Title: Cosmology and particle physics of flux compactifications

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Abstract:

1

Introduction

In the next few years, we have high hopes of learning a great deal more about two subjects that tie deeply into microphysics:

1. Particle physics @ the TeV scale
LHC, dark matter searches, ...

2. Inflationary cosmology
WMAP yrs > 1, Planck, ...

I will talk about how recent advances in string theory may help us build models to confront the lessons from 1, 2.

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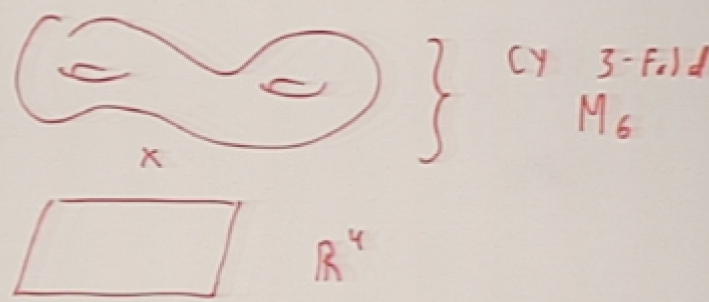
Flux Stabilization

A very well studied set of string models arises from Calabi-Yau compactification from $10d \to 4d$:



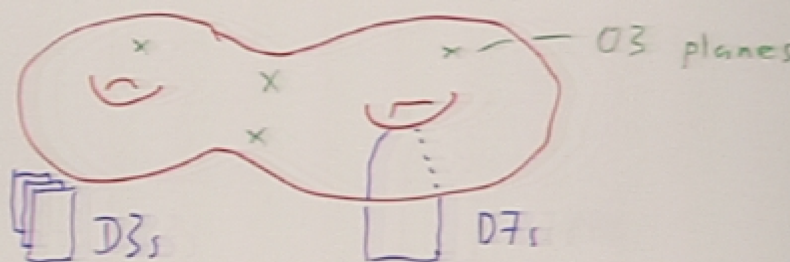
- $\to$ 4d $\mathcal{N}=1$ SUSY in heterotic string (when supplemented by choice of $E_8 \times E_8$ gauge bundles)

- $\to$ 4d $\mathcal{N}=2$ SUSY in IIA / IIB strings

$\mathcal{N}=2$ is of no "real world" interest $\to$

③

in type II, break to $\mathcal{N}=1$ by "orientifolding" (adding space-filling D-branes and O-planes) :



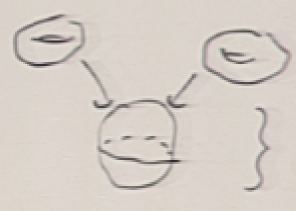
- $\mathcal{N}=1$ gauge theories arise on the branes, from open string sectors.

NOTE : In IIB, this data of a CY n-fold + branes is well summarized by an auxiliary CY (n+1)-fold which is elliptically fibered $\leftrightarrow$ F-theory. Roughly speaking, the branes source variation of the IIB axio-dilaton

④

$$\tau = C_0 + \frac{i}{g_s}$$ Vafa

But τ (by S-duality) lives in UHP / $SL(2,\mathbb{Z})$; so can replace τ by an auxiliary torus whose cplx structure captures dilaton variation :



} varying T^2 fiber

} base n-fold in F-theory

All such constructions come, at leading order, with numerous "moduli fields" -- $\mathcal{N}=1$ chiral multiplets ϕ_i with

$$V(\langle\phi_i\rangle) = 0 \quad \forall \langle\phi_i\rangle$$

(e.g. dilaton, kähler + complex str moduli of M_6, and brane motions).

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There are tens of thousands of known such Calabi-Yau moduli spaces.

Moduli are a problem for making contact with 1) + 2):

- In particle theory models, clearly we want $\cancel{SUSY}$ $\Rightarrow$ moduli must be fixed with $\langle F_\phi \rangle \neq 0$ for some ϕ. (5^{th} force bounds, cosmological moduli problem $\rightarrow$ "large" M_ϕ: good).
- In inflationary scenarios arising from compactification of 10d string theory on M_6 of radius R:

$$\int d^{10}x \sqrt{g_{10}}\, R_{10} + \cdots \qquad \Rightarrow$$

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$$\int d^4x \sqrt{g_4}\, R_4 + \frac{1}{R^{12}} V_{eff}(\phi_i)$$

steep $\frac{1}{(Vol)^2}$ comes from Weyl rescaling to Einstein frame

- Energy sources from reduction on M_6 cannot grow faster than R^6 $\Rightarrow$

$$\boxed{V \sim \frac{1}{R^6} \text{ or steeper, at large } R}$$

So any potential inflationary energy source $\Rightarrow$ decompactification unless the Kähler moduli are stabilized. Very similar argument $\rightarrow$ must fix dilaton or $g_s \rightarrow 0$ instead of inflation.

⑦

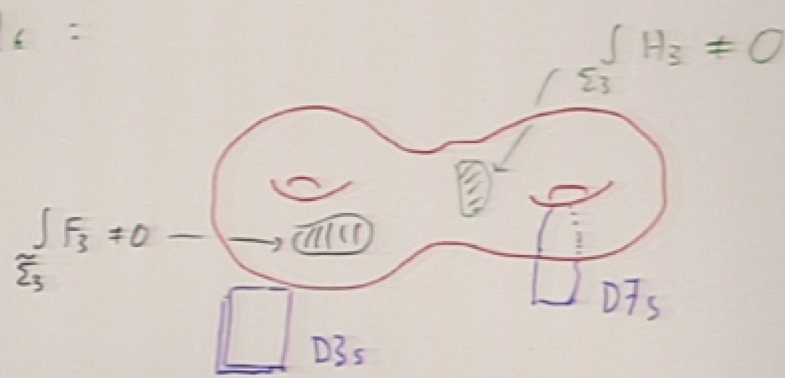
Happily, in the last few years, we have started to get control over moduli stabilization and ~~SUSY~~ in some circumstances.

E.g. KKLT construction

IIB theory has two p-form field strengths

$$H_3 = dB_2 \qquad F_3 = dC_2$$

→ can consider their fluxes threading M_6 :



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This results in an energy cost (c.f. $\frac{1}{8\pi}\int |\vec{E}|^2 + |\vec{B}|^2$ in Maxwell theory) $\rightarrow$ the 4d $\mathcal{N}=1$ theory develops a moduli-dependent superpotential:

$$W = \int_{M_6} (F_3 - \tau H_3) \wedge \Omega \qquad \text{GVW}$$

Generic choices of $F, H \Rightarrow$

- stabilize complex structure of M_6

  masses $\sim \alpha'/R^3$

- Stabilize axio-dilaton τ

  GKP

- "No-scale" SUGRA $\rightarrow$ accomplish this with $V=0$ at leading order.

Still, W is independent of overall volume $\Rightarrow$ effective theory of light moduli

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has volume modulus ρ with :

$$K = -3 \ln [-i(\rho - \bar{\rho})] + \alpha' \text{ corr}$$

$$W = W_0 \leftarrow \text{constant};$$

$$\int (F - \tau H) \wedge \Omega \,\Big|_{\text{minimum}}$$

Witten '96 $\Rightarrow$ W acquires ρ dep. in exponentially small (instanton or gaugino condensate) terms, in models with divisors of appropriate topology :

$$W = W_0 + A\, e^{-b\rho} + \cdots$$

- Small $W_0 \Rightarrow \exists$ SUSY vacuum for $\rho > 1$ ("self-consistent")
- ρ mass can be $\gg 10^{-3}$ eV (moduli mass bound from 5th forces)

⑩

∃ many ways to add $\cancel{\text{SUSY}}$:

Dynamics at end of warped throat (→ low $\cancel{\text{SUSY}}$ scale Λ)

GKP

SK, Pearson Verlinde

· F-terms for complex moduli or dilaton (must tune to get small)

Saltman, Silverstein; Denef, Douglas

· Some new ideas I'll describe shortly (Florea, SK, Surcek ...).

Note that the small value of Λ

$$V = e^{K}\left(\sum_{i,j} D_{\phi_i} W \, g^{i\bar{j}} D_{\bar{\phi}_j} \overline{W} - 3\frac{|W|^2}{M_P^2}\right) + \cdots$$

results only by tuning constant W_0 against $\cancel{\text{SUSY}}$ F or D terms.

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KKLT
Douglas
[illegible]f

- The fact that one <u>can</u> tune microphysics to get $g_s \ll 1$, W_0 small is due to large # flux vacua.

- Note that the small W_0 tune is one that is <u>always</u> performed in realistic $\mathcal{N}=1$ sugra models <u>anyway</u>:

- TeV scale sparticles $\rightarrow \langle F \rangle < 10^{11}$ GeV
- But $|F|^2 - 3\frac{|W|^2}{M_P^2} \cong 0 \Rightarrow$

$W|_{vac} = W_0$ <u>must be small</u>.

Here, that same tune helps to achieve controlled moduli stabilization.

$\exists$ many similar constructions in other strings, e.g. in IIA fluxes alone can classically stabilize all moduli

DeWolfe et al
Zwirner et al
Ibanez...

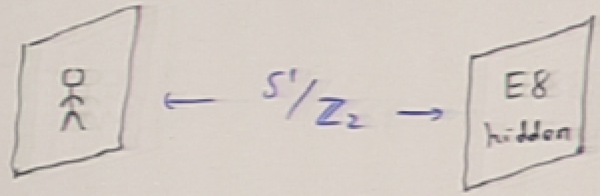
I'll use the IIB picture in discussing contact w/ particle physics + inflation.

Models of Particle Theory

Let's pretend the world is well described by a SUSY SO(10) GUT. Fits well with hierarchy stabilization, and gauge coupling unification.

How to engineer such models with SUSY built in? (I'll talk very heuristically about work in progress w/ Florea, Svrcek).

Traditional approach :



Horava-Witten

- Heterotic string easily → GUTs
- Tune size of 5th dim → gauge/gravity unification
- ~~SUSY~~ in hidden E_8

Standard approach in literature was (c.f. Kaplunovsky / Louis) to just <u>assume</u> modulus F-term + derive soft SUSY breaking that results. Here, we'll :

- provide microscopic underpinning
- Try to improve mechanism (it has flavor problems, usually)

We'll work in F-theory picture :

- F-theory on K3 fibration over surface B ≈ Heterotic on elliptic 3-fold over B

Friedman, Morgan, Witten worked out many aspects of the dictionary.
(Slogan: E8 walls ⟷ D7 stacks)

Happily, it is the heterotic models on elliptic 3-folds that have been intensely studied by Donagi/Ovrut/Pantev ... ; using "spectral cover construction," they can make pseudo-realistic GUTs.
Via FMW, we can map these to IIB.

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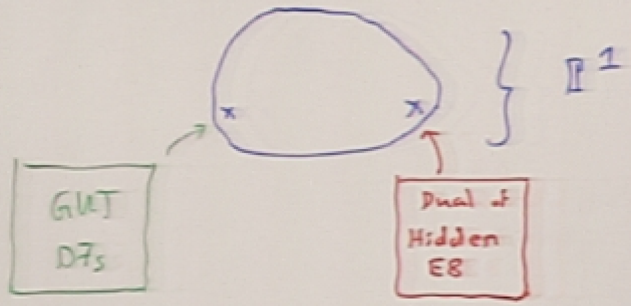
- Assume KKLT stabilization of the F-theory model $\Rightarrow$ IIB picture:



- All closed string moduli fixed at "high scale" (heterotic dual $\leftrightarrow$ non Kähler mess)
- ~~SUSY~~ ?

Easy solution: PUT DSB gauge theory in Hidden E8.

Can explicitly make models of

- SO(10) with 1 $\underline{16}$
- SU(5) with 1 $\underline{\bar{5}} + \underline{10}$

in hidden sector

in addition to the observable GUT.

These theories break SUSY at their dynamical scale Λ_H, by an old argument of Affleck - Dine - Seiberg :

- No flat directions at tree level
- $\exists$ global + R-symmetries ; 't Hooft anomaly matching → no plausible spectra for confining pion Lagrangian
- So, global symmetries must be spontaneously broken by dynamics. But, this → Goldstone bosons ; SUSY unbroken → must "complexify" Goldstones !?

But no flat dirs → this isn't possible → must have $\cancel{\text{SUSY}}$ at Λ_H !

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More direct arguments (Murayama, ...) of 90s provide strong support for this picture.

- So, hidden sector breaks SUSY at (exponentially small) Λ_H. In string theory Λ_H is field-dependent; but moduli fixed at high scale (compared to Λ_H^2/M_P) → no runaway problem!

- The KKLT "small W_0" tune can (in suitable models) then be related to the tune required to get

$$\boxed{|F|^2 \sim \Lambda_H^4 = 3\frac{|W|^2}{M_P^2}}$$

Problem:

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In this picture:

the $\mathbb{P}^1$ must be "big" to have control ($> l_s$) $\Rightarrow$ leading SUSY is communicated to us via "gravity mediation." This name is misleading; what it has always meant (in string theory) is "via dim 6 operators in Kähler pot." E.g. if $\langle F_X \rangle = \Lambda_H^2$ and Q_i are the quark superfields

$$\mathcal{L}_{eff} \supset \cdots + \int d^4\theta \, \frac{1}{M_P^2} \, c_i \, X^\dagger X \, Q_i^\dagger Q_i$$

$$\Rightarrow (m^2_{squark})_i \sim c_i \, \Lambda_H^4 / M_P^2$$

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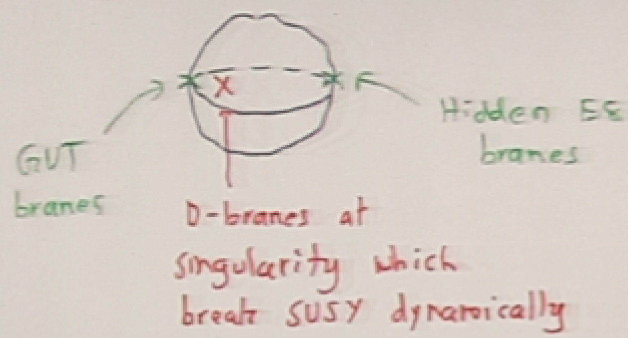
This is a disaster because c_i are generally distinct $\mathcal{O}(1)$ #s $\rightarrow$ no squark degeneracy $\rightarrow$ killed by FCNCs.

The problem's essence was emphasized by Hall, Kostelecky + Raby '86 -- gravity mediation is sensitive to M_P physics, and whatever physics determines flavor in M_c, gravity mediation can see it.

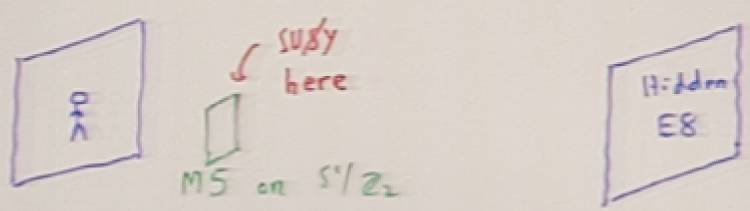
Most obvious fix: "Gauge mediation" Dine, Nelson, ...

Use "messenger fields" with mass $\ll M_{GUT}$, charged under SM, to transmit SUSY splittings to MSSM. (can't use the two E_8 walls (or their duals); instead:



- Examples of such local $\cancel{\text{SUSY}}$ brane models have been developed recently by Berenstein et al, Hanany et al
- $(D7)_{GUT} - (D3)_{\cancel{SUSY}}$ strings are the messengers.

Such models will $\Rightarrow$ gauge mediation in string theory w/o flavor problems of "hidden E8" breaking. Their heterotic dual:



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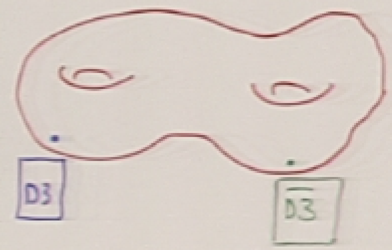
<u>Inflation in String Theory</u>

The simplest idea, once you have a stabilized compactification, is to add some module that inflates: e.g. brane inflation.



Dvali, Tye; Burgess et al; ...

D3 - $\overline{D3}$ pair can attract via Coulomb interaction; inflation ends via the celebrated 3-$\overline{3}$ tachyon condensation (Sen, ...).

In terms of canonically normalized "brane separation field" ϕ:

$$V(\phi) = 2T_{D3}\left[1 - \frac{1}{2\pi^3}\frac{T_{D3}^{3}}{M_{10}^{8}\,\phi^4}\right] + \cdots$$

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Some issues: (well known)

- Inflationary slow-roll parameters

$$\epsilon = \frac{M_P^2}{2} \left(\frac{V'}{V}\right)^2$$

$$\eta = M_P^2 \left(\frac{V''}{V}\right)$$

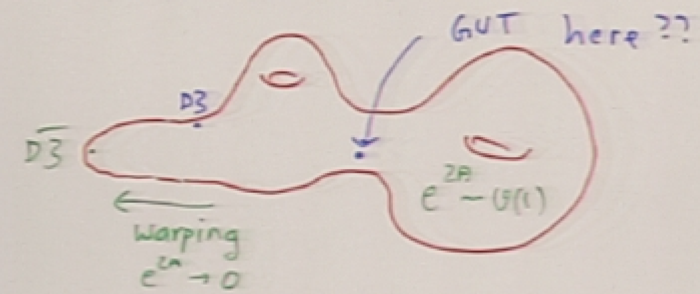
$\rightarrow$ in terms of interbrane distance "r" and CY radius R

$$\eta \sim O(1) \cdot \left(\frac{R}{r}\right)^6$$

But, can't separate by $r \gg R$ in a compact space of size R! (Anisotropy could help, but turns out not to).

- Scale of V is a bit high for parameters (R, g_s) of vanilla GUT models ...

Naively, both of these issues can be resolved by introducing a warped geometry ala Randall-Sundrum:



$$ds_{10}^2 = e^{2A}(y)\, \eta_{\mu\nu}\, dx^\mu dx^\nu + e^{-2A(y)}\, \tilde{g}_{mn}(y)\, dy^m dy^n$$

- Then, mass of D3 warped down $\rightarrow$ attraction is less $\Rightarrow$ slower roll
- Scale of V ~ D3 tension is also reduced; can keep "vanilla" scales out in bulk of CY.

IIB Calabi-Yau models with flux can easily → such warped throats (Giddings, SK, Polchinski following Klebanov, Strassler) and by now such models have been well studied as candidates for inflation (KKLMMT, ...).

- η - problem <u>does</u> generically arise; need for at least $1/N_e$ tuning
- Re-heating SM <u>can</u> be problematic

Kofman, Yi; Burgess, Cline; Shiu... Frey et al

- Possible <u>striking</u> signatures: (may also arise in other braney models)

i) Cosmic Superstrings

$D-\bar{D}$ annihilation proceeds via

Tye, ... ; Copeland Myers Polchinski; Dvali; ...

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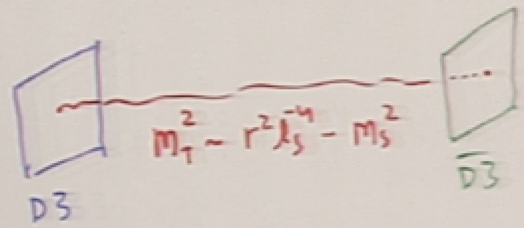
condensation of a <u>complex</u> "tachyon"

field T when $r < l_s$:



Mexican hat potential for T

$$V \sim (|T|^2 - v^2)^2$$

$\Rightarrow \quad \pi_1$ (vacuum manifold) $\approx \mathbb{Z}$

So Kibble mechanism $\Rightarrow$ expect cosmic string production (maybe correlation length is so small that get overproduction? Cline et al)

These are IIB D-strings or, more generally, (p,q) strings.

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Cosmic strings are generally believed to enter a "scaling solution" where

$$\frac{\Omega_{string}}{\Omega_{dominant}} \sim \text{const.}$$

during radiation / matter domination. The ratio is fixed by $G_N \cdot \mu_{string}$, and data $\Rightarrow$

$$G\mu \leq 10^{-7}$$

But, many classes of models of brane inflation (e.g. KKLMMT) $\Rightarrow$

$$10^{-12} \leq G\mu \leq 10^{-7}$$

Firouzjahi; Tye

The stability of the strings is highly model dependent; but strings in this $G\mu$ range are visible via $\begin{cases} \text{Lensing} \\ \text{Gravity waves} \end{cases}$

$\uparrow$ Damour Vilenkin

$\Rightarrow$ we may get lucky!

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Damour Vilenkin

(27)

In the most optimistic scenario, ther could be visible <u>networks</u> of (p,q) strings.

ii) Non-Gaussianity of CMB fluctuations

Normally, to get measurable Non-Gaussian signature in inflationary fluctuations, one needs either :

- fluctuations don't arise from inflaton (curvaton or modulated reheating) Dvali et al, Kofman --
- Higher derivative terms matter :

$$\mathcal{L} = \mathcal{L}_{inf}(\phi) + \frac{1}{M^4}(\nabla\phi)^4 + \cdots$$ Creminelli ...

It's been difficult to see how conventional models of 2nd type can be "natural".

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Recent idea: Relativistic branes in throat (Silverstein, Tong)

The DBI action which governs D-branes:

$$S \sim T_3 \int d^4x \sqrt{-g} \left[1 - (\nabla_\mu \phi)^2 \right]^{1/2}$$

(generalizing $\sqrt{1-\dot{x}^2}$ of relativistic particle).

So in a regime where accelerations are small, $\exists$ a reliable expansion

$$\mathcal{L} \sim \frac{1}{2}(\partial\phi)^2 - V(\phi) + \sum \underset{\substack{\uparrow \\ \text{Calculable}}}{C_n} (\partial\phi)^{2n}$$

Based on this $\mathcal{L}$, expanding DBI in appropriate "throats," Alishahiha, Silverstein & Tong find non slow roll but inflating models with "$f_{NL} \gg 1$".

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[Really the shape of 3-pt function has much more data, cf Babich et al].

So at least some stringy models make striking predictions for the ESA Planck satellite ...

In general given richness of 3 pt function (if visible), I think more effort should be expended filling out space of models with measurable Non-Gaussianity ...

Gravity waves from inflation

A well known argument (Lyth '96) says

$r \equiv$ tensor to scalar ratio $\gtrsim .07 \Rightarrow$

(29a)

Super Planckian inflationary model :

$\Delta\phi > M_P$ during our 60 e-folds

This is not obviously possible in quantum gravity. Canonical example is

$$V = \frac{1}{2} m^2 \phi^2 \qquad \text{"chaotic inflation"}$$

$$\Delta\phi \approx 15\ M_P \rightarrow N_e \approx 60$$

BUT : How to forbid

$$\delta V = \sum_n C_n \frac{\phi^{n+4}}{M_P{}^n}$$

at a level sufficient to keep V flat over $\Delta\phi \gg M_P$?

Natural inflation (Freese et al) $\rightarrow$

can accomplish w/ axions "a" with

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29b

<u>Problem</u> : Achieving $f > M_P$ for any single axion partner of a Kähler or dilaton mode in string theory, may be impossible.

<u>BUT</u> : Combining natural inflation with idea of "assisted inflation" (Liddle et al)

$\Longrightarrow$

<u>Can</u> seemingly obtain models of Super Planckian inflation with observable "r" in string theory, through collective motion of many axions arising in Calabi-Yau models

Dimopoulos
SK
McGreevy
Wacker

The crucial points in arguing that such models can exist are:

- N indep shift symmetries for $a_i \rightarrow$

$$V = \sum_i V(a_i)$$

} each field feels Hubble friction from N others

to good enough approximation $\rightarrow$

ϵ, η die like $\frac{1}{N}$

- Axions descend from gauge symmetries of string $B_{\mu\nu} \rightarrow$ no large symmetry breaking by "small black holes"

- N-dependent "species" corrections are computable and seem sufficiently small to allow working models.

At any rate, observable "r" would certainly vastly narrow {UV reasonable models}.

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Conclusion

The recent advances which strongly suggest existence of a "landscape" of string vacua, also $\Rightarrow$ promising avenues for constructing:

- GUTs with detailed SUSY dynamics
- Acceptable inflationary models

Of course $\exists$ much room for improvement in both our technical, and more importantly, our conceptual understanding of the landscape (eternal inflation? anthropics?? Vacuum selection principles???)