Abstract: Within the Minimal Supersymmetric Standard Model (MSSM), LHC bounds suggest that scalar superpartner masses are far above the electroweak scale. Given a high superpartner mass, nonthermal dark matter is a viable alternative to WIMP dark matter generated via freezeout. In the presence of moduli fields nonthermal dark matter production is associated with a long matter dominated phase, modifying the spectral index and primordial tensor amplitude relative to those in a thermalized primordial universe. Nonthermal dark matter can have a higher self-interaction cross-section than its thermal counterpart, enhancing astrophysical bounds on its annihilation signals. I will review recent progress in this program, and discuss how we can constrain the contributions to the neutralino mass from the bino, wino and higgsino using existing astrophysical bounds and direct detection experiments for models with nonthermal neutralino dark matter. Using these constraints we will then see how expected changes to inflationary observables result from the nonthermal phase.
Inflation was simple

Non-gaussianity is small \[ f_{NL} \sim O(1) \]

Still some motivation to keep searching

1. Different shapes could be important
2. \[ f_{NL} = 1 \] sets an important benchmark

\[ \mathcal{L} = \int d^4x \left[ \frac{1}{2} \dot{\phi}^2 - V(\phi) + \frac{c}{M^2} (\partial \phi)^4 + \ldots \right] \]

However, simple single field inflation can account for the data.
Cosmic Dark Ages

- Dynamical Symmetry Breaking (e.g. SUSY)
- Higgs / Strongly coupled dynamics?
- EWSB Phase Transition
- QCD Phase Transition
Two questions to get us started:

#1 How do changes in the post-inflationary history alter constraints on inflationary model building?

#2 How do changes in the cosmic history effect the expected properties of dark matter?
Many probes on microscopic properties of Dark Matter

Collider Probes

Direct Detection

Indirect Detection

DM → SM

DM → SM

Dark Matter

recoil energy (lens of fate)

generation

6.5 kpc
For clarity:
In the rest of the talk I will assume we live in a world with Supersymmetry

However!
This need not be the case
(The main points will not rely on the existence of SUSY).
(happy to elaborate afterwards)
**Assumption:** Supersymmetry
i.e., we need to address the (big) hierarchy problem, dark matter, gauge coupling unification, Coleman–Mandula, …

**Caveat:** We may not need physics beyond the Standard Model?

No hierarchy problem if no new mass scale.

And SUSY doesn’t seem to help with Cosmological Constant.
Assumption: Supersymmetry
l.e., we need to address the (big)
hierarchy problem, dark mater,
gauge coupling unification,
Coleman–Mandula, …

Caveat: We may not need physics beyond the
Standard Model?

No hierarchy problem if no new mass scale.

And SUSY doesn’t seem to help with
Cosmological Constant.
SUSY and Hierarchies after LHC

SUSY can stabilize the Electroweak Hierarchy

No sign of SUSY yet.

It's a little too hot for 135 GeV...
SUSY and Hierarchies after LHC

Scalars heavy, fermions can be light
Split SUSY


✓ Gauge Coupling Unification
✓ Dark Matter
✓ No Flavor, CP problems

 Scalars heavy, Fermions light
(Fermions carry R-symmetry, scalars do not.)
Another possibility
Perhaps nature allows for some tuning (1/1000)?

Advantage: Addresses a potential cosmological problem
Another possibility
Perhaps nature allows for some tuning (1/1000)?

Advantage: Addresses a potential cosmological problem
The Cosmological Moduli Problem

Moduli generically displaced.

Energy stored in condensate.

Oscillations when $H = m_{\text{soft}}$ with amplitude $\Delta \phi$

Scalar condensate $\rho = \frac{1}{a^2}$ $p = 0$

$\frac{\rho}{\rho_f} \sim a(t)$ Danger for BBN
Moduli Decay gravitationally

\[ \Gamma (\Phi \rightarrow YY) \sim \frac{m_\Phi^3}{m_P^2} \]

Reheat: \( T_r \sim \left( \frac{m_\Phi}{10 \text{TeV}} \right)^{3/2} \text{MeV} \)

\[ \int_x \rightarrow \int_x \left( \frac{T_r}{T_f} \right)^3 \]

Ex:

\[ m_\Phi \sim 10 \text{TeV} \rightarrow T_r \sim \text{MeV} \quad T_f \sim \text{GeV} \]

\[ \int_{\text{JM}} = 10^{-9} \int_x^{\text{fin}} \]

