String Theory and Cosmology

Based on work by a large community...
My collaborators on related projects:

Stanford colleagues: Kallosh, Linde, Dimopoulos, Kachru-Poor
Students: Giryavets, Liu, McAllister, Schulz
TIFR: Tripathy, Trivedi
Princeton: DeWolfe, Maldacena, Verlinde
UCSB: Giddings, Polchinski
MIT: Taylor
Rutgers: Denef, Douglas, Florea
Harvard: Arkani-Hamed, Gukov

Some important related works:

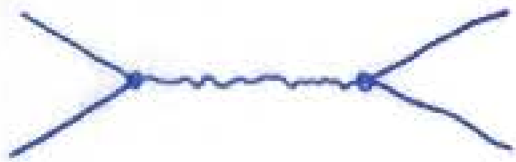
"Landscape": Bousso, Polchinski
Maloney, Silverstein, Strominger
Susskind
Banks, Dine, Gorbatov
Ashok, Douglas
Denef, Douglas
Denef, Douglas, Florea

String Compactifications: Polchinski, Strominger
Becker, Becker
Gukov, Vafa, Witten
Dasgupta, Rajesh, Sethi
Curio, Klemm, Lüst, Theisen

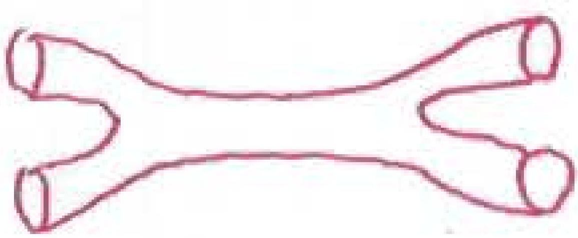
Brane inflation: Dvali, Tye
Alexander
Dvali, Shafi, Solganik
Burgess et al
Tye et al
Copeland, Myers, Polchinski
Silverstein, Tong
Jackson, Jones, Polchinski

Introduction

The basic premise in string theory is that point particles and the associated Feynman diagrams



are replaced by loops of string and the associated "pant diagrams"

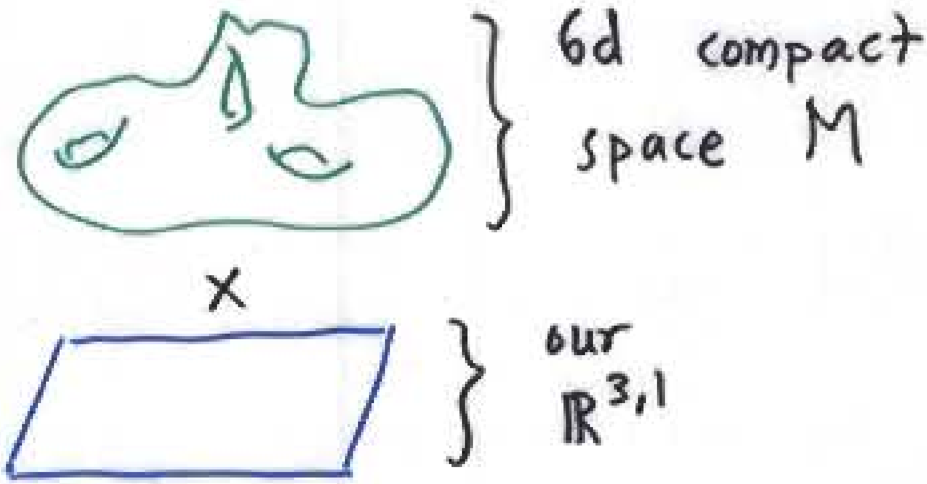


The resulting theory has some striking features:

- UV finite theory of quantum gravity interacting with gauge fields and charged matter ... 

- Predicts the spacetime dimension -- the answer is 10! ?? ☹ ??

Not necessarily a disaster. Can imagine we live in a string cosmology which at late times asymptotes to



Possible to find examples which, e.g.,

- Yield 4d $\mathcal{N}=1$ SUSY as an effective theory below scale $1/R$ of M
- Have "Standard Model-like" gauge group with 3 generations etc.

For such solutions:

- M should be a so-called "Calabi-Yau manifold" ($\gtrsim 10^4$ known) [see picture]
- Particle theory at energies $\ll M_s$ has properties that sensitively depend on details of M

