SUPERSYMMETRY FOR ASTROPHYSICISTS

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SLAC Summer Institute

Graphic: N. Graf
I’m giving summer school lectures titled, “Supersymmetry for Astrophysicists.” What should I talk about?

- Astrophysicist #1: “Beats me. I couldn’t care less about supersymmetry. Maybe you can get out of it somehow.”

- Astrophysicist #2: “Dark matter, of course. Isn’t that the only motivation for supersymmetry?”
OUTLINE

LECTURE 1: SUSY ESSENTIALS
- Standard Model; SUSY Motivations; LSP Stability and Candidates

LECTURE 2: NEUTRALINOS
- Properties; Production; Direct Detection; Indirect Detection; Collider Signals

LECTURE 3: GRAVITINOS
- Properties; Production; Astrophysical Detection; Collider Signals
First discuss motivations for supersymmetry. Why?

- Supersymmetry is the best motivated framework for new particle physics
- Generic properties vs. special models (What do these shaded regions mean?)
- Direct implications for astrophysics
**STANDARD MODEL**

- **Matter Particles**
  - Quarks and leptons
  - Spin ½ fermions

- **Force Particles**
  - Photon (EM)
  - $W$, $Z$ (weak)
  - Gluons (strong)
  - Spin 1 bosons

- **Higgs Particle**
  - Undiscovered
  - Spin 0 boson

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Force Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>$\nu_e$ e neutrino</td>
<td>$g$ gluon</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>$\nu_\mu$ $\mu$ neutrino</td>
<td>$\gamma$ photon</td>
</tr>
<tr>
<td>$t$ top</td>
<td>$\nu_\tau$ $\tau$ neutrino</td>
<td>$W$ $W$ boson</td>
</tr>
<tr>
<td>$d$ down</td>
<td>$e$ electron</td>
<td>$Z$ $Z$ boson</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>$\mu$ muon</td>
<td></td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>$\tau$ tau</td>
<td></td>
</tr>
</tbody>
</table>

3 → I  II  III  ← Generations
Matter Particles

- Most of the unexplained parameters of the SM are here

- Interactions determined by unusual quantum numbers

- Masses span at least 11 orders of magnitude
  - Neutrinos ~ eV
  - Electron: 511 keV
  - Top quark: 171 GeV

- The top quark is heavy!
**Force Particles**

- Couplings $\alpha \equiv g^2/(4\pi)$ at $m_Z$
  - $\alpha_{EM} = 0.007818 \pm 0.000001$
  - $\alpha_{weak} = 0.03381 \pm 0.00002$
  - $\alpha_s = 0.118 \pm 0.002$

- At observable energies,
  $\alpha_{EM} < \alpha_{weak} < \alpha_s$

- Precisely measured

- Scale-dependent – the quantum vacuum has dielectric properties
Force Particles

- **Masses**
  - \( m_\gamma = 0 \): U(1) conserved
  - \( m_g = 0 \): SU(3) conserved
  - \( m_W = 80 \text{ GeV} \): SU(2) broken
  - \( m_Z = 91 \text{ GeV} \): SU(2) broken

- SU(2) is broken, the others aren’t
Higgs Particle

- Mass
  - Direct searches: $m_h > 115$ GeV
  - Indirect constraints from precision data: $40$ GeV $< m_h < 200$ GeV
NATURALNESS

• We know 3 fundamental constants
  – Special relativity: speed of light $c$
  – Quantum mechanics: Planck’s constant $h$
  – General relativity: Newton’s constant $G$

• From these we can form the Planck mass

\[ M_{\text{Pl}} = \sqrt{\frac{hc}{G}} \approx 10^{19} \text{ GeV} \]

• Why are $m_h$, $m_W$, $m_Z$, … $<< M_{\text{Pl}}$?
Gauge Hierarchy Problem

\[ m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \]

In the SM, \( m_h \) is naturally \( \sim \Lambda \), the largest energy scale.

