Cosmological Moduli, Dark Matter, and Possible Implications for the LHC

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Based on work with:

**Berkeley:** Piyush Kumar
**Columbia:** Brian Greene, Simon Jude, Janna Levin, Amanda Weltman
**Davis:** Nemanja Kaloper
**McGill:** Robert Brandenberger
**Michigan:** Sera Cremonini and Konstantin Bobkov, Gordon Kane, Jing Shao
**Trieste / CERN:** Bobby Acharya
Standard Model Landscape

Higgs Moduli Space (VEVs) $\mathbb{R}^1$

$\langle h \rangle$

$246 \text{ GeV}$

$\infty$ $\cdots$ $\infty$

$\infty$ $\cdots$ $\infty$
Kaluza-Klein Landscape

\[ R \equiv \sqrt{G_{55}} \rightarrow \phi \]

\[ \psi(\vec{x}, y) = \sum_n \psi_n(\vec{x}) e^{iny/R} \]

Radion Moduli Space \( \mathbb{R}^1 \)
Field Theory Moduli Spaces

Observations and Puzzles

• (Uncountably) Infinite number of vacua
• Small masses / weak couplings?
• High level of symmetry (not just a bunch of U(1)'s)?
• Cosmological Constant -- Anthropic needed?

\((10^{-3} \text{ eV})^4\)
Can knowledge of UV Completion address these issues?

aka: String Theory
String Moduli Spaces

- Couplings and masses are derived quantities

\[ G_N = \frac{g_s^2}{M_s^2 V_6} \]

\[ g_s \sim e^{\langle \phi \rangle} \quad V_6^{1/6} \sim e^{\langle \psi \rangle} \]

\[ \alpha_{GUT} = \frac{g_s^2}{V_6} \]

- Observation --> \[ G_N = (6.674280.00067) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}. \]

Hope for finite moduli space OR an explanation

Vafa Conjecture = always finite volume
Standard Model Landscape

Moduli Space (VEVs) $\mathbb{R}^1$

$-\infty \quad \text{?} \quad \infty$

$\langle \phi \rangle$
Standard Model Landscape

Moduli Space (VEVs) \( \mathbb{R}^1 \) ?

Finite \( \langle \phi \rangle \) Finite
String

Standard Model Landscape

Moduli Space (VEVs) $\mathbb{R}^1$

Finite $\quad ?

$\langle \phi \rangle$

Turn on Flux

$\int_X F_p = \mathbb{Z} \quad \rightarrow \quad$ Discretum
String

Standard Model Landscape

Moduli Space (VEVs) $\mathbb{R}^1$ ? $\mathbb{R}^1$

Turn on Flux

$\int_X F_p = \mathbb{Z}$ → Discretum

Dualities

$\langle \phi \rangle \leftrightarrow \frac{1}{\langle \phi \rangle}$
String

Standard Model Landscape

Moduli Space (VEVs) \( \mathbb{R}^1 \)

Turn on Flux

\[
\int_X F_p = \mathbb{Z}
\]

Discretum

Dualities

\[
\langle \phi \rangle \leftrightarrow \frac{1}{\langle \langle \phi \rangle \rangle}
\]

Points of Enhanced Symmetry

Finite \( \langle \phi \rangle \)
String Theory on a Circle

\[ R \equiv \sqrt{G_{55}} \rightarrow \phi \]

\[ A_{\mu}^{R/L} = G_{\mu 5} \pm B_{\mu 5} \]

\[ \leftarrow 2R \rightarrow \]
String Theory on a Circle

\[ R \equiv \sqrt{G_{55}} \rightarrow \phi \]

\[ A_{\mu}^{R/L} = G_{\mu 5} \pm B_{\mu 5} \]

Additional Massive States

\[ m_\chi^2 = M_s^2 \left( \omega^2 R^2 - 4 \right) \]
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Additional Massive States

\[ m^2_\chi = M_s^2 (\omega^2 R^2 - 4) \]

Enhanced Symmetry

\[ R \rightarrow 1 = M_s^{-1} \quad \omega = \pm 2 \quad m_\chi \rightarrow 0 \]
\[ U(1) \rightarrow SU(2) \]
Moduli Trapping at Enhanced Symmetry Points (ESPs)

S.W. hep-th/0404177, Kofman, et al. hep-th/0403001

Motion on Moduli Space

\[ \varphi \rightarrow \varphi(t) \]
\[ m_\chi = g\phi(t) \]

\[ \langle \varphi \rangle = 0 \]
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Adiabaticity fails when,

\[ \frac{\dot{m}_\chi}{m_\chi^2} \sim \mathcal{O}(1) \]
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Motion on Moduli Space

\[ \varphi \rightarrow \varphi(t) \]
\[ m_{\chi} = g\phi(t) \]

Adiabaticity fails when,

\[ \frac{m_{\chi}}{m_{\chi}^2} \sim O(1) \]

\( (\varphi_0, \chi_0) \)
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Motion on Moduli Space

\( \varphi \rightarrow \varphi(t) \)

\( m_\chi = g\phi(t) \)

Adiabaticity fails when,

\[
\frac{\dot{m}_\chi}{m_\chi^2} \sim \mathcal{O}(1)
\]

Near ESP modes become excited

-Particle production-

\[
n_k \approx \exp \left( -\frac{\pi k^2}{g\nu_0} \right)
\]
Moduli Trapping at Enhanced Symmetry Points (ESPs)

S.W. hep-th/0404177, Kofman, et. al. hep-th/0403001

Backreaction and Trapping

\[ V_{\text{eff}} = \frac{1}{2} g^2 \chi^2 \varphi(t)^2 \]

\[ \langle \chi^2 \rangle = \frac{\rho \chi}{\omega^2} = \frac{\rho \chi}{g^2 \varphi^2} \]

Constant Force of Attraction

\[ \ddot{\varphi} + 3H \dot{\varphi} = -gn_\chi \frac{\varphi}{|\varphi|} \]
Moduli Trapping

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Studies of Moduli Dynamics

Toroidal Compactifications:
- S.W. hep-th/0404177
  Related ideas -- “String Gas Cosmology”:

Conifold:
- Mohaupts & Saueressig hep-th/0410272 & hep-th/0410273
- Greene, Judes, Levin, S. W., Weltman hep-th/0702220

Brane positions:
- Kofman, Linde, Liu, Maloney, McAllister, Silverstein hep-th/0403001
- Silverstein-Tong hep-th/0310221

M-theory:
- Cremonini & S.W. hep-th/0601082

ISS and Finite Temperature:
- Craig, Fox, and Wacker hep-th/0611006

Conclusion: Moduli Trapping is generic property of moduli spaces w/ UV completion including gravity
Do we expect to encounter an ESP?
Ergodic (“Chaotic”) Motion and Vacuum Sampling

Motion on moduli space

$$G_{i,j}(\varphi) \partial_\mu \varphi^i \partial^\mu \varphi^j$$
Ergodic ("Chaotic") Motion and Vacuum Sampling

Motion on moduli space

\[ G_{i,j}(\varphi) \partial_\mu \varphi^i \partial^\mu \varphi^j \]

Poincare Surface of Sections

Ergodic Motion
Classical Moduli Dynamics
Horne & Moore  hep-th/9403058

Axio-dilaton in 4D

\[ S_4 = \frac{1}{2\kappa^2} \int d^4 x \sqrt{-g} \left( R - \frac{1}{2} \frac{\partial_\mu \tau \partial^\mu \bar{\tau}}{(\text{Im } \tau)^2} - \frac{\kappa^2}{4\pi} \text{Tr} \left[ a F \tilde{F} - \frac{1}{g_s} F^2 \right] + \ldots \right) \]

\[ \tau = a + ig_s^{-1} \]

\[ H = \frac{SL(2, \mathbb{R})}{SO(2)} \]
Axio-dilaton in 4D

\[ S_4 = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left( R - \frac{1}{2} \frac{\partial_\mu \tau \partial^{\mu} \bar{\tau}}{(Im\tau)^2} - \frac{\kappa^2}{4\pi} Tr \left[ aF\bar{F} - \frac{1}{g_s} F^2 \right] + \ldots \right) \]

\[ \tau = a + ig_s^{-1} \]

\[ H = \frac{SL(2, \mathbb{R})}{SO(2)} \]

Additional Discrete Symmetries

\[ \mathcal{M} = \frac{SL(2, \mathbb{R})}{SO(2) \times SL(2, \mathbb{Z})} \]

\[ \frac{1}{g_s} \leftrightarrow g_s \]
Classical Moduli Dynamics

\[ \text{Weak Coupling} \]

\[ \text{Im } \tau = g_s^{-1} \]

\[ \text{Re } \tau = a \]

\[ \tau \rightarrow \frac{a\tau + b}{c\tau + d} \quad \text{ad} - bc = 1 \]
Classical Moduli Dynamics

Weak Coupling

\[ \text{Im } \tau = g_s^{-1} \]

\[ \text{Re } \tau = a \]

\[ \tau \rightarrow \frac{a\tau + b}{c\tau + d} \quad ad - bc = 1 \quad \frac{1}{g_s} \rightarrow g_s \]
Classical Moduli Dynamics

Weak Coupling

\[ Im \, \tau = g_s^{-1} \]

\[ Re \, \tau = a \]

\[ \tau \rightarrow \frac{a \tau + b}{c \tau + d} \quad ad - bc = 1 \]

\[ \frac{1}{g_s} \rightarrow g_s \]
Aspects of Moduli Stabilization

- Two aspects of moduli stabilization:
  - Generate potential -- a lot of work has been done (e.g. Fluxes, gaugino condensation, instantons etc...)
  - Fix at the minimum and remain there! -- (not so much progress)
Duality fixed points are absolute extrema of effective potential for all times (protected by symmetries)

e.g. see work of Dine and Banks
Moduli trapping
--> why we begin there (initial conditions)
Moduli trapping
--> why we begin there (initial conditions)

Configurations with:
more symmetry / lighter particles are favored
The “Dilaton”

Sera Cremonini (Michigan) & S.W. hep-th/0601082 (see also work by Brustein)

- BPS techniques suggest that attractor lies outside perturbative region
- Kahler moduli typically have shift symmetry -- require non-perturbative effects
Assume “Dilaton” is stabilized at weak coupling

e.g. Gaugino Condensation
Prior to Stabilization, it is a dynamical degree of freedom...

It could dominate the energy density:
  e.g. The “Pre-Big Bang”

It could be subdominant with other energy/matter present:
  e.g. String Gas Cosmology
Early String Universe --> FRW Universe???
Dilaton gravity w/ sources

$$\dot{\phi}_s = \pm \sqrt{N H_s^2 + e^{\phi_s} \rho_s} ,$$

$$\dot{H}_s = \pm H_s \sqrt{N H_s^2 + e^{\phi_s} \rho_s} + \frac{1}{2} e^{\phi_s} (p_s + \Delta_{\phi} \mathcal{L}_m)$$
Dilaton gravity w/ sources

\[ \dot{\phi}_s = \pm \sqrt{N H_s^2 + e^{\phi_s} \rho_s} , \]
\[ \dot{H}_s = \pm H_s \sqrt{N H_s^2 + e^{\phi_s} \rho_s + \frac{1}{2} e^{\phi_s} (p_s + \Delta \phi \mathcal{L}_m)} \]

Discrete and conserved charge!!!

\[ e = N H_s^2 + e^{\phi_s} \rho_s \]
Geometric Precipices in String Cosmology

Nemanja Kaloper and S.W. arXiv:0712.1820

String Phase

(+) $H_s$

RDU Phase

(-) $H_s$

$\varphi_s'$
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\[ e = N H_s^2 + e^{\phi_s} \rho_s \]
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\[ e = N H_s^2 + e^{\phi_s} \rho_s \]

Must Violate NEC
Effect on Dark Matter / LHC
Approximate Moduli

Scalar Condensate forms

\[ \Delta \Phi \rightarrow \Delta E \]

Typically evolve like pressure-less matter

\[ \rho_m \sim \frac{1}{a^3} \quad p = 0 \]

Density grows relative to radiation

--> Danger for BBN!
 Scalars and CDM Inverse Problem

- Modified Expansion History -- larger cross-sections allowed
- Non-thermal Production -- larger cross-sections allowed
- Entropy Production can dilute existing CDM

**Modified expansion**

\[
\Omega_X = \Omega_{X}^{std} \sqrt{\frac{\rho}{\rho_r}}
\]

**Non-thermal Production**

\[
\Omega_X \sim \frac{m_X}{\langle \sigma v \rangle T_r} \sim \Omega_{X}^{std} \left( \frac{T_f}{T_r} \right)
\]
Scalars and CDM Inverse Problem

- Modified Expansion History -- larger cross-sections allowed
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Modified expansion

\[ \Omega_X = \Omega_X^sd \sqrt{\frac{\rho}{\rho_r}} \]

Non-thermal Production

\[ \Omega_X \sim \frac{m_X}{\langle \sigma v \rangle T_r} \sim \Omega_X^{\text{std}} \left( \frac{T_f}{T_r} \right) \]

All have parametric dependence on fundamental theory !!!!

G2 Result

Arxiv:0804.0863   B. Acharya, K. Bobkov, G. Kane, P. Kumar, J. Shao and S.W.

WMAP

$$\Omega_{cdm} h^2 = 0.111 \pm 0.006$$

Best case for relic density

$$\Omega_{lsp} h^2 = 0.27 \left( \frac{m_{lsp}}{100 \text{ GeV}} \right)^3 \left( \frac{3.26 \times 10^{-7} \text{ GeV}^{-2}}{\langle \sigma v \rangle} \right) \left( \frac{4}{D_X} \right)^{1/2} \left( \frac{2 m_{3/2}}{m_{X_i}} \right)^{3/2} \left( \frac{100 \text{ TeV}}{m_{3/2}} \right)^{3/2}$$

Sensitive to moduli stabilization and underlying geometry
Given larger cross-sections:
Can we detect decays in the galactic halo today?
Wino-like Neutralinos - Positron Excess

Could excess be due to annihilating dark matter?

Bino-like requires large “boost” factor

$$\text{Flux} \sim \langle \sigma v \rangle \times \left( \frac{\rho_{\chi}^{\text{halo}}}{m_\chi} \right)^2$$

Wino leading decay channel:

$$\chi + \chi \rightarrow W + W \rightarrow e^+ + X$$
Positron Excess -- Annihilating Dark Matter?

![Graph showing positron excess vs energy](image)
Positron Excess -- Annihilating Dark Matter?

Pamela data on the way...?
Summary

• Early universe / high energy -- landscape is sampled in finite time

• Vacua with higher symmetry are attractors

• Dynamics suggest slightly broken symmetries and light masses are possible (stabilize near ESPs)

• Many vacua ruled out by their origin (branch) and *dis*connection with our late time universe (Precipices of the Landscape)

• Not enough to find a vacuum, we must now how we cosmologically evolved here

• Not too early to think about experiment -- hints -- inflation / dark matter?
String Landscape?