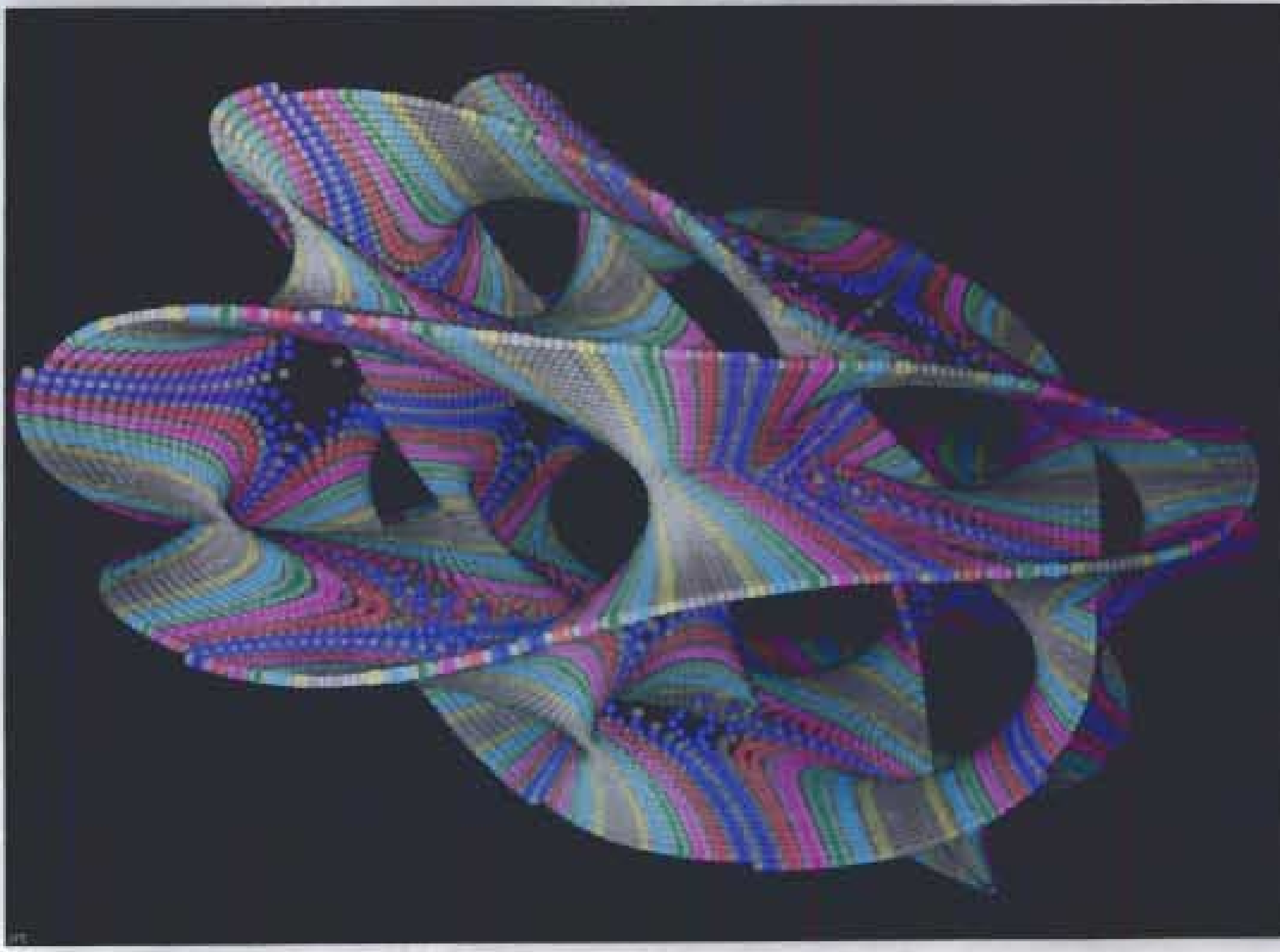
E.g. N_{gen} = # generations of SM Fermions, Yukawa couplings of light particles ⟷ topological + geometrical data about M

You've heard all of this before (~1986)

So, why aren't we DONE yet?

First, some qualifications of that sentiment...

lots of progress since mid 80s. E.g.:



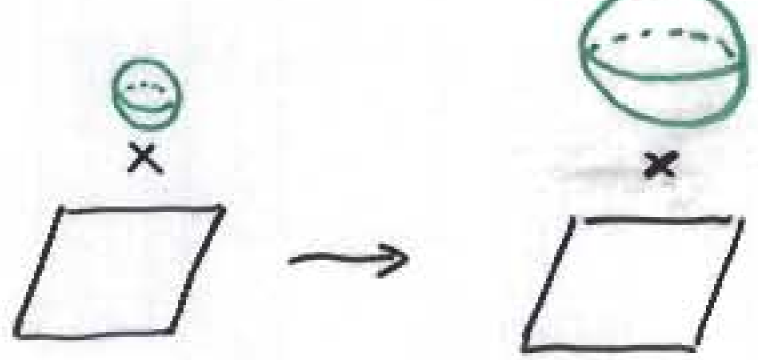
- We now understand simple non-perturbative effects in string theory ⇒ <u>many</u> insights into dynamics of 4d quantum field theories ...
- In <u>very</u> simple backgrounds, we can formulate the theory non-perturbatively (in terms of gauge theory!).

For very symmetric analogues of black holes, we can precisely compute the BH entropy predicted by Bekenstein & Hawking, by counting microstates!