\( m_h \sim 100 \text{ GeV}, \ \Lambda \sim 10^{19} \text{ GeV} \) \( \rightarrow \) cancellation of 1 part in \( 10^{34} \)
Supersymmetry is a qualitatively new class of symmetry
Superpartners

• Translations: particle $P$ at $x \rightarrow$ particle $P$ at $x'$

• SUSY: particle $P$ at $x \rightarrow$ particle $\tilde{P}$ at $x$, where
  – $P$ and $\tilde{P}$ differ in spin by $\frac{1}{2}$: fermions $\leftrightarrow$ bosons
  – $P$ and $\tilde{P}$ are identical in all other ways (mass, couplings)

• New particles
  – Superpartners of matter particles: Spin 0 bosons, add “s” (selectron, sneutrinos, squark, …)
  – Superpartners of force particles: Spin $\frac{1}{2}$ fermions, add “ino” (photino, Wino, …)
  – Superpartners of Higgs particles: Spin $\frac{1}{2}$ fermions, “Higgsinos”
SUSY AND NATURALNESS

\[ m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 (m_f^2 - m_f^2) \ln(\Lambda/m_h) \]

Dependence on \( \Lambda \) is softened to a logarithm.

SUSY solves the gauge hierarchy problem, even if broken, provided superpartner masses are \( \sim 100 \) GeV.
Higgs Doubling

- SUSY requires 2 Higgs doublets to cancel anomalies and to give mass to both up- and down-type particles.

- E.g., anomaly cancelation requires $\Sigma Y^3 = 0$, where $Y$ is hypercharge and the sum is over fermions. This holds in the SM.

- SUSY adds an extra fermion with $Y = -1$:
  \[
  \begin{pmatrix}
  h^0 \\
  h^-
  \end{pmatrix}
  \equiv
  \begin{pmatrix}
  h^0_d \\
  h^-_d
  \end{pmatrix}
  \Rightarrow
  \begin{pmatrix}
  \tilde{H}^0_d \\
  \tilde{H}^-_d
  \end{pmatrix}
  \]

- To cancel the anomaly we add another Higgs doublet with $Y = +1$:
  \[
  \begin{pmatrix}
  h^+_u \\
  h^0_u \\
  h^+_u
  \end{pmatrix}
  \Rightarrow
  \begin{pmatrix}
  \tilde{H}^+_u \\
  \tilde{H}^0_u
  \end{pmatrix}
  \]
SUSY PARAMETERS

SUSY breaking introduces many unknown parameters. These are

- Masses for sleptons and squarks: $m_{f_{ij}}^2$
- Masses for gauginos: $M_1$, $M_2$, $M_3$
- Trilinear scalar couplings (similar to Yukawa couplings): $A_{f_{ij}}$
- Mass for the 2 Higgsinos: $\mu \tilde{H}_u \tilde{H}_d$
- Masses for the 2 neutral Higgs bosons: $B H_u H_d + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2$
- The 2 neutral Higgs bosons both contribute to electroweak symmetry breaking:
  \[ v^2 = (174 \text{ GeV})^2 \Rightarrow v_u^2 + v_d^2 = (174 \text{ GeV})^2 \]
  The extra degree of freedom is called $\tan \beta = v_u / v_d$
**TAKING STOCK**

- **SUSY is a single symmetry, which implies many new particles**

- **Many new parameters, but**
  - Dimensionless couplings are fixed (no “hard” breaking)
  - Dimensionful parameters are allowed (soft breaking), but should be ~ 100 GeV
  - Even the dimensionful parameters cannot be arbitrary

<table>
<thead>
<tr>
<th>Analogy</th>
<th>Soap Bubble</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Parameter</td>
<td>Length L</td>
<td>$M_{Pl}$</td>
</tr>
<tr>
<td>Small Parameter</td>
<td>L - H</td>
<td>$m_h$</td>
</tr>
<tr>
<td>Symmetry explanation</td>
<td>Rotational invariance</td>
<td>SUSY</td>
</tr>
<tr>
<td>Symmetry breaking</td>
<td>Gravity</td>
<td>$M_{SUSY}$</td>
</tr>
<tr>
<td>Natural if</td>
<td>Gravity weak</td>
<td>$M_{SUSY}$ small</td>
</tr>
</tbody>
</table>
R-PARITY AND STABLE SUPERPARTNERS

• One problem: proton decay

\[ p \quad \begin{cases} d_R \quad \tilde{s}_R \quad e_L^+ \\ u_R \quad \tilde{u}_L \\ u \quad \pi^0 \end{cases} \]

• Forbid this with R-parity conservation: \( R_p = (-1)^{3(B-L)+2S} \)
  - SM particles have \( R_p = 1 \), SUSY particles have \( R_p = -1 \)
  - Requires 2 superpartners in each interaction

• Consequence: the lightest SUSY particle (LSP) is stable and cosmologically significant. What is the LSP?
# Neutral SUSY Particles