For electroweak mass moduli, BBN is spoiled!
UV Completions of SUSY
(Top-down Approaches add Moduli, tuning ~ 1/1000)

S. Watson (Arxiv:0912.3003)
with B. Acharya, G. Kane, P. Kumar (Arxiv:0908.2430)

✓ Unification
✓ Dark Matter
✓ No moduli problems

Moduli get masses:

\[ m_\phi \simeq m_{3/2} \simeq 100 - 1000 \text{ TeV} \]

\[ m_{3/2} = \frac{\Lambda_{SUSY}^2}{m_p} \]
SUSY after LHC data suggests spectrum with heavy scalars and light dark matter
SUSY models after LHC all seem to favor a Non-thermal History for Dark Matter.
Planck Bayesian Analysis for post-inflation model selection

<table>
<thead>
<tr>
<th>Model</th>
<th>Instant Reheating</th>
<th>History 1</th>
<th>History 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\ln(\mathcal{E}/\mathcal{E}_i)$</td>
<td>$\Delta\chi^2_{\text{eff}}$</td>
<td>$\ln(\mathcal{E}/\mathcal{E}_i)$</td>
</tr>
<tr>
<td>$n = 4$</td>
<td>-14.9</td>
<td>25.9</td>
<td>-18.8</td>
</tr>
<tr>
<td>$n = 2$</td>
<td>-4.7</td>
<td>5.4</td>
<td>-7.3</td>
</tr>
<tr>
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<td>-5.4</td>
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</tr>
<tr>
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<td>-8.9</td>
</tr>
<tr>
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<td>-7.1</td>
<td>6.1</td>
<td>-9.1</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>-4940.7</td>
<td>9808.4</td>
<td>...</td>
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**History 1 (Blue)**

- $T_r = 10^8$ GeV
- $w_{\text{eff}} = -1/3 \ldots 1/3$

**History 2 (Grey)**

- $T_r = 700$ GeV
- $w_{\text{eff}} = -1/3 \ldots 1$
Planck Bayesian Analysis
for post-inflation model selection

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History 2 (Grey)

$T_r = 700$ GeV

$w_{\text{eff}} = -1/3 \ldots 1$
Universe with **SUSY Prior**

Additional change from standard case

\[ \Delta N = -10.68 + \frac{1}{18} \ln \left( \frac{g_*(T_r^c)}{10.75} \right) \left( \frac{T_r}{3 \text{ MeV}} \right)^4 \left( \frac{m_p}{\Delta \sigma} \right)^3 \]

\[ \Delta n_s = (n_s - 1) \left[ -\frac{5}{16} r - \frac{3}{64} \frac{r^2}{n_s - 1} \right] \Delta N, \]

\[ \Delta r = r \left( n_s - 1 + \frac{r}{8} \right) \Delta N. \]

\[ \Delta N_{\text{total}} \approx 20 \]
More freedom for inflationary constraints with SUSY

ArXiv:1307.2453

with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)
Is a universe with SUSY less restrictive?

We will return to this in a moment…
Our second question:

#2

How do changes in the cosmic history effect the expected properties of dark matter?

- Dynamical Symmetry Breaking (e.g. SUSY)
- Higgs / Strongly coupled dynamics?
- EWSB Phase Transition
- Dark Matter WIMPs
- QCD Phase Transition
The Cosmological Moduli Problem

Moduli generically displaced.

Energy stored in condensate.

Example:

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

High Energy: \( H \gg m_{3/2} = \text{TeV} \) \( \langle \phi \rangle \approx M \left( \frac{H}{M} \right)^{1/(n+1)} \)

Low Energy: \( H \ll M \) \( \langle \phi \rangle \approx 0 \)
Condensate decays and reheats universe

\[ \Gamma \approx \frac{m^3}{m_p} \quad T_r \approx \left( \frac{m_p}{10^{10} \text{TeV}} \right)^{3/2} \text{MeV} \]

\( \Phi \) decays \( \rightarrow \) Std. Model \( \rightarrow \) SUSY partners \( \rightarrow \) LSP

(\text{Neutrolino})

How much Dark Matter?