Moduli & the "landscape" of string theory

Given a choice of M, can often deform it slightly (change metric in extra dims) →

another solution :



Can vary size & shape of M

In the 4d physics, this freedom ⟹ ∃ <u>moduli</u> : scalar fields ϕ_i with

$$V(\langle\phi_i\rangle) = 0 \quad \forall \text{ possible } \langle\phi_i\rangle$$

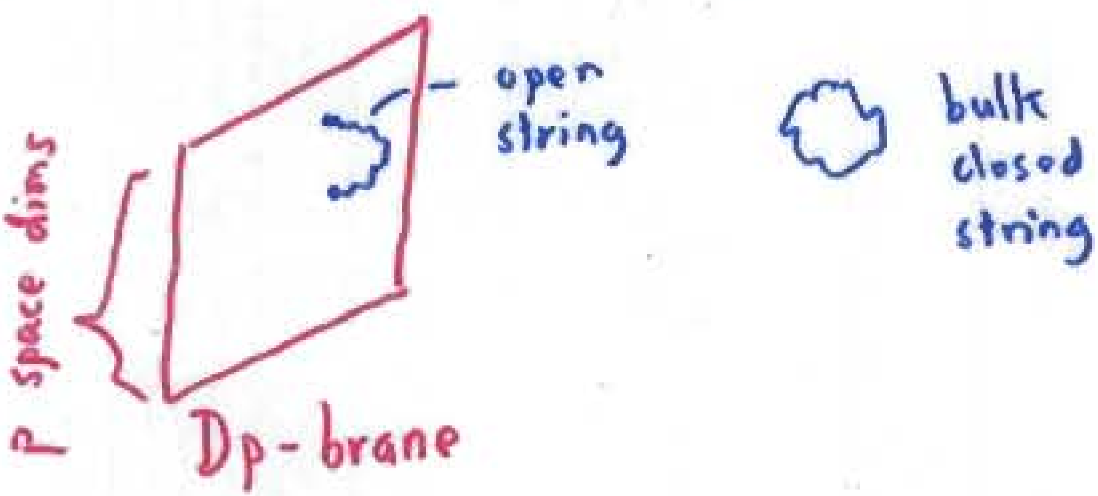
But different VEVs $\langle\phi_i\rangle$ → inequivalent physics (eg Yukawa couplings, particle masses vary as functions of $\langle\phi\rangle$).

Existence of such scalars would → all kinds of problems :

- Equivalence principle violations?
- Time varying α ?
- Energy in ϕ can ruin cosmology

Since such fields would be a disaster experimentally, and ruin predictivity, we should eliminate them. Can we see them developing a potential in a calculable way?

Yes, because string theory is not just a theory of strings!



- Just like particle couples to gauge field via

$$\int_{\text{worldline}} A$$

Dp-1 branes couple to p-index gauge fields

$$\int_{\text{worldsurface}} A_p$$

So ∃ p+1 form field strengths

$$F_{p+1} = dA_p + \cdots$$

Now recall we have six extra dims curled up on M :

For each (p+1) cycle in M, can turn on

$$\int_{\Sigma_{p+1}} F_{p+1} \in \mathbb{Z}$$

Just a gauge flux, quantized by an analogue of Dirac quantization.

This is very analogous to turning on a $\vec{B}$ field (but in extra dims). But remember

$$E \sim \frac{1}{8\pi} \int \left(|\vec{E}|^2 + |\vec{B}|^2 \right)$$

So these extra dim'l gauge fluxes will cost energy!

Two Important Consequences

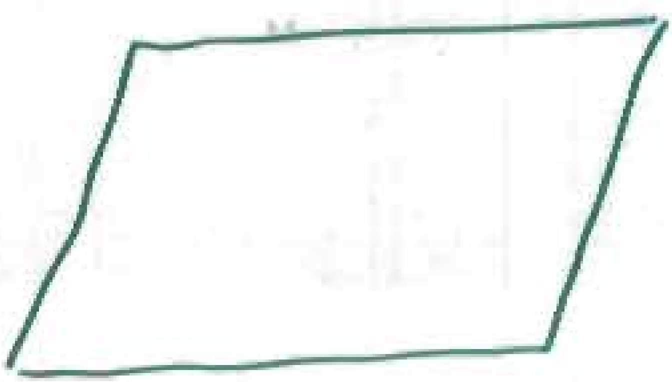
① The energy cost of a given flux depends on detailed geometry of M ⇒

> Fluxes generate a potential for moduli : $V_{n_1,\dots,n_k}(\phi_i)$

where $n_1 = \int_{\Sigma_1} F$, $n_2 = \int_{\Sigma_2} F$, ... and typically k can run up to ~100s.

This lifts the degeneracy and produces a landscape of string vacua:

Before:




visualparadox.com

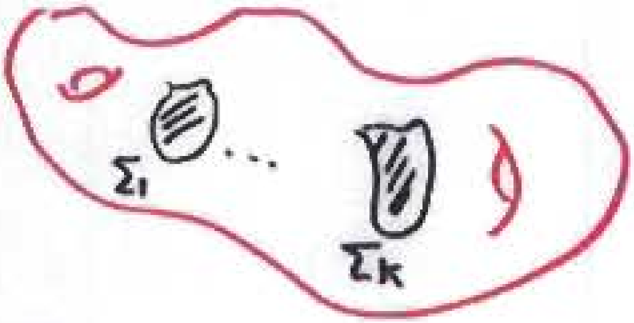
There is increasing evidence that this rich landscape includes maximally symmetric 4d vacua with:

- $\Lambda = 0$ (Supersymmetric)
- $\Lambda < 0$ AdS, sometimes SUSY
- $\Lambda > 0$ (nonsusy, always metastable ??)

Interesting:

- Strings in dS space raise confusing conceptual questions (some of which are relaxed by metastability)
- Observed accelerated expansion → we should be happy that it appears $\Lambda > 0$ has a home ∈ string theory!

② How many possibilities are there?



$\Sigma_1, \ldots, \Sigma_K$ $(p+1)$ cycles. Get to choose

$$\int_{\Sigma_i} F_{p+1} = n_i$$

- For detailed reasons, not all choices of n_i allowed -- usually $\sum n_i^2 < N^2$ where N related to topology of M ($N^2 \sim$ 100s).
- Assuming $V_{n_1,\ldots,n_K}(\phi)$ has a critical pt for each choice →

$$\boxed{\#\ \text{vacua} \sim N^K}$$

} naively can exceed 10^{100}

- This is a lot of vacua.
- They are NOT "randomly" distributed on the former moduli space. For at least one very large class of examples, there is a detailed theory that tells one

$$N_{vac}(\langle\phi\rangle) \text{ for any } \langle\phi\rangle \in \mathcal{M}$$ Ashok, Douglas

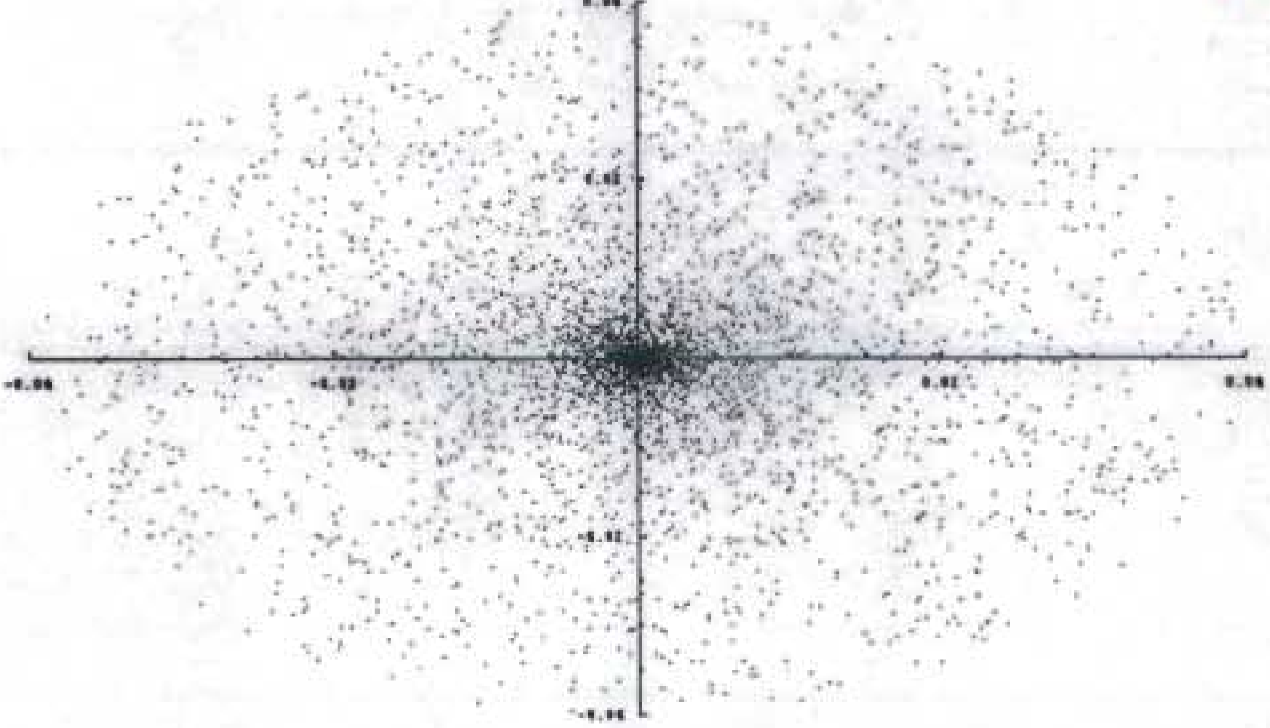
- This theory can be checked by calculating the locations of large #s of vacua in some examples, and it works!
- Interesting feature: ∃ "attractor loci" where a large fraction of vacua lie. These vacua share certain properties; this could eventually → a new, "stringy" notion of naturalness. [see figure]

Attractor --

c.f. Dvali's work...