<table>
<thead>
<tr>
<th>Spin</th>
<th>U(1) $M_1$</th>
<th>SU(2) $M_2$</th>
<th>Up-type $\mu$</th>
<th>Down-type $\mu$</th>
<th>$m_\tilde{\nu}$</th>
<th>$m_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G graviton</td>
</tr>
<tr>
<td>3/2</td>
<td>Neutralinos: ${\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\tilde{G}$ gravitino</td>
</tr>
<tr>
<td>1</td>
<td>$B$</td>
<td>$W^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>$\tilde{B}$ Bino</td>
<td>$\tilde{W}^0$ Wino</td>
<td>$\tilde{H}_u$ Higgsino</td>
<td>$\tilde{H}_d$ Higgsino</td>
<td>$\tilde{\nu}$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>$H_u$</td>
<td>$H_d$</td>
<td>$\tilde{\nu}$</td>
<td>sneutrino</td>
</tr>
</tbody>
</table>

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FORCE UNIFICATION

- Can the 3 forces be unified, e.g., SU(3) x SU(2) x U(1) $\rightarrow$ SO(10)?

- Superpartners modify the scale dependence of couplings

- With TeV superpartners, 3 couplings meet at a point!
  - No free parameters
  - % level “coincidence”
  - Coupling at unification: $\alpha^{-1} > 1$
  - Scale of unification
    - $Q > 10^{16}$ GeV (proton decay)
    - $Q < 10^{19}$ GeV (quantum gravity)

- SUSY explains $\alpha_{\text{EM}} < \alpha_{\text{weak}} < \alpha_{s}$

- Gaugino mass unification implies $M_1:M_2:M_3 \approx \alpha_1:\alpha_2:\alpha_3 \approx 1:2:7$, the Bino is the lightest gaugino

Martin (1997)
TOP QUARK MASS

- Force unification suggests we can extrapolate to very high energy scales
- All parameters (masses, couplings) have scale dependence
- The top quark Yukawa coupling has a quasi-fixed point near its measured value
- SUSY “explains” heavy top

Polonsky (2001)
SCALAR MASSES

- How do scalar masses change with scale?

- Gauge couplings increase masses; Yukawa couplings decrease masses

- $H_u$ has large top quark Yukawa, but no compensating strong interaction

- $H_u$ is the lightest scalar. In fact, it’s typically tachyonic!
ELECTROWEAK SYMMETRY BREAKING

• The Higgs boson potential is

\[ V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 \]
\[ - (B H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2 \]

• Minimizing this, one finds (for moderate/large tan\(\beta\))

\[ \frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - |\mu|^2 \approx -m_{H_u}^2 - |\mu|^2 \]

• EWSB requires \(m_{H_u}^2 < 0\)

SUSY explains why SU(2) is broken and SU(3) and U(1) aren’t
SNEUTRINOS AND HIGGSINOS

- Lightest physical scalars are typically the right-handed sleptons

- Sneutrinos
  - have SU(2) interactions, and so are typically heavier
  - Disfavored as LSPs by direct searches

- EWSB also fixes Higgsino mass $\mu$

$$
\frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - |\mu|^2
$$
LECTURE 1 SUMMARY

• The Standard Model is incomplete

• SUSY provides elegant solutions
  – Naturalness
  – Force unification
  – Electroweak symmetry breaking

• Proton decay $\rightarrow$ R-parity, stable LSP

• Natural LSPs: neutralino (Bino/Higgsino), gravitino
OUTLINE

LECTURE 1: SUSY ESSENTIALS
The Standard Model; Motivations; Key Features

LECTURE 2: NEUTRALINOS
Properties; Production; Direct Detection; Indirect Detection; Collider Signals

LECTURE 3: GRAVITINOS
Properties; Production; Astrophysical Detection; Collider Signals
LAST TIME

• SUSY provides elegant solutions to SM problems
  – Naturalness
  – Force unification
  – Electroweak symmetry breaking

• SUSY predicts a new partner particle for every known particle (+ extra Higgs doublet)

• Proton decay $\rightarrow$ R-parity, lightest superpartner is stable, potentially significant dark matter
Thermal Relic Abundance

- The Boltzmann equation:

\[
\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right]
\]

- \( n \approx n_{eq} \) until interaction rate drops below expansion rate:

\[
n_{eq} \langle \sigma v \rangle \sim H \quad (mT)^{3/2}e^{-m/T} \quad T^2/M_{Pl}
\]

- The universe expands *slowly*! Mass \( m \) particles freeze out at \( T \sim m/25 \)

\[\chi \chi \rightarrow f \bar{f} \quad f \bar{f} \rightarrow \chi \chi\]
• The amount of dark matter left over is inversely proportional to the annihilation cross section:

\[ \Omega_{DM} \sim <\sigma_A v>^{-1} \]

• What is the constant of proportionality?

• Impose a natural relation:

\[ \sigma_A = k\alpha^2/m^2 \] , so \( \Omega_{DM} \sim m^2 \)

Remarkable “coincidence”: \( \Omega_{DM} \sim 0.1 \) for \( m \sim 0.1 – 1 \) TeV, The mass range predicted for superpartners
SUPERSYMMETRY BREAKING

• How are superpartner masses generated?

• EWSB in the standard model:

<table>
<thead>
<tr>
<th>EWSB Sector</th>
<th>Mediating Interactions</th>
<th>Observable Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>h → v</td>
<td>h, q, l</td>
<td>q, l</td>
</tr>
</tbody>
</table>

EWSB parameterized by v. Mediating interactions (Yukawa couplings) → observable spectrum

• Hidden sector SUSY Breaking:

<table>
<thead>
<tr>
<th>SUSY Breaking Sector</th>
<th>Mediating Interactions</th>
<th>Observable Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z → F</td>
<td>Z, ñ, ñ̃</td>
<td>ñ, ñ̃</td>
</tr>
</tbody>
</table>

SUSY breaking parameterized by F (dimension 2). Mediation mechanism → observable spectrum
GRAVITY-MEDIATED SUSY BREAKING

• There are $M_{Pl}$-suppressed interactions. Minimal assumption: use these as the mediating interactions:

\[
\begin{align*}
  c_{ij} \frac{Z^\dagger Z}{M_{Pl}^2} \phi_i^* \phi_j & \rightarrow \text{scalar masses} \\
  c_a \frac{Z}{M_{Pl}} \lambda_a \lambda_a & \rightarrow \text{gaugino masses} \\
  c_{ijk} \frac{Z}{M_{Pl}} \phi_i \phi_j \phi_k & \rightarrow \text{A terms} \\
  c \frac{Z^\dagger Z}{M_{Pl}^2} \phi_i \phi_j & \rightarrow \text{B term}
\end{align*}
\]

• The gravitino mass is

\[
m_{\tilde{G}} \sim F/M_{Pl}
\]

• For $F \sim (10^{10} \text{ GeV})^2$, when $Z \rightarrow F$, the gravitino and all superpartner masses are $\sim 100$ GeV.

• Assume that the gravitino is not the LSP for this lecture.
SUPERSYMMETRIC MODELS

• To get further, determine relic densities, detection rates, etc., we must specify the SUSY parameters

• Two choices
  – scan parameters model-independently
  – Choose models that embody many of the nice features discussed last time
AN EXAMPLE: MINIMAL SUPERGRAVITY

- Defined by 4+1 parameters
  - $m_0$: universal scalar mass
  - $M_{1/2}$: universal gaugino mass
  - $A_0$: universal trilinear scalar coupling
  - $\tan \beta$: ratio of Higgs vevs
  - $\text{sign}(\mu)$: $|\mu|$ determined by EWSB

- Includes naturalness, force unification, radiative EWSB

- LSP candidates: Slepton, neutralino
mSUGRA LSP

Bino fraction of $\chi$ LSP in mSUGRA with $A_0 = 0$, $\mu > 0$. Left shaded region has $\tilde{\tau}$ LSP. Remaining shaded region excluded by LEP chargino search.
The lightest neutralino is

\[ \chi = a_B \tilde{B} + a_W \tilde{W}^0 + a_{H_u} \tilde{H}_u^0 + a_{H_d} \tilde{H}_d^0 \]

Neutralino mass matrix:

\[
\begin{pmatrix}
M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\
0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\
-m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\
m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0
\end{pmatrix}
\]
RELIC DENSITY

• Neutralinos annihilate through many processes. [→]
But there are essentially two classes:

• Fermion diagrams
\[ \chi \text{ are Majorana fermions:} \]
Pauli exclusion → \[ S = 0 \]
\[ L \text{ conservation } \rightarrow P \text{ wave suppression} \]
\[ \frac{m_f}{m_W} \text{ suppression} \]

• Gauge boson diagrams
suppressed for \[ \chi \approx \text{Bino} \]

Bottom line: annihilation is typically suppressed, \[ \Omega_{DM} h^2 \] is typically high
Contributions to Neutralino WIMP Annihilation

Jungman, Kamionkowski, Griest (1995)
Cosmologically Preferred SