Gravity and Strings

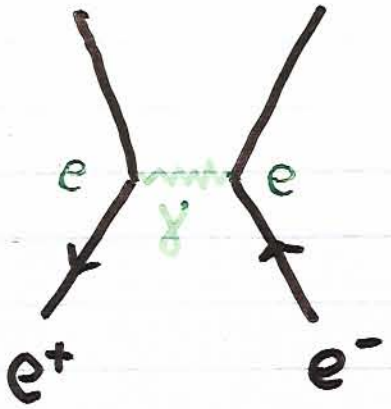
String theory = 2-3 quarters at UCSB

$\Rightarrow$ impressionistic view of some feature introducing important ideas

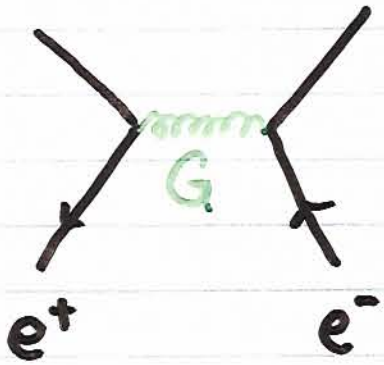
Question of the day:

Why is gravity so weak?

e.g.



$\propto \quad e^2 = \alpha \quad (\hbar = c = 1$



(*)

$$\int d^4x \sqrt{-g} \left[\frac{R}{G_N} + \mathcal{L}(\psi_e) \right]$$

expand: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ ← metric

$\leftarrow h^3$, etc.

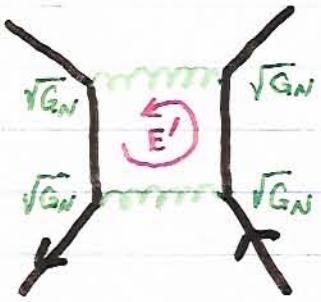
$$\rightsquigarrow \int d^4x \left(h^{\mu\nu} \Box_K h_{\mu\nu} + \sqrt{G_N}\, h^{\mu\nu} T_{\mu\nu} + \cdots \right)$$

$[G_N] = M^{-2} \rightsquigarrow G_N = M_{\text{Planck}}^{-2}$ $\quad (M_P^{-(2+n)}$ w/ extra dim

$\Rightarrow$ (*) $\propto G_N E^2$; small if $E \ll M_P \sim 10^{19}$ Ge

Why is energy so low?

Quantum corrections



$$\sim \quad G_N^2 \int dE' E'^3 = \infty$$

↑ dim analysis

More G_N's $\Rightarrow$ worse divergences

"Non-renormalizable" (non-predictive)

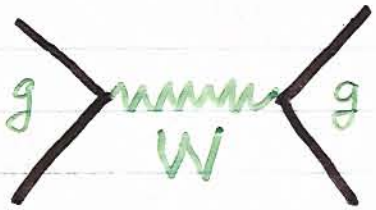
$\leftrightarrow$ $[G_N] = M^p$ $\quad p<0$

Compare 4-fermi:

$$\mathcal{L}_4 \sim G_F J_W^\mu J_{W\mu} \; ; \quad [G_F] = M^{-2}$$

But: $\mathcal{L}_4 \sim \dfrac{g^2}{M_W^2} J_W^\mu J_{W\mu}$

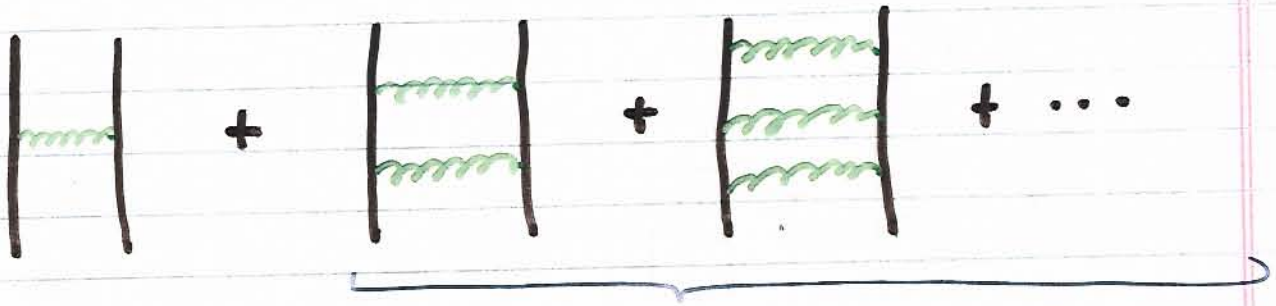
from



Renormalizable, predictive

Why do we care about predictivity?

1. High energy scattering



Important at $E \gtrsim M_p$

→ **Black hole** formation
(maybe $M_p \sim$ TeV ??? Large/warped dims)

2. Cosmology: early on, $E_{typical} \gtrsim M_p$

⇒ need for initial conditions

3. Black holes: what happens
   - inside
   - when Hawking evaporate

4. Dark energy ??

5. Boundary condition for lower energy physic
   → Standard Model

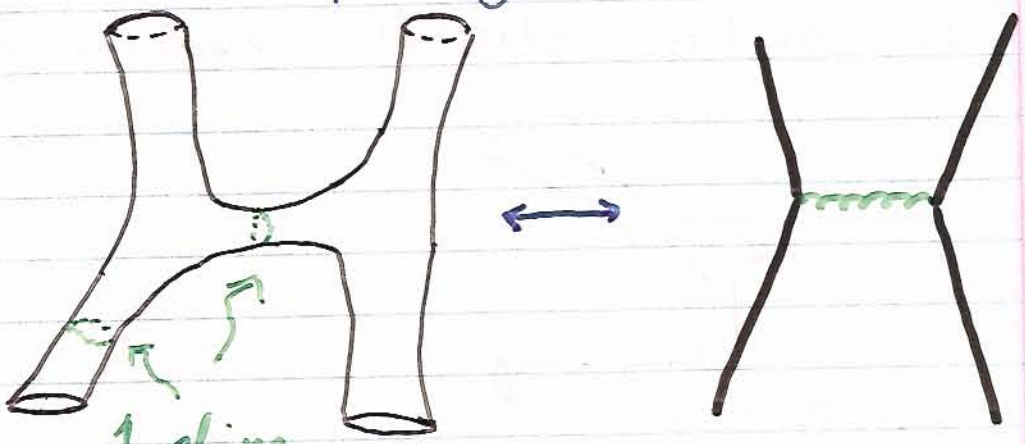
+ more ...

Gravity?

No convincing underlying field theory...

note  + ...

But a more surprising <u>classical</u> modification:

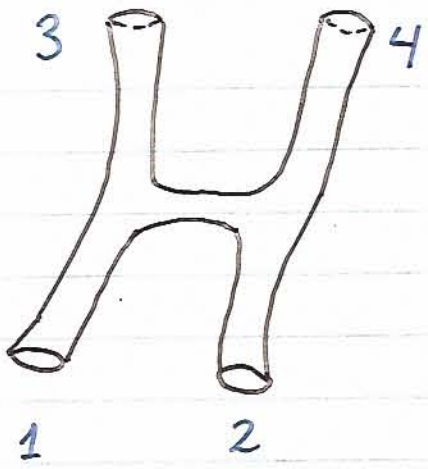


$$\text{Amplitude} \sim \int \mathcal{D}(\text{worldsheets})\, e^{i\,\text{Area}}$$

(analagous to QFT via Schwinger)

How do we know this gives gravity?

Compute:



$$A_{4T} = \int \mathcal{D}[WS]\, e^{i\,\text{Area}}$$

$$= \frac{\Gamma\left(-\frac{\alpha' s}{4}-1\right)\Gamma\left(-\frac{\alpha' t}{4}-1\right)\Gamma\left(-\frac{\alpha' u}{4}-1\right)}{\Gamma\left(-\frac{\alpha'(s+t)}{4}-2\right)\Gamma\left(-\frac{\alpha'(t+u)}{4}-2\right)\Gamma\left(-\frac{\alpha'(s+u)}{4}-2\right)}$$

"Virasoro - Shapiro"

$$s = -(p_1+p_2)^2 \qquad t = -(p_1+p_3)^2 \qquad u = -(p_1+p_4)^2$$

$$[\alpha'] = M^{-2} \qquad \alpha' = M_{string}^{-2}$$

resonances (poles) at : $\begin{matrix} s \\ t \\ u \end{matrix} = \cancel{-\frac{4}{\alpha'}}, 0, \frac{4}{\alpha'}, \cdots$

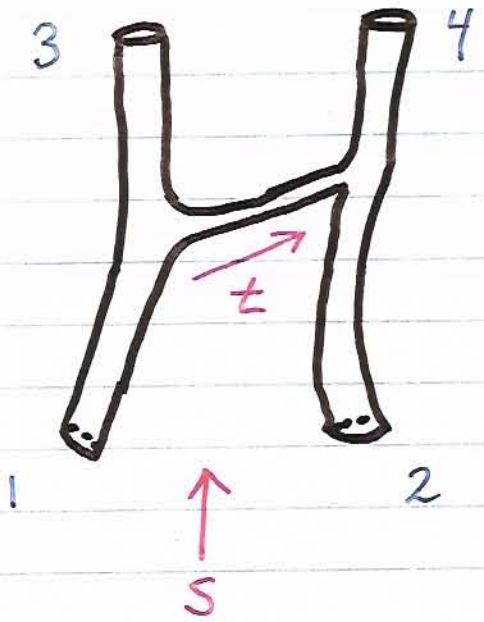
(exercise)

eliminated in SUSY version

$s = 0 \longleftrightarrow$ massless $\quad m^2 = 0$

spin ??

Another limit: $s \to \infty$, t fixed ("Regge")



$$A_{4T} \sim s^{2+\frac{\alpha' t}{2}} f(t) \qquad \text{(exercise)}$$

$\uparrow$ J

$t = 0 \Rightarrow J = 2$

General result (Feynman, ...):

interacting spin 2 massless particle $\Rightarrow$

gravity

Some catches (or, bonuses)

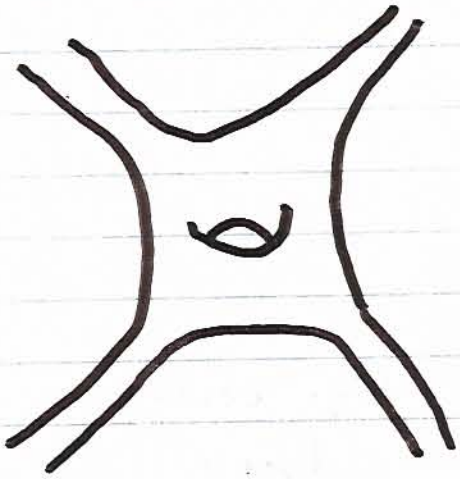
* Only works in $D = 26$ dimensions

* Really only sensible theory if <u>SUSY</u>
  ($\Rightarrow D = 10$)

(In fact, SUSY first <u>discovered</u> in string theory)

But, then, **nonrenormalizability cured:**

e.g.



<u>no</u>
high-energy divergence

UV finite!

Reason: In position space, singularity from coincident interaction points

Strings: no special interaction points

(deeper reason: duality ...)

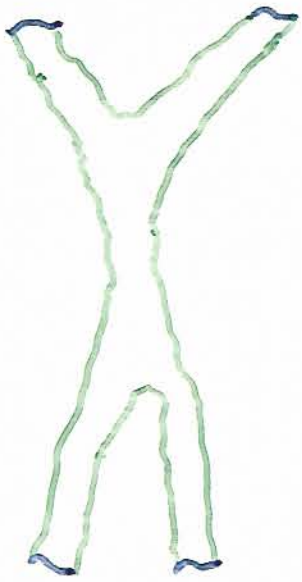
$\Rightarrow$ Strings UV finite order-by-order in perturbation theory.

What about gauge theories?

← Charges, eg. N of $SU(N)$

closed

open



$$A_{4T} = \int \mathcal{D}[WS]\, e^{i\,\text{Area}} = \frac{\Gamma(-\alpha's-1)\,\Gamma(-\alpha't-1)}{\Gamma(-\alpha's-\alpha't-2)}$$

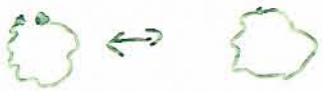
$\longrightarrow$ $m^2 = 0$, $J = 1$

Non-abelian gauge bosons

Many possibilities?

No: tight structure

Open + closed : $SO(32)$



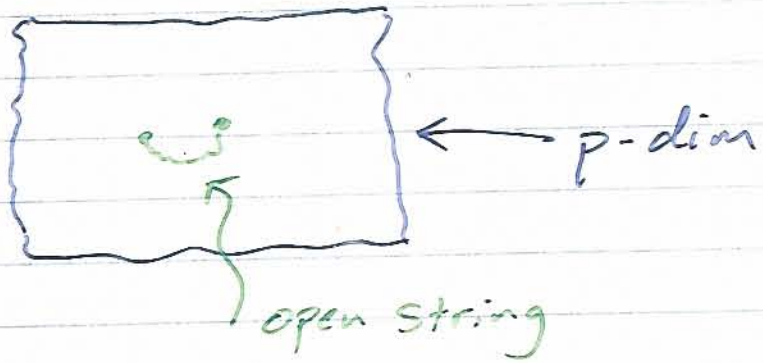
Closed : IIA, IIB → No gauge group (a priori)

$Het_{E_8 \times E_8}$, $Het_{SO(32)}$ → differ mechani

The theory also predicts

Dp-branes

"Dirichlet"



$\rightsquigarrow$ other gauge groups ...

(localized ... not Poinc. invt.)

Naïvely $\rightsquigarrow$ more possible constructions, but at same time allow one to show all 5 theories are different versions of the same theory

("duality symmetries")

Taking stock so far:

Gravity ✓

Fermionic matter ✓ (Bonus #1, from SUSY)

Gauge symmetry ✓

But

$D = 10$

Wrong gauge group ?

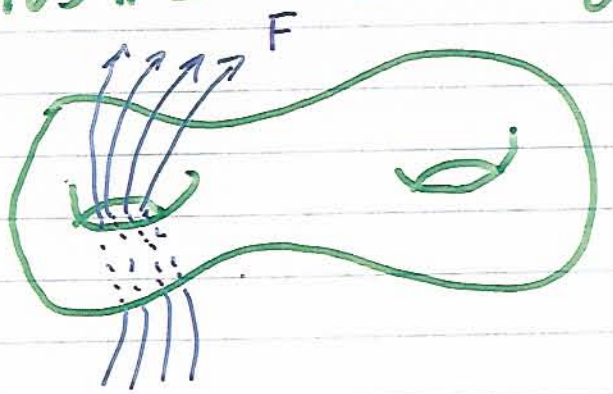
Generations ?

... Solve one problem - $D=10$ -
and get mechanisms to solve others

Idea: 9+1 dim configured as

If $R_c \lesssim \frac{1}{\text{TeV}}$, no reason to have noticed. (Or even bigger, w/ brane worlds)

Bonus #2: Break gauge symmetry



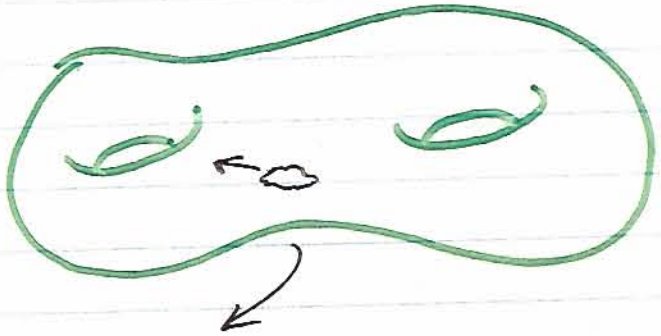
Gauge field configuration ~ trapped flux ⇝ e.g.

$$E_8 \longrightarrow E_6 \longrightarrow SO(10) \longrightarrow SU(3)\times SU(2)\times U($$

$SO(10)$: good grand unification group

(or can get Standard model from intersecting branes...

Bonus #3: Generations



String configuration described by wavefunction $\psi(x,y)$ (like for QM particle, eg. on circle)

roughly, $\not{\partial}_{10}\psi = \not{\partial}_4\psi + \not{\partial}_6\psi = 0$

↑ Dirac operator

↑ lightest oscill. state

$\not{\partial}_6\psi = m\psi$ "normal modes"

↖ 6D Evalue ↔ 4D mass

Can have several mode wavefunctions w/ same charge ⇝

$$\begin{pmatrix} \nu_e \\ e \\ u \\ d \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \\ c \\ s \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \\ t \\ b \end{pmatrix}$$

... easy to replicate.

Summary, so far.

Assume strings.

Get :
- gravity - UV finite
- gauge theories (→ Standard model)
- fermions
- generations
- scalars (~ Higgs - from compact)

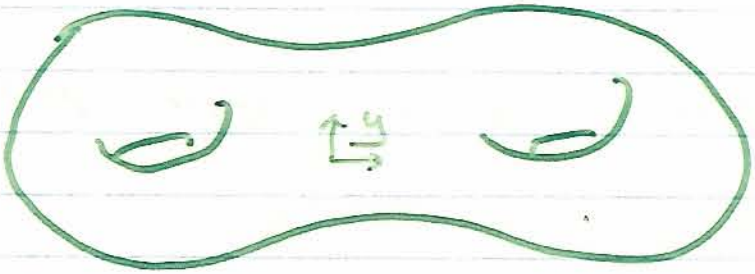
So, some say

"Theory of everything" (TOE)

(I prefer "Theory of all physics," TOP)

Before we get too elated ...

What fixes compact space M ??



The equations of motion of string theory?

To a good approximation:

$$R_{mn}(y) = 0$$ (vacuum Einstein eqns)

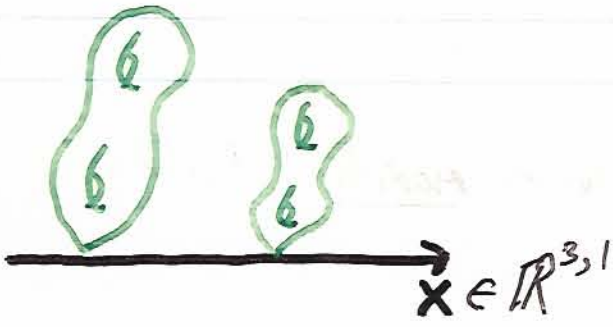
R_{mn}: Ricci

$\rightsquigarrow$ "Calabi-Yau manifold"

Many solutions

- Many topologies (though connected in S.T.)
- Many brane configurations
- Continuous families

... size, shape



e.g. $R(x)$

Massless moduli fields

All apparently bad news.

- loss of predictivity
- massless scalars, gravitationally coupled

$\rightsquigarrow$ 5th forces
time dep. couplings
extra matter
} Not seen experimentally

But ...

there are newer ideas how to solve, with more complicated configurations ...

First, one more ingredient: fluxes

E.M.: A_μ; $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$F_{\mu\nu}$ antisymmetric

$$S_{Maxwell} = \int F^2$$

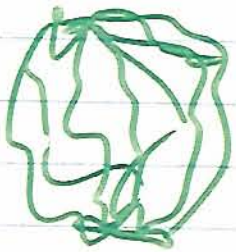
q-form flux: $A_{\mu_1 \cdots \mu_{q-1}}$

$$F_{\mu_1 \cdots \mu_q} = \partial_{\mu_1} A_{\mu_2 \cdots \mu_q} \pm \text{perms}$$

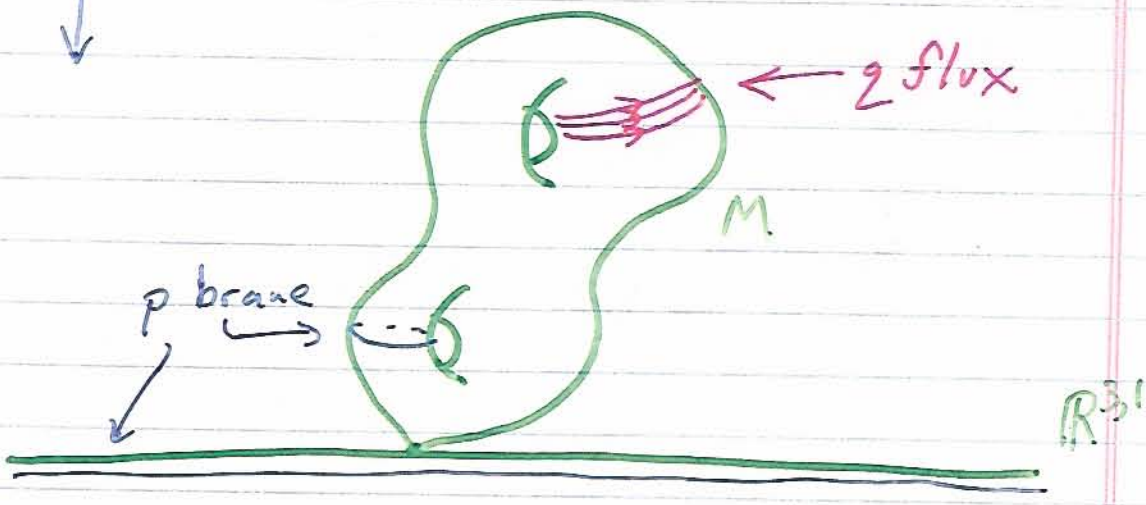
$$S_q = \int F_q^2$$

... also present in string theory

Cartoon of cosmological evolution:



"Quantum geometry"



Can "freeze in":

p-branes - spacefilling

q-fluxes

Their energies depend on sizes/shapes

$E_p \propto R^{p-3}$; $\int F_q = \text{fixed} \Rightarrow E_q = \int F_q^2 \propto \frac{1}{R^{2q}}$

$$E_{tot}(R) = E_1(R) + E_2(R) + \cdots = V(R)$$

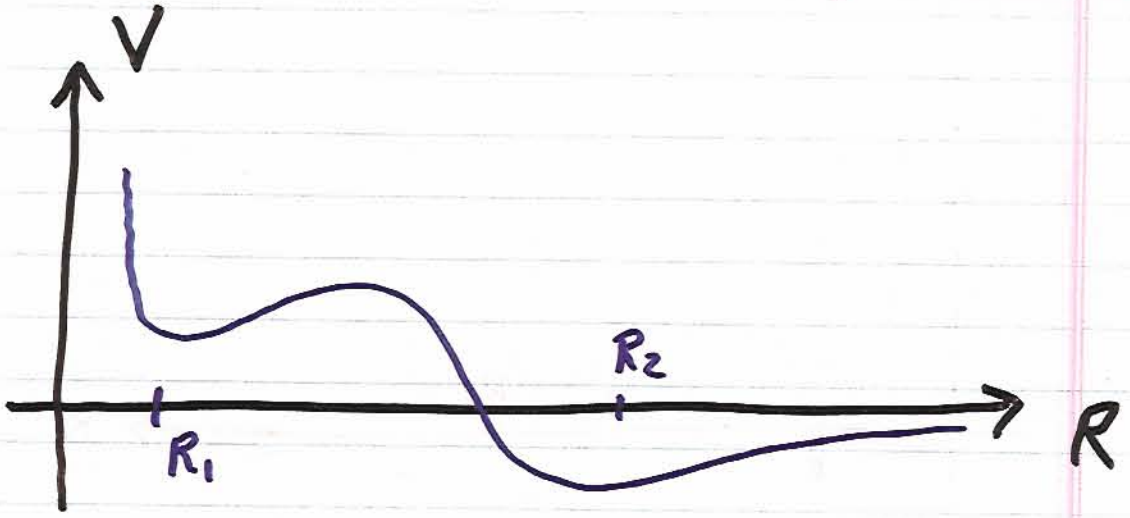
... potential for $R(x)$

4 dim "effective theory"

$$S = \int d^4x \sqrt{-g} \left(R - (\nabla R)^2 + V(R) + \cdots \right)$$

$\Rightarrow$ Combination of effects can fix moduli

eg.



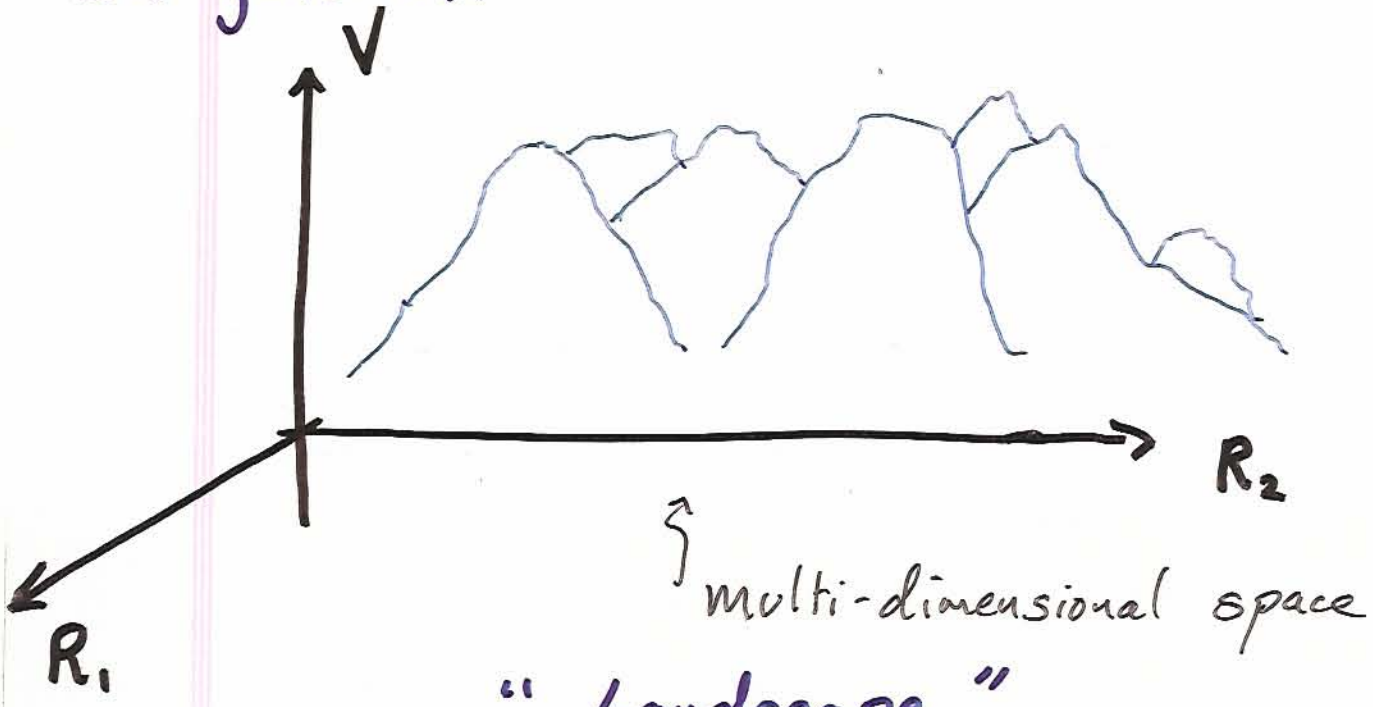
Moreover:

$V(R_1) = \Lambda_{eff} > 0$ de Sitter

$V(R_2) = \Lambda_{eff} < 0$ anti de Sitter

So: energy from fluxes, branes, ... trapped in extra dimensions may explain the presence of **dark energy (Λ)**

In general:

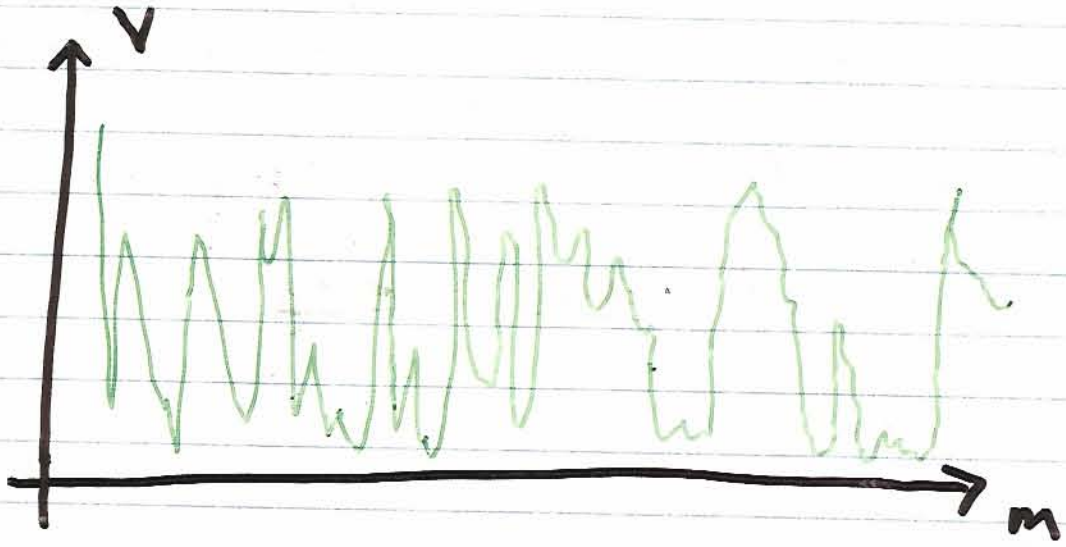


"Landscape"

Another problem: typically $V(R_i) \sim M_p^4 \sim 10^{120} \Lambda_{obs}$

But ...

Many vacua randomly distributed



$\Rightarrow$ if enough (yes), can have vacua w/

$$\Lambda \sim \Lambda_{obs}$$

Since Λ_{obs} is ~ the maximum allowed for galaxy formation ($\rightarrow$ life.) perhaps the entire landscape is populated (many different regions), and we evolved where life is possible, ie $\Lambda \sim \Lambda_{ob}$

"Anthropic principle"

This picture is new, under test, but plausible.

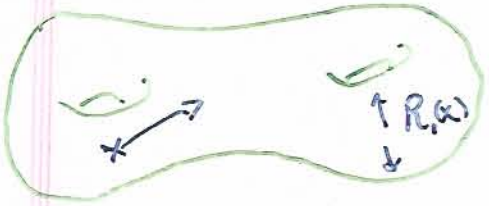
Potential issue - does it really emerge from a complete string theory analysis ... ?

approximations ...

time dependence ...

Other aspects of the "landscape"

* Inflation candidates: eg



D3 brane
y(x)

moduli, brane motion

(brane collisions ... ?)

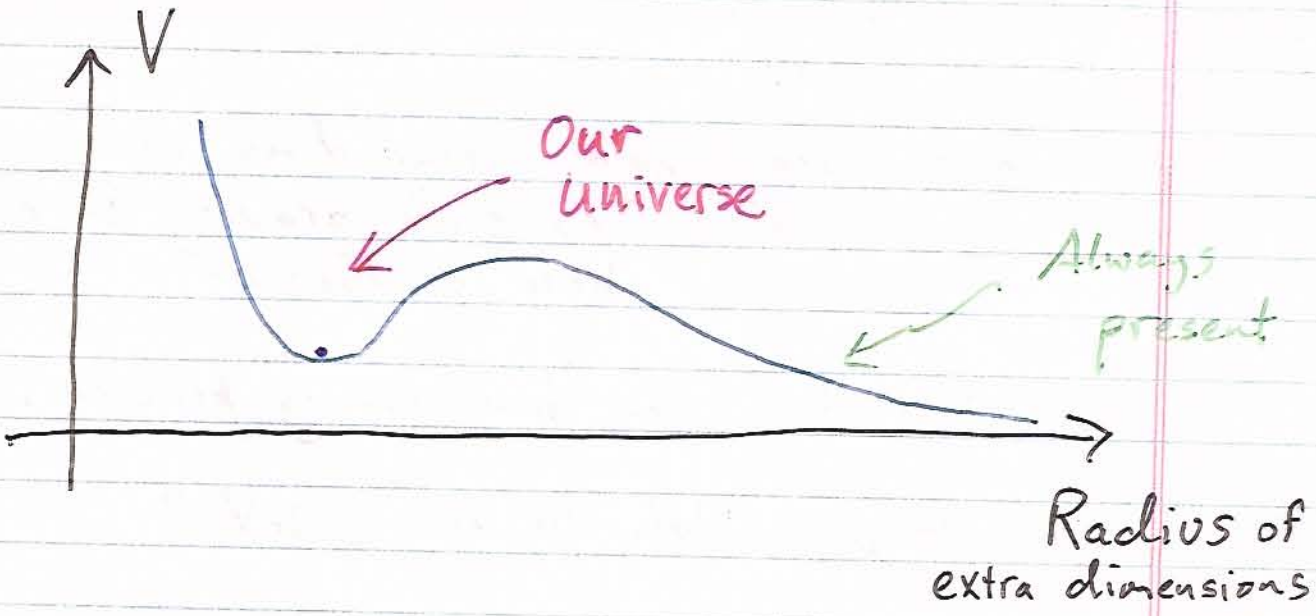
* Some points may have large dims. or large "warping" ⇝ TeV scale gravity and black hole production at accelerators.

* Have eliminated one "fine-tuning" problem (Λ).

Is m_{susy} likely to be ~ TeV?

debate continues ...

* Ultimate fate of the Universe.



$\Rightarrow$ our universe is unstable

extra dimensions will grow

"Spontaneous decompactification"

The end of the Universe is a good place to end this survey.

Summary

* String theory resolves the nonrenormalizability problem of perturbative gravity.
* It predicts: susy, fermions, gauge theories, generations, ...
* Candidate "TOP"
* Moduli (size/shape) problem is critical
* One resolution via frozen fluxes/branes
* ~> dark energy
* landscape - likely, under investigation
* inflation candidates? TeV scale gravity? high M_{susy} ??
* Spontaneous decompactification