GKP +

Randall - Sundrum

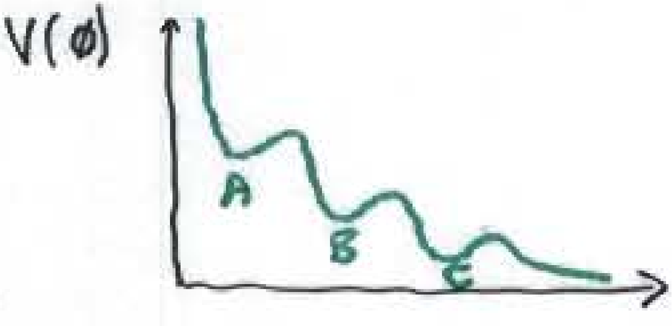


Vacua near conifold $\psi = 1$

- Clearly, # flux varua on fixed M >> # of different choices of M's topology, so the daunting task is to get a handle on the space of flux vacua.

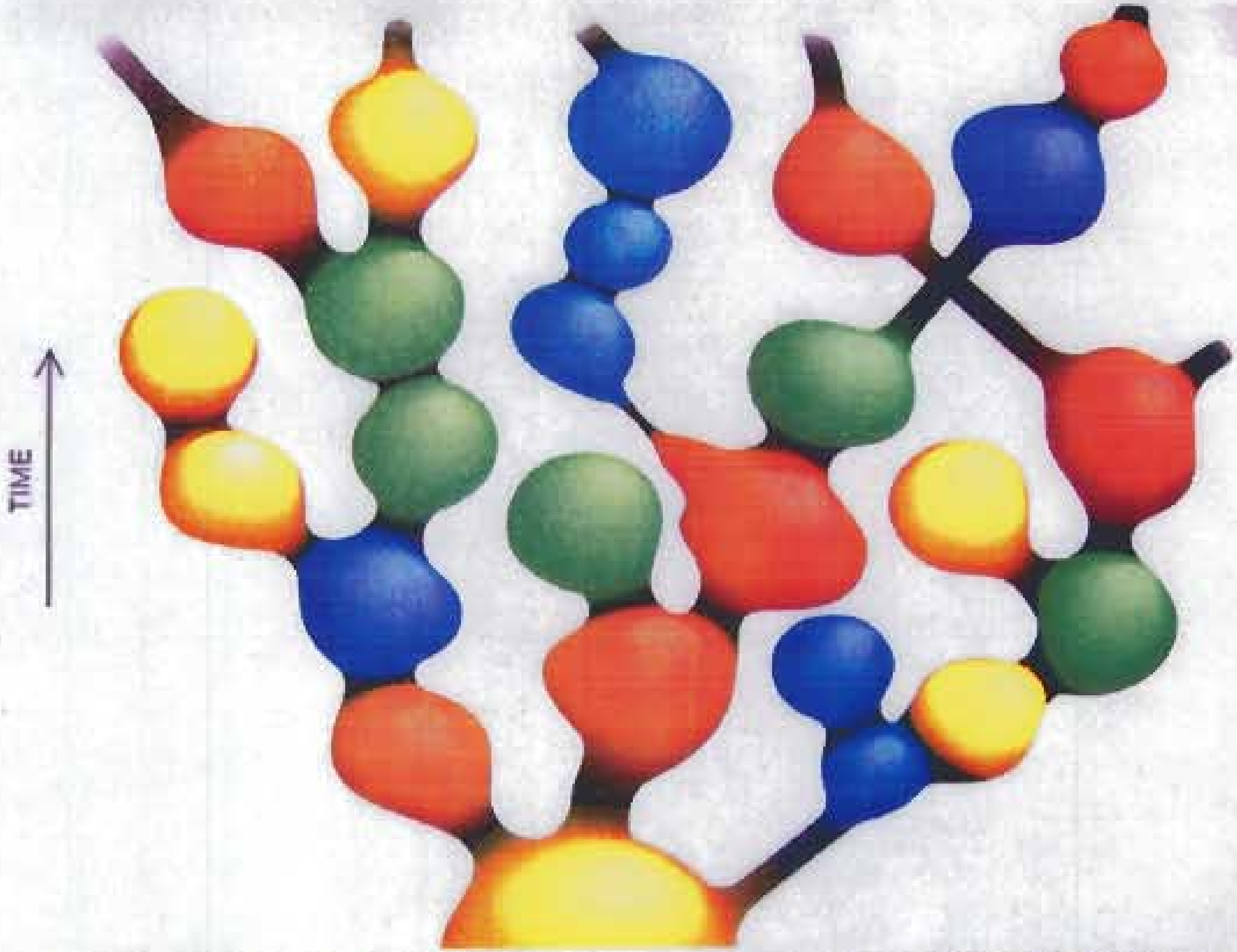
This complicated and diverse landscape:

- Offers a natural home for Linde/Steinhardt/Vilenkin's "eternal inflation"



Start universe off in A → it eternally inflates, bubbling off phases of B, C, ...
[see picture]

- Sharpens our worry that small Λ_{obs} may be <u>accomodated</u> but not <u>explained</u>



SELF-REPRODUCING COSMOS appears as an extended branching of inflationary bubbles. Changes in color represent "mutations" in the laws of physics from parent universes. The properties of space in each bubble do not depend on the time when the bubble formed. In this sense, the universe as a whole may be stationary, even though the interior of each bubble is described by the big bang theory.

Instead of tangling with these thorny issues, I now change tracks. Say we find the right M and fluxes. Can we look to string theory for new ideas (or microscopic confirmation of old ideas) about early universe cosmology?

(New Ideas About) Inflation & String Theory

In order to explain:

- absence of GUT relics (e.g. monopoles)
- flatness of observed universe
- "horizon problem" (different parts of sky w/ similar properties, not naively in causal contact)

inflationary theories postulate that

in early Universe, there was a phase of exponential expansion

Guth; Linde; Albrecht & Steinhardt

$$a(t) \sim e^{Ht}$$

- dilutes monopoles & other monsters
- balloons away curvature → flatness

Distant points were in causal contact, before exponential explosive growth...

The typical ingredients in "slow-roll" inflation include:

Inflaton field ϕ with $V(\phi)$ that has

- $\epsilon \equiv M_P^2 \left(\frac{V'}{V}\right)^2 \ll 1$

This means flat pot'l, like $\Lambda \Rightarrow a \sim e^{Ht}$ ✓

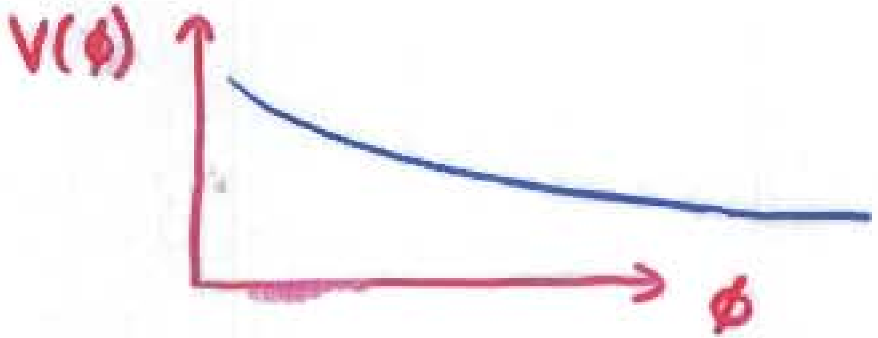
Here, H is fixed by

$$M_P^2 H^2 \sim V(\phi)\big|_{\text{inflation}}$$

- Also want

$$\eta = M_P^2 \frac{V''}{V} \ll 1$$

so inflation (flat V) lasts long enough as ϕ rolls



Over the range where ϵ, η small as ϕ rolls, you inflate $\Rightarrow$

$$N_e \sim \frac{1}{M_P^2} \int \frac{V}{V'} \, d\phi \quad \text{e-folds}$$

In typical models, you <u>want</u>:

- $N_e \gtrsim 60$
- $\eta \leq .01$, ϵ smaller

  (very simple models, $\eta \sim 1/N_e$)

Finally, observed $\frac{\delta\rho}{\rho}$ can arise from fluctuations of ϕ as it slow rolls →

$$\frac{\delta\rho}{\rho} \sim \frac{1}{M_p^3} \frac{V^{3/2}}{V'} \sim 2 \times 10^{-5}$$

So a good inflationary theory should:

i) Explain what ϕ is and why $V(\phi)$ is so flat

ii) Explain how inflation ends, and the quarks & leptons get reheated

iii) Explain where $\frac{\delta\rho}{\rho}$ comes from

Typical inflationary models have had

$$H_{inf} \lesssim 10^{14}\ GeV$$

More recently, models where the various roles (inflaton, reheating field, $\frac{\delta\rho}{\rho}$, ...) are divided among >1 field are being explored (c.f. Hybrid inflation:

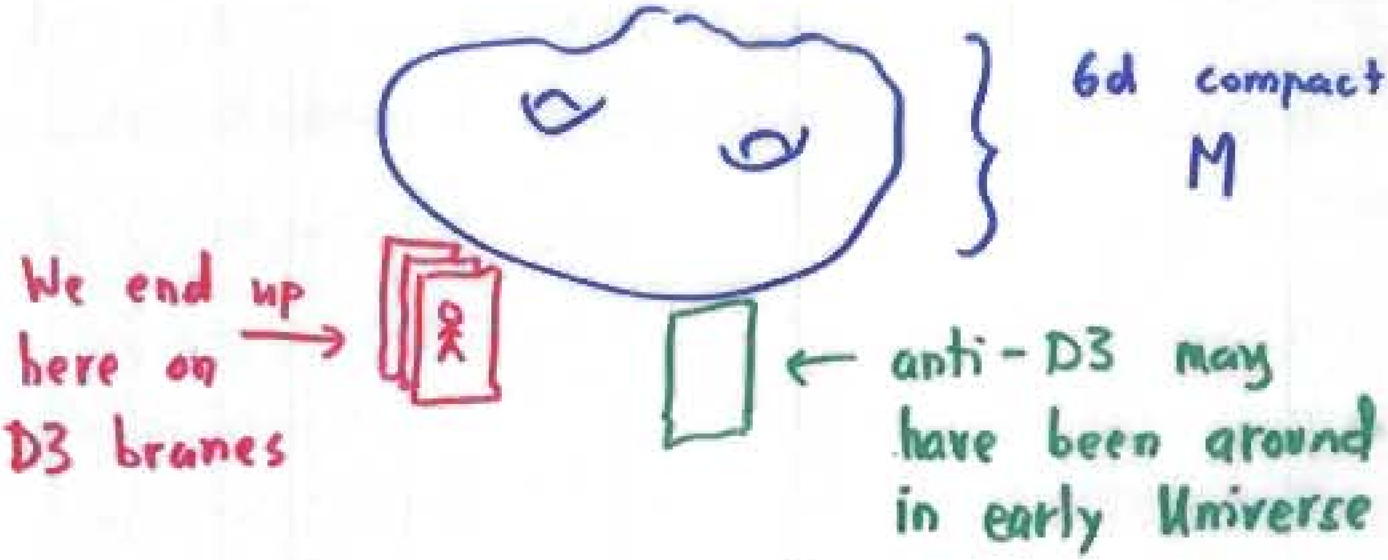
).

In the past few years, several new ideas have come out of string theory.

i) Brane inflation

We already introduced Dp branes earlier.

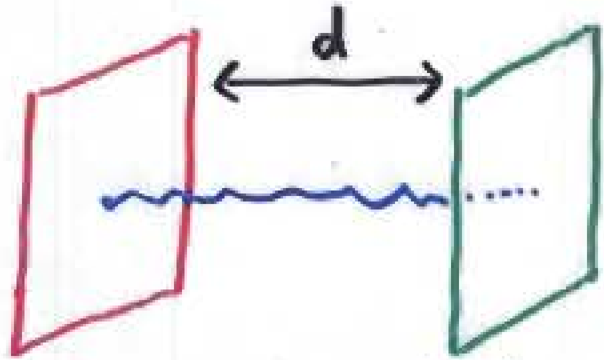
Now, imagine: Dvali, Tye



Just like an $e^+ e^-$ attract, the D3s and $\overline{D3}$ will attract!

- Candidate inflaton = brane separation in M

When the branes and anti-brane are close to each other, a tachyon develops:



$$m_T^2 = \left(\frac{d}{l_s^2}\right)^2 - m_s^2$$

tachyonic at $d \sim l_s$

So brane separation "d" is inflaton.

Tachyon "T" is waterfall field of hybrid inflation.

T condenses ⇒ one D3 + $\overline{D3}$ annihilate!

- At finite g_s, energy from brane tensions ⇒ closed string modes
- Other D3s left ⇒ much energy should go into their open strings ⇒ reheating!

So in such a model both

i) What is inflaton
ii) How does reheating work

} tied to physics of branes in string theory

<u>Important Caveat</u>: It is not true that "generic" branes ⊥ to M will → slow roll inflation. But in special cases one can show the brane separation <u>would</u> act as a good inflaton → consistent embedding of inflation into a full quantum gravity theory.

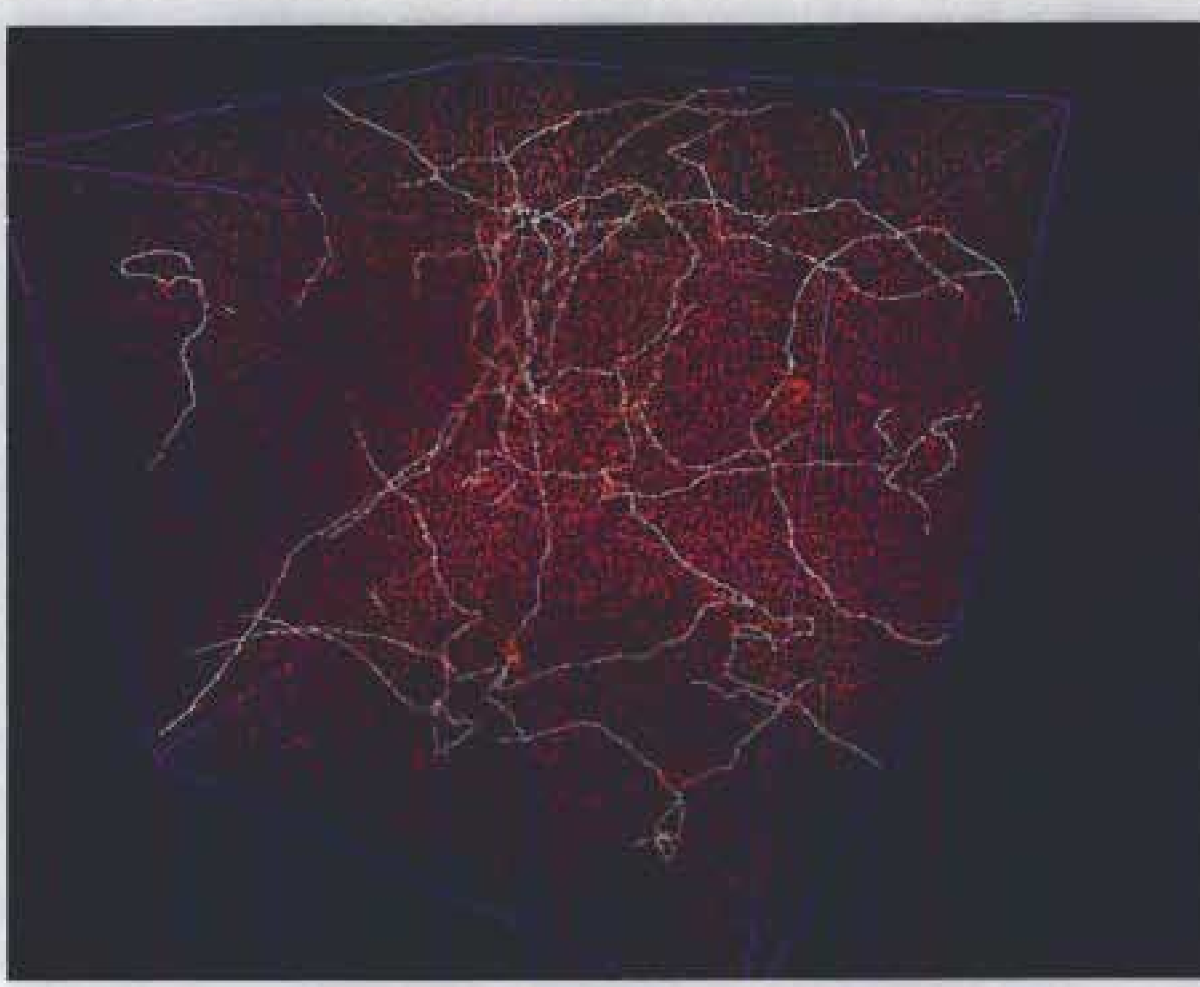
In such a theory, we would know what had banged in the Big Bang -- branes collided!

("Big bang as brane damage")

Interesting features of such models:

- Can easily get $H_{inf} \sim 10^{10}$ GeV or less → no gravitational waves from inflation will be detectable
- The complex "T" field whose condensation ends inflation, has a mexican hat potential. So by the kibble mechanism, it will produce cosmic strings (D1 branes) when it condenses, as it will slide off the top of the hat differently in distant regions.

Tye et al; Copeland Myers, Polchinski



If we let $\mu \equiv$ string tension, then cosmic strings with

$$G_N \mu \gtrsim 10^{-6}$$

are forbidden (CMB power spectrum).

However, the same reasoning that yields $H \approx 10^{10}$ GeV during inflation in these models, also says

$$G_N \mu \approx 10^{-10}$$

So as long as the string network scales w/ Hubble expansion, this is OK.

As they evolve, the strings sometimes develop cusps → strong, non-gaussian emission of gravitational waves.

Work of Damour and Vilenkin suggests that future experiments could then be sensitive to emission from cosmic strings with small $G\mu$:

LIGO I	$G\mu \gtrsim 10^{-10}$
LIGO II	$G\mu \gtrsim 10^{-11}$
LISA	$G\mu \gtrsim 10^{-13}$

If we're <u>very lucky</u> there could be a whole multiplet of strings with predictable ratios of μ.

To say the least, it would be remarkable to see fundamental or D1 strings stretched across the sky!

Conclusion

Current snapshot of string theory :

- Can accomodate Standard Model-like particle theories
- Can probably accomodate inflation of the sort we need to explain horizon, flatness, ...
- May be able to accomodate today's Λ

In studying any of these issues in depth, most striking feature is the diverse array of possibilities the theory encompasses.

Many people thinking about possible stringy signatures in cosmology, but there is no "generic" signature that is known yet.

c.f. Kaloper, Kleban, Lawrence, Shenker

Of course, there are also deep "fundamental" issues to grapple with:

- How do you <u>define</u> string theory? (AdS/CFT, matrix theory work in very simple cases...)
- How does string theory deal with spacelike singularities (Bangs/Crunches)? Shenker et al, Horowitz et al

Microphysical explanation of the Gibbons-Hawking entropy of de Sitter space? (A counting exists for the dS flux vacua). Silverstein

⋮

Deeper understanding here may help us in dealing with the more immediate questions.