The Cosmological Moduli Problem (revisited)

Scott Watson
Syracuse University

Reevaluating the Cosmological Origin of Dark Matter.
e-Print: arXiv:0912.3003

Acknowledgements:
Bobby Acharya, Konstantin Bobkov, Dan Feldman, Phill Grajek, Gordy Kane, Piyush Kumar, Aaron Pierce, Dan Phalen, Jing Shao
Conclusions

Non-thermal cosmology provides a viable alternative to the well motivated thermal scenario.

Unlike the thermal case, a non-thermal history would imply a direct connection to fundamental theory and an observational window on the properties of the early universe.

Working directly with fundamental theories non-thermal models can lead to predictions which are falsifiable in current and near term experiments.
Non-thermal Cosmologies

The idea of a non-thermal history is not new. Many phenomenological based “toy models” exist in the literature.

- Anomaly Mediated SUSY breaking
- Affleck-Dine condensates / Baryogenesis
- Wimpzillas
- Q-balls
- Many more....

Can these ideas be realized within fundamental theory?
Non-thermal Cosmologies

Establishing the likelihood of a non-thermal cosmology is important for a number of reasons:

- It may alter the origin and expected properties of dark matter
- It may result in new benchmarks for discovery at LHC
- It may provide a window of opportunity for probing the early universe and fundamental theory (much like inflation)
Cosmic History
Precision Cosmology

Cosmic Energy Budget Today

- Dark Energy 72%
- Dark Matter 23%
- Baryons 5%
- Early universe remarkably homogeneous
- Very small density contrast (1:100,000) at time of decoupling of CMB

All suggest physics beyond the standard model.
Thermal Microscopic History

Dark Matter Abundance from Thermal Production

\[ \Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left( \frac{10^{-26} \text{cm}^3 \cdot s^{-1}}{\langle \sigma v \rangle} \right) \]

Dark Matter WIMPs?
Thermal Microscopic History

Dark Matter Abundance from Thermal Production

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- Cosmological Measurement
- Weak Scale Physics

Dark Matter WIMPs?
Are things so simple?
**Thermal Microscopic History**

**Dark Matter Abundance from Thermal Production**

\[ \Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left( \frac{10^{-26} \text{cm}^3 \cdot s^{-1}}{\langle \sigma v \rangle} \right) \]

*Assumed thermal equilibrium was reached*
*Assumed radiation dominated universe at freeze-out*
*Assumed no entropy production after freeze-out*
*Assumed no other sources of cdm (e.g. late decays)*
Microscopic History

- Inflation
- QCD Phase Transition
- Dynamical Symmetry Breaking (e.g. SUSY)
- Higgs / Strongly coupled dynamics?
- EWSB Phase Transition
- Dark Matter WIMPs
- BBN
- QCD Phase Transition
- CMB
LightScalars in the Early Universe

Light scalars are a generic prediction of physics beyond the standard model

- Some have a geometric interpretation (e.g. extra dimensions), others are scalar partners of standard model fermions (SUSY)

- Low energy parameters become dynamical fields in early universe

  \[ \langle h \rangle \rightarrow h(t, \vec{x}) \quad \text{and} \quad m, g \rightarrow m(h), g(h) \]

- Many of these fields pass through cosmological phases where they have little or no potential: “Approximate Moduli”
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 \]
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 + V_{soft} \]
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}} \varphi^{4+2n} \]
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}} \varphi^{4+2n} + V_{SUGRA} \]
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}} \varphi^{4+2n} + V_{SUGRA} + V_{np} \]
Approximate Moduli

Moduli Potential

$$V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}} \varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal}$$
Approximate Moduli

Moduli Potential

\[ V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}} \varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal} \]

Example:

\[ V(T, H, \varphi) = 0 + m_{soft}^2 \varphi^2 - H^2 \varphi^2 + \frac{1}{M^{2n}} \varphi^{4+2n} \]

\[ \langle \varphi \rangle \sim M \left( \frac{H}{M} \right)^{\frac{1}{n+1}} \quad H \gg m_{3/2} \sim \text{TeV} \]

\[ \langle \varphi \rangle \approx 0 \quad H \ll M \]

\[ \Delta \Phi \rightarrow \Delta E \quad \text{Scalar Condensate} \]
Scalar Condensates

Scalar Condensate forms

$\Delta \Phi \to \Delta E$

Coherent Oscillations

$V(\Phi) \sim \Phi^\gamma$, \quad $p = \left( \frac{2\gamma}{2 + \gamma} - 1 \right) \rho$.

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$p$</th>
<th>Notes</th>
</tr>
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<tr>
<td>0</td>
<td>$p = -\rho$,</td>
<td>$\Lambda$</td>
</tr>
<tr>
<td>1</td>
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<td>tadpole</td>
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<td>$p = 0$,</td>
<td>matter</td>
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<tr>
<td>4</td>
<td>$p = \frac{1}{3} \rho$,</td>
<td>radiation</td>
</tr>
<tr>
<td>$\pm \infty$</td>
<td>$p = \rho$,</td>
<td>stiff fluid</td>
</tr>
</tbody>
</table>
Cosmological Moduli Problem


Decay Gravitationally

\[ \Gamma_{\phi} \sim \frac{m_{\phi}^3}{m_p^2} \]
Cosmological Moduli Problem

Decay Gravitationally
\[ \Gamma_\varphi \sim \frac{m_\varphi^3}{m_p^2} \]

Two possibilities:

Stable
\[ m_\varphi < T eV \quad \rightarrow \quad \rho_{mod} < \rho_c \quad \rightarrow \quad m_\varphi < 10^{-26} \text{ eV} \]
Cosmological Moduli Problem


Decay Gravitationally

\[ \Gamma_\varphi \sim \frac{m_\varphi^3}{m_p^2} \]

Two possibilities:

Stable

\[ m_\varphi < T \text{eV} \quad \rightarrow \quad \rho_{mod} < \rho_c \quad \rightarrow \quad m_\varphi < 10^{-26} \text{ eV} \]

Decay

\[ m_\varphi > T \text{eV} \quad T_r > 1 \text{ MeV (BBN)} \quad \rightarrow \quad m_\varphi > 10 \text{ TeV} \]

Concern: Decay to secondaries (model dependent) --> e.g. gravitino problem
Thermal relics and the Cosmological Moduli Problem

\[ \Omega_{cdm} \sim \frac{m_x}{T} \left( \frac{H}{T^2 \langle \sigma v \rangle} \right)_{T=T_f} \]

- **Alter cosmic expansion**

- **Alter cross-section** after freeze-out
  - Phase transition (changing coupling) after freeze-out
    (Cohen, Morrissey, and Pierce - arXiv:0808.3994)

- **Non-thermal Production** (e.g. Decay of Light Scalar)
**Example: Non-thermal Production of Dark Matter**

- **Initial Radiation Phase**
  - Dark matter from direct decay
  - Entropy produced (dilute relic densities)
  - Radiation dominated universe
  - Baryons?

- **Moduli Domination begins** \( H \sim m_\phi \)

- **Standard Thermal WIMP freeze-out**

- **Moduli Decay and Reheat** \( H \sim \Gamma_\phi \)
**Example:** Non-thermal Dark Matter from Light Scalars

**Moroi and Randall -- hep-ph/9906527**

**Dark Matter from Scalar Decay:**

- Moduli generically displaced in early universe
- Energy stored in scalar condensate
  \[
  \Delta \Phi \rightarrow \Delta E
  \]
- Typically decays through gravitational coupling
  \[
  T_r \simeq \left( \frac{m_\phi}{10 \text{ TeV}} \right)^{3/2} \text{ MeV}
  \]
- Large entropy production dilutes existing dark matter of thermal origin
  \[
  \Omega_{cdm} \rightarrow \Omega_{cdm} \left( \frac{T_r}{T_f} \right)^3 \text{ Thermal abundance diluted}
  \]
Example: Dark Matter from Scalar Decay

Dark Matter will be replenished
Given $T_r < T_f$ then dark matter populated non-thermally

$$\Omega_{cdm} \sim \frac{m_x}{T} \left( \frac{H}{T^2\langle \sigma v \rangle} \right)_{T = T_f} T = T_r$$

$$\Omega_{cdm}^{NT} = 0.23 \times \left( \frac{10^{-26}\text{cm}^3/\text{s}}{\langle \sigma v \rangle} \right) \left( \frac{T_f}{T_r} \right)$$

Allowed values still imply weak-scale physics
"WIMP Miracle" survives
Are other cosmic histories possible?

Yes.
Is a non-thermal history an exotic or a robust possibility?
Guidance from Fundamental Theory

What is needed from a top-down approach:

- 4D Effective theory
- Spontaneously broken SUSY
- Explanation for how $M_{EW SB} \ll M_p$
- Small and Positive Vacuum Energy

In String theory, all these problems are related and are essentially a problem of stabilizing scalars.
What were the key ingredients?

1. “Light” Scalar
   \[ m_\phi \approx 10 \text{ TeV} \]

2. Gravitationally coupled
   \[ \Gamma_\phi \approx \frac{m_\phi^3}{M_p^2} \]

3. Stable dark matter particle
   \[ m_x \approx 100 \text{ GeV} \]
What were the key ingredients?

1. "Light" Scalar
   \[ m_\phi \approx 10 \text{ TeV} \]

Light enough for decay after freeze-out, Heavy enough to evade BBN bounds

3. Stable dark matter particle
   \[ m_x \approx 100 \text{ GeV} \]
The Cosmological Moduli Problem


“Model Independent properties and cosmological implications of the dilaton and moduli sectors of 4-d strings”
Carlos, Casas, and Quevedo -- Phys. Lett. B318, 1993

\[ V = e^{\frac{K}{m_p}} |D W|^2 - 3m_{3/2}^2 m_p^2 \]

Shift symmetry
\[ \Phi = \phi + i a \quad \rightarrow \quad W \neq W(\Phi) \]
The Cosmological Moduli Problem


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\[ V = e^{\frac{K}{m_p^2}} |DW|^2 - 3m_{3/2}^2 m_p^2 \]

Shift symmetry

\[ \Phi = \phi + ia \quad \rightarrow \quad W \neq W(\Phi) \]

Zero vacuum energy, stabilize scalar, break SUSY (spontaneously)

\[ \Delta V(\Phi) = m_{3/2}^2 m_p^2 f \left( \frac{\Phi}{m_p} \right) \]

Mismatch with UV minimum

\[ m_\phi \sim m_{3/2} \sim \text{TeV} \]
Stabilizing the String Vacuum

If scalars stabilized near points of enhanced symmetry this can prevent the formation of condensates (Dine)

Study dynamics:
- Scalars typically sample all of field space in finite time
- These points are dynamical attractors (new d.o.f.)
Stabilizing Scalars in String Theory

Include addition degrees of freedom: Gauge Fields / Branes

Most scalars will receive string scale masses and “stringy physics” will decouple from the low energy theory

\[ m_z \approx M_s \approx 10^{17} \text{ GeV} \]

However, at least one light scalar typically remains

\[ W(\phi) = W_0 + Ae^{-a\phi} \]

Nonperturbative stabilization at dS vacuum (w/ hierarchy respected)

\[ m_\phi \approx m_{3/2} \approx \text{TeV} \]
Recipe for string vacuum (IIB)

Step One:

Flux provides stabilizing potential for many of the scalars in the theory (e.g. dilaton and structure moduli)

String scale masses

\[ m_z \approx M_s \approx 10^{17} \text{ GeV} \]

At low scales most string scale physics decouples

\[ W = W_0 \]
Recipe for string vacuum (IIB)

Step One:

\[ W = W_0 \]

Want: \( m_{3/2} \approx \text{TeV} \)

\[ m_{3/2} = \frac{|W_0|}{M_p^2 V_6} \]

\[ W_0 \ll 1 \quad \text{(KKLT)} \]

or

\[ V_6 \gg 1 \]

“Large Volume”

\[ V_6 \approx 10^{14} \]
Recipe for string vacuum (IIB)

Step Two:

Some scalars naturally remain light
(Axionic shift symmetry / No scale structure)

Stabilize by non-perturbative dynamics

$$ W = W_0 + Ae^{-aX} $$

SUSY restored, Anti-deSitter Minimum

$$ V \ll 0 $$
Recipe for string vacuum (IIB)

Final Step:

Uplift (anti-brane / charged matter / string corrections) minimum to dS, **SUSY broken**

Result:

If $W_0$ appropriately tuned (exponential and discrete) to preserve hierarchy:

$$m_\phi \simeq \log \left( \frac{m_p}{m_{3/2}} \right) m_{3/2}$$
Other models with possible non-thermal contribution:

- **Large Volume Compactifications**
  e.g. Conlon and Quevedo -- arXiv:0705.3460

- **F-theory**
  Heckman, Tavanfar, and Vafa-- arXiv:0812.3155

- **M-theory on G2 manifolds**
  Acharya, et. al. -- arXiv:0804.0863

\[
W = W_0 + c_1 f(\phi)e^{-aX} + c_2 e^{-bX}
\]
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Remarks

- Many open questions:
  Embedding visible sector, uplifting, path to 4d, SUSY breaking

- Gaugino (dark matter ) has three robust patterns

- Light scalar may be robust prediction
  "A Non-thermal WIMP Miracle", Acharya, et. al. -- 0908.2430
A Non-thermal WIMP Miracle

If scalars stabilized without reintroducing electroweak hierarchy and accounting for small and positive vacuum energy this typically implies:

\[ m_\phi \approx m_{3/2} \approx \text{TeV} \quad \text{A new "WIMP" miracle} \]

- Scalar decays into Dark Matter and radiation \( \phi \rightarrow X \)

- Initial abundances diluted \( \Omega_{\text{cdm}} \rightarrow \Omega_{\text{cdm}} \left( \frac{T_r}{T_f} \right)^3 \)

- Dark Matter produced in accordance with cosmological constraint with higher cross-section

\[ \Omega_{\text{cdm}} \sim \frac{m_x}{T} \left( \frac{H}{T^2 \langle \sigma v \rangle} \right) \bigg|_{T=T_r} \]
Some Phenomenological Implications of a Non-thermal history
SUSY Model Constraints Enforcing WMAP (blue)

Ellis, et. al. 2005
SUSY Model Constraints *Without* Enforcing WMAP (blue)

\[ \tan \beta = 10, \mu > 0 \]

Gelmini, Gondolo, Soldatenko, Yaguna hep-ph/0605016
PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

\[ \Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r) \]

Microphysics    Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)

Taken alone probably not a compelling case for dark matter
Larger cross-section can address PAMELA excess

Figure by Ran Lu (grad student MCTP)
Pamela anti-protons

Figure by Ran Lu (grad student MCTP)
Fermi predictions

Figure by Ran Lu (grad student MCTP)
Photon-baryon heating during ionization from dark matter annihilation

Slatyer, Padmanabhan and Finkbeiner 0906.1197
Conclusions

Non-thermal cosmology provides a viable alternative to the well motivated thermal scenario.

Unlike the thermal case, a non-thermal history would imply a direct connection to fundamental theory and an observational window on the properties of the early universe.

Working directly with fundamental theories non-thermal models can lead to predictions which are falsifiable in current and near term experiments.
Experimental Result Leads to Excitement and Controversy
by Dennis Overbye

To the physicist, the above expression succinctly summarizes the recent surprising results coming from the Large Hadron Collider (LHC) located in Geneva, Switzerland. The equation symbolically represents the amount of dark matter in the universe, which from the initial findings of the experiment seem to fall short of expectations coming from cosmological observation.