\[ \Omega_{DM} = \Omega_{DM}^{TH} \left( \frac{T_r}{T_f} \right)^3 + 0.23 \left( \frac{10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle} \right) \left( \frac{T_f}{T_r} \right) \]

\[ \text{Ex:} \quad m_p \sim 10 \text{TeV} \quad T_r \sim \text{MeV} \quad T_f \sim \text{GeV} \]

\[ \Omega_{DM} = 10^{-9} \Omega_{DM}^{TH} + 0.23 \times 10^3 \left( \frac{10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle} \right) \]
Dark matter will be of non-thermal origin:

\[ \Omega_{\text{dm}}^{NT} h^2 \simeq 0.10 \left( \frac{m_X}{100 \text{ GeV}} \right) \left( \frac{10.75}{g_*} \right)^{1/2} \left( \frac{3 \times 10^{-23} \text{ cm}^3/\text{s}}{\sigma v} \right) \left( \frac{10 \text{ MeV}}{T_r} \right) \]

\[ \Omega_{\text{obs}}^h h^2 \simeq 0.12 \]

Restrict Mass and Cross-section by dark matter experiments!

- Restrict Reheat temperature
- Reduce freedom for Planck constraints

Diagram:
- Moduli dominate until 2nd reheating
- Shift in relevant mode \( \Delta \nu \rightarrow \Delta \nu \)
Many probes on microscopic properties of Dark Matter
Indirect Detection of Dark Matter

Dark Matter Annihilates

8.5 kpc
Pamela anti-protons

\[
\frac{\overline{n}}{d^2r/dE}
\]

\begin{align*}
\text{Kinetic Energy (GeV)}
\end{align*}

with G. Kane and Ran Lu (Michigan)
Cosmic Ray (astro)Physics is Messy

Expected Positron Flux

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

Microphysics     Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)
Stronger Constraints from Gammas—FERMI LAT

Observations of 15 Dwarf Spheroidals

Fermi Collaboration:
Arxiv:1310.0828
Stronger Constraints from Gammas — FERMI LAT

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Indirect Detection Constraints from FERMI
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)

Excluded by FERMI
Current and Future Constraints from Xenon
ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)
Summary of our Results

ArXiv:1307.2453
with R. Easther (Auckland), R. Galvez, and O. Ozsoy (Syracuse)

• For pure wino SUSY Dark Matter we find a lower bound on the reheat temperature of around 700 MeV, substantially reducing the theoretical prior.

• General SUSY WIMPs are also constrained, but a little more model dependence must be considered (e.g. tan beta, etc..)

• Lesson learned: Theory Priors (e.g. world with SUSY) + Cosmological constraints (Planck) + Dark Matter Detection (microscopic), allow us to begin to probe the “Dark Ages”.

• Additional data improves these bounds
Recent results of Fan and Reece

Fan and Reece 1307.4400
See also: Cohen, Lisanti, Pierce, and Slatyer 1307.4082

Reheat temperature must be above 1 GeV for wino
Recent results of Fan and Reece

Fan and Reece 1307.4400
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Reheat temperature must be above 1 GeV for wino
Partial list of many things I did not mention

- **Gravitino Problem** (model dependent -- difficult issue)
  For an explicit example that works see: Arxiv:0908.2430 with B. Acharya, G. Kane, P. Kumar

- **Baryogenesis?**
  Affleck-Dine + moduli decay can address this more work should be done:
  e.g. Arxiv:1108.5178 with Kane, Shao, and Yu

- **Isocurvature Constraints and Dark Radiation**
  (To appear very soon with L. Iliesiu, Doddy Marsh, K. Moodley)

- **Gravity Waves / Preheating?** (work in progress with T. Giblin)

- **Effect on CMB last scattering and reionization** (work in progress with Cora Dvorkin)

- **In some models moduli can be lighter**
  e.g. **Large Volume Stabilization in Type IIB** (work in progress with K Sinha and M. Cicoli)

- **Behavior of moduli during inflation — are they displaced?**
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- **Consequences for Matter Power Spectrum**
  (To appear with O. Ozsoy and J. Neelakanta — with grads at SU)
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Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Thermal History

- Planck
- Inflation
- $10^{15}$ GeV
- TeV
- GeV
- MeV
- eV
- CMB

Radiation Phase (instant reheating)

Scalar Oscillations Dominate

Thermal DM Freeze-out

Particles Decay and Reheat

Alternative History

- Planck
- Inflation
- $10^{15}$ GeV
- TeV
- GeV
- MeV
- eV
- CMB
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

\[ \dot{\rho}_\sigma = -3H\rho_\sigma - \Gamma_\sigma \rho_\sigma, \]
\[ \dot{\rho}_r = -4H\rho_r + (1 - B_\chi)\Gamma_\sigma \rho_\sigma + \frac{\langle \sigma v \rangle}{m_\chi} \left[ \rho_\chi^2 - \rho_{\chi,eq}^2 \right], \]
\[ \dot{\rho}_\chi = -3H\rho_\chi + B_\chi \Gamma_\sigma \rho_\sigma - \frac{\langle \sigma v \rangle}{m_\chi} \left[ \rho_\chi^2 - \rho_{\chi,eq}^2 \right], \]

"Instant Reheating"

\[
\log \left( \frac{\rho_\chi}{\rho} \right) \]

Dark Matter annihilations
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Mode enters Horizon

Longer moduli phase, lower reheat temperature = more suppression
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Mode enters Horizon

Reheating

Longer moduli phase, lower reheat temperature
= more suppression
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Scalar domination
\[ \frac{\delta \rho_{\text{c}}}{\rho_{\text{c}}} \sim a(t) \]

Radiation domination
\[ \frac{\delta \rho_{\text{c}}}{\rho_{\text{c}}} \sim \log a(t) \]

Mode enters Horizon

Mode enters Horizon later, so less growth

Reheating

Reheating

\[ \log(a) \]
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

see also: Arxiv:1106.0536 Erickcek and Sigurdson

**IF:** Most of the dark matter produced from decays

**THEN:** Enhanced growth of structure on small scales possible.

**IF:** Most of the dark matter produced thermally after reheating

**Then:** New suppression scale to determine smallest primordial structures.

\[ \lambda \sim k_{\tau}^{-1} \sim H_{\tau}^{-1} \]
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Also see related: Arxiv:1106.0536 Erickcek and Sigurdson

Scales to determine smallest structures (linear regime):

Free-streaming Scale
After kinetic decoupling, dark matter can free-stream erasing structure

\[ \lambda_f(t) = \int_{t_{\text{RH}}}^{t} \frac{\langle v \rangle}{a} \, dt, \]

Kinetic Decoupling and Acoustic Oscillations
Prior to kinetic decoupling, dark matter perturb couple to radiation oscillations and erase structure.

\[ \lambda_{k,d} \sim H^{-1} \bigg|_{T=T_{k,d}} \]

Horizon Size at Reheating (non-thermal history)
Moduli domination can lead to suppression (or growth)

\[ \lambda_t \sim H^{-1} \bigg|_{T=T_t}, \]

Largest scale (lowest temperature) determines cutoff
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Also see related: Arxiv:1106.0536 Erickcek and Sigurdson

Scales to determine smallest structures (linear regime):

Free-streaming Scale
After kinetic decoupling, dark matter can free-stream erasing structure

\[ \lambda_{\text{fsh}}(t) = \int_{t_{\text{fsh}}}^{t} \frac{\langle v \rangle}{a} \, dt, \]

Kinetic Decoupling and Acoustic Oscillations
Prior to kinetic decoupling, dark matter perturbations couple to radiation oscillations and erase structure.

\[ \lambda_{k,d} \sim H^{-1}|_{T=T_{k,d}} \]

Horizon Size at Reheating (non-thermal history)
Moduli domination can lead to suppression (or growth)

\[ \lambda_{r} \sim H^{-1}|_{T=T_{r}} \]

Largest scale (lowest temperature) determines cutoff
Split-SUSY and the Matter Power Spectrum

To appear with O. Ozsoy and J. Neelakanta

Decoupling Temperature (GeV)

Reheat sets scale of structure

Reheating sets smallest size if

\[ T_{kd} > T_r \]
CMB: Last Scattering Surface and a Non-thermal History

Ruled out by WMAP

Planck forecast
CVL

Slatyer, Padmanabhan and Pekkanen 09065

\[ f \propto \text{cm}^{-3}\text{s}^{-1} \]

\[ \text{DM Mass [GeV]} \]

1. XDM m_\chi = 2500 GeV, BF = 500
2. XDM m_\chi = 2500 GeV, BF = 100
3. XDM m_\chi = 2500 GeV, BF = 100
4. XDM m_\chi = 2500 GeV, BF = 100
5. XDM m_\chi = 2500 GeV, BF = 100
6. m_\chi = 250 GeV, BF = 200
7. m_\chi = 150 GeV, BF = 500
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9. XDM m_\chi = 150 GeV, BF = 500
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