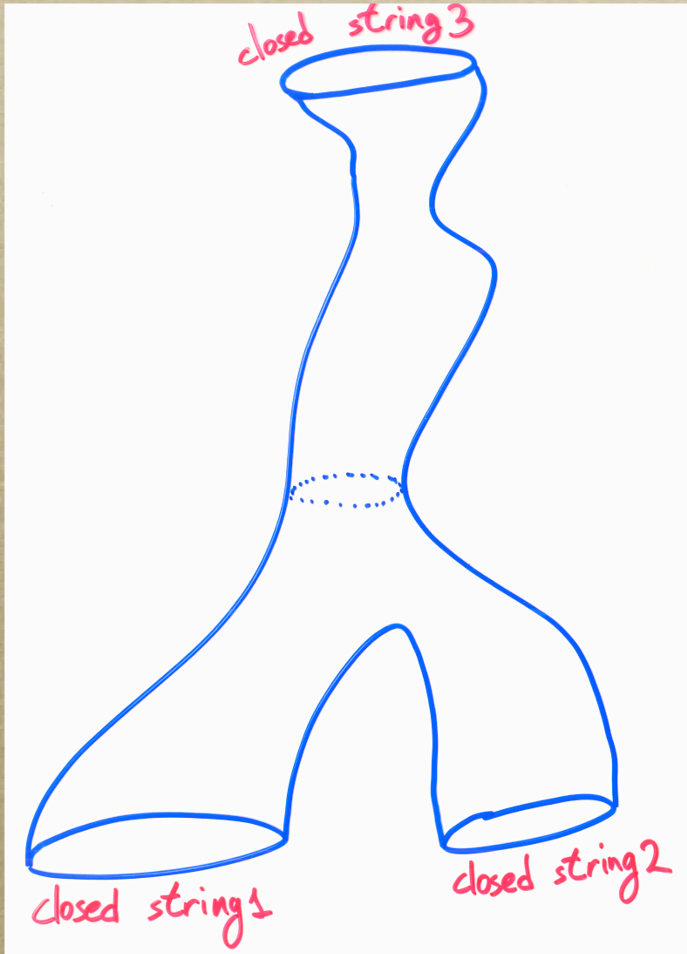
point particle and gauge field:	*string and its gauge potential:*
$\int A \cdot dX \qquad F = dA$	$\int B \cdot dS \qquad H = dB$
 particle worldline	 string worldsheet

TIME

If strings are indeed fundamental objects, then $B_{\mu\nu}$ will play a role as fundamental as A_μ.

- *string sigma-model action:*
- $$S = \int G_{\mu\nu}\,\partial_a X^\mu \partial_b X^\nu h^{ab} + B_{\mu\nu}\,\partial_a X^\mu \partial_b X^\nu \epsilon^{ab}$$
- *interactions: joining and splitting of strings*





Notions of Particle Physics:

- *classically: small strings as particles*
- *quantization:*
  - *quanta of excitations correspond to particles*
  - *closed strings:* $G_{\mu\nu}, B_{\mu\nu}, \phi$
  - *open strings:* A_μ
- *consistency requires that D=10 and existence of massless excitations*

Models based on Compactification

superstrings are consistent only in D=10

6 dimensions are compact and too small to be observed.

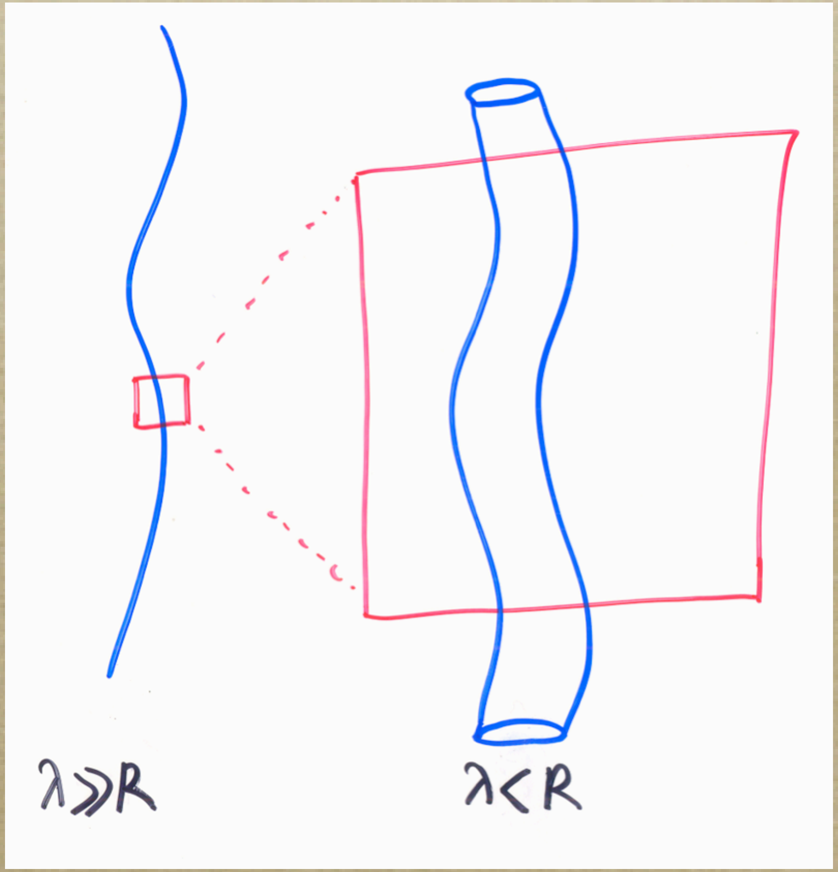
the radius, R, is a free parameter

→ *a massless scalar*

BAD NEWS:

4-D physics depends crucially on the value of this parameter!

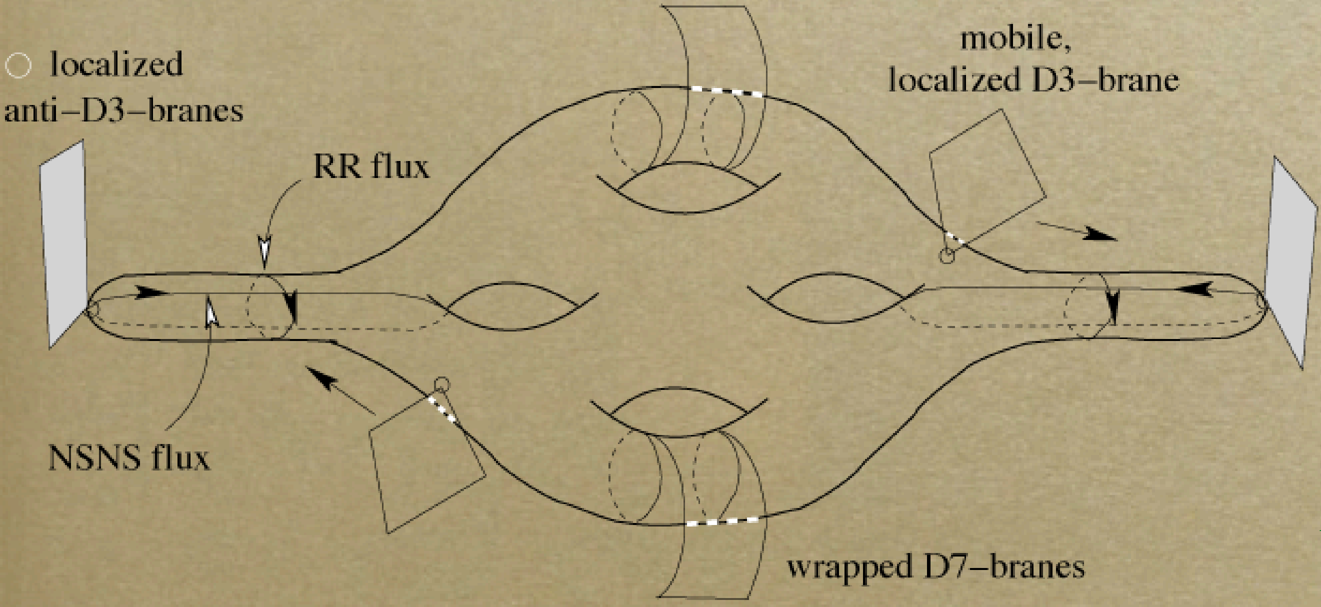
→ *the moduli problem*



Solving the moduli problem by fluxes

Giddings, Kachru, Polchinski, 2001
(Randall--Sundrum Models 1999)

- more complicated compactification manifolds --> a zoo of scalar fields.
  - parameterize shapes and volume of the internal manifolds
- problematic: not observed in Nature
  - low energy (4-D) physics crucially depends on the values of such scalars.
- GKP: turning on fluxes can fix some of the moduli.



Kachru, Kallosh, Linde, Maldacena,
McAllister and Trivedi, 2003
Burgess, Martineau, Quevedo, Rajesh, Zhang;
Antoniadis, Bachas, Fabre,Partouche, Taylor;
D'Auria, Ferrara, Gargiulo, Trigiante,Vaula;
Blumenhagen, Lust, Taylor;
Becker, Becker, Haack and Louis;
Berg, Haack, Kors;
Cascales, Saad, Uranga;
Curio, Krause, Lust;
Blumenhagen, Cvetic, Marchesano, Shiu;
....

a concrete example later....

one more player: the D-brane

Polchinski, 94

- hyper-surfaces where the open strings can end.
- - normal to the surface: Dirichlet boundary conditions
- - along: Neumann b.c.; string ends move at the speed of light.
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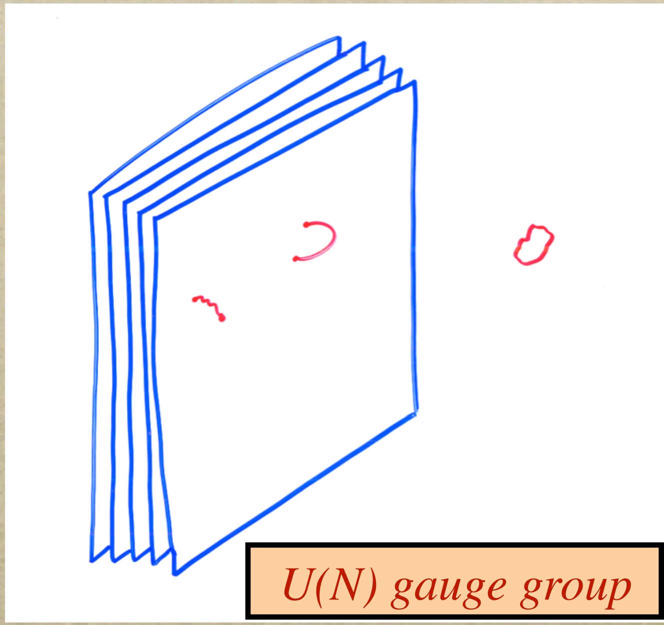
- D-branes: interpreted as a large massive object in spacetime analogue of a monopole, in higher dimensions.



U(N) gauge group

D-branes: trap open strings, Standard Model-like matter.
Bulk: Gravity (closed string) lives in the bulk.

Trapping: similar to the trapping of zero modes on defects (vortices, domain walls) in solids.

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Generic Predictions of String Cosmology

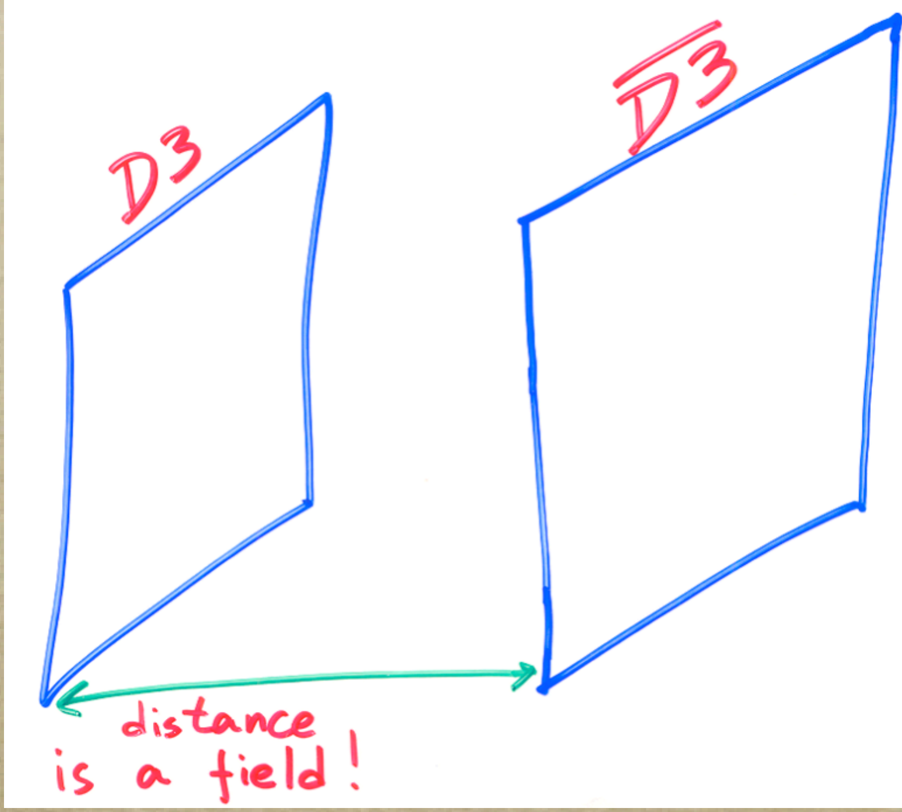
not visible in power spectrum of density fluctuation and CMB anisotropy measurements.

- *short/large distance modification of gravity*
- *perhaps no initial conditions needed*
- *matter & gravity can "see" different dimensions of spacetime*
- *cosmic string production ~ 10% in CMB anisotropy: observable in LIGO, (next) WMAP*
- *small blackhole signals in accelerators*
- *extra dimensions: missing energy as gravitons escape;*
  - may manifest as dark energy in the uncompactified directions
- *many more perturbations modes -- tensor, scalar --> higher dimension signatures*

a few models...

Brane-Inflation: Dvali & Tye 1998

brane motion can provide inflation.



- *a pair of D-brane and anti--D-brane moving in the extra dimensions*
- *the separation is described by a scalar field*
- *anti--D-brane breaks supersymmetry and gives rise to a weak attractive potential.*
- *brane tension has the correct equation of state:* $p = -\rho$

BUT:

Many other moduli needed to be fixed (eliminated) in this model before it can give rise to inflation.

Arkani-Hamad, Dvali, Dimopoulos 98
Antoniadis, ADD 98
Randall, Sundrum 99
Dvali, Gabadadze, Porrati 2000

∘ *Large Extra Dimensions:*

Gravity and SM matter can sense different spacetime dimensions.

- *open strings are confined to the worldvolume of the D-branes.*
- *gravity freely propagates in all directions.*

A proposal to solve the hierarchy problem
--why gravity is so much weaker than other forces:

- *the fundamental mass scale,* m*, can be as low as the weak scale*
- *the observed Planck scale,* M*, is related to* m *by (in the case of one extra dimension)*

$$G_N = \frac{1}{M^2} = \frac{g}{m^2}, \quad g = \frac{1}{m\,R_e}$$

R_e = *radius of the extra dimension.*

experimental update: $R_e \leq 10^{-6}$ *metre*

Severe constraints on phenomenologies.
Unique signatures in colliders, cosmological observations as well as desktop gravity experiments.

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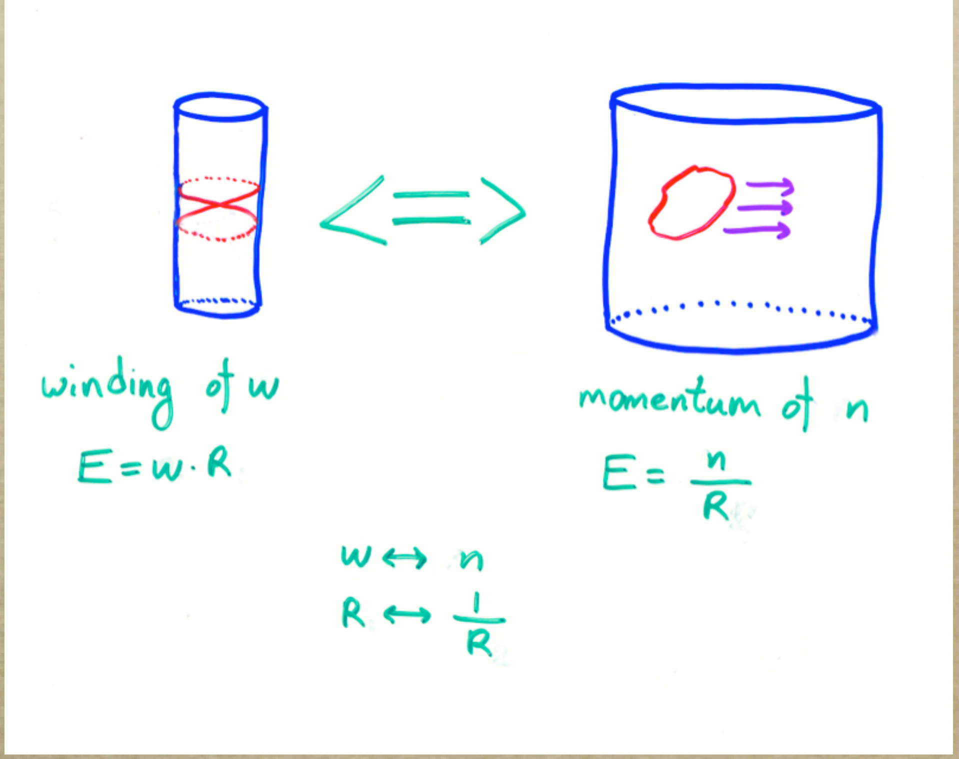
Duality: first encounter of stringy geometry

Consider a closed string winding around a circle.

momentum = n

winding = ω



The effective mass of this particle:

$$M^2 = (\tfrac{n}{R} - \omega R)^2 + (\tfrac{n}{R} + \omega R)^2$$
$$= \frac{n^2}{R^2} + \omega^2 R^2$$

This formula is invariant under

$$\omega \leftrightarrow n \qquad R \leftrightarrow \frac{1}{R}$$

R=1 is special!

String gas cosmology:

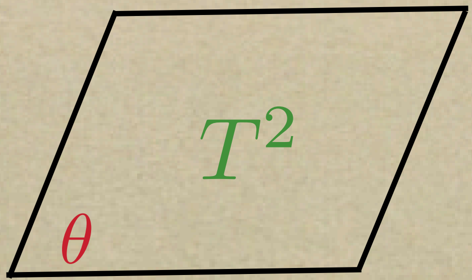
Brandenberger and Vafa 1988

new symmetry: T-duality
new degree of freedom: winding modes

- *an attempt to explain why only three out of the ten dimensions become large*
- *strings wind a 9-D spatial torus at $R=1$ at the beginning of the universe*
- *winding numbers are topological charges:*
  - equal and opposite charged strings can pair annihilate
- *emergence of three big spatial dimensions:*
  - winding and anti-winding modes can annihilate effectively only in 3D-space.

a take with flux stabilization

Brandenberger, YKEC, Watson 2004
Brandenberger, YKEC, Langfelder, in prep.



$$R_1 = R_2 = 1$$

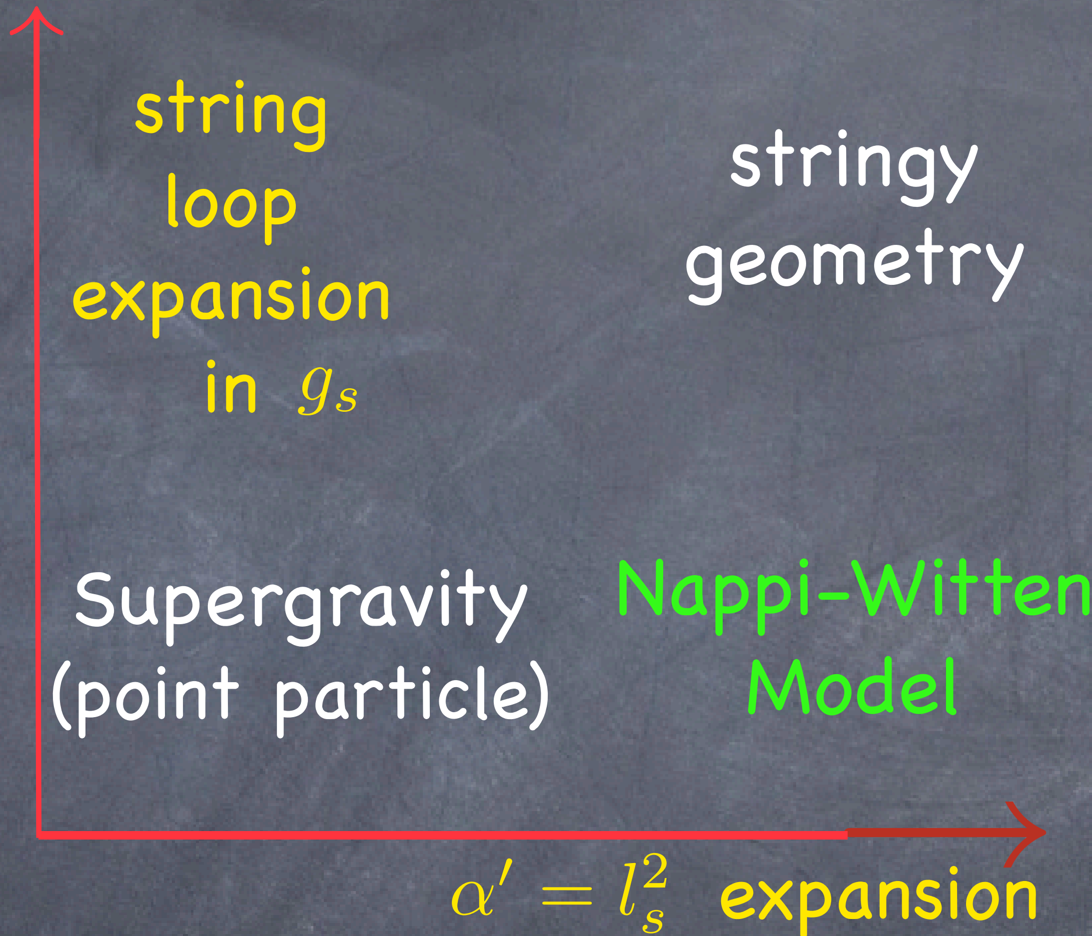
θ = *inclination angle*

- *The size the torus is fixed by T-duality symmetry in SGM but the shape,* θ *is not.*
  - singularity occurs when the torus collapses.

- *introduce* $B_{mn} = \begin{pmatrix} 0 & b(t) \\ -b(t) & 0 \end{pmatrix}$

- $\theta = \frac{\pi}{2}$ *is indeed a solution to the Einstein equations. Stable under small perturbations, and the fluxes also equilibrate.*

- *introduce Ramond-Ramond flux stabilizes the dilaton,* ϕ
  --> 4-D coupling constant is also fixed!



Sigma model:

$$S = \int G_{\mu\nu}\,\partial_a X^\mu \partial_b X^\nu h^{ab} + B_{\mu\nu}\,\partial_a X^\mu \partial_b X^\nu \epsilon^{ab}$$

Solving String Theory in Flux Background

-- going beyond weak gravity

YKEC, Freidel, Savvidy 2003

- *A hard problem--the only thoroughly and explicitly solved string model is in Minkowski space:* $G_{\mu\nu} = \eta_{\mu\nu}, \quad B_{\mu\nu} = 0$
- *the metric:* $ds^2 = dx^+ dx^- + da_1^2 + da_2^2 + H\,(a_1\, da_2 - a_2\, da_1)dx^+$
- *B-field:* $B = H\,\epsilon_{ij} a^i da^j dx^+$ *with constant field strength,* H
- *Complete solution:*
  - classical equations of motion; quantization; the spectrum;
  - explicit construction of the string vertex operators;
  - compute the scattering amplitudes of gravitons, photons, etc....
- *New effects: quantum long string states.*
- *observe a duality in the scattering amplitudes:*

$$\left\{ \begin{matrix} H \to \infty \\ curvature \to \infty \end{matrix} \right\} \longleftrightarrow \left\{ \begin{matrix} H \to 0 \\ curvature \to 0 \end{matrix} \right\}$$

Concluding...

Time is ripe to stand up to the challenge of experiments and observations.

LHC ...

WMAP, SDSS, Planck,
QUIET, CLOVER, ALMA
BiCEP, Polarbear I
Boomerang, SuZIE, AmI
SPT, ACT, APEX, SZA
SN1a, SNAP, LSS, LISA
VIRGO, ATLAS, LIGO
...

predictions

constraints

refinements
new models

signatures

Brane-World
Randall-Sundrum scenarios
ADD model, extra dimensions
KKLMMT
Ekpyrotic Universe
Pre-Big Bang
bouncing universe
String Gas Model
. . .

more stringy/radical ideas

Only then will String theory be accepted as a theory of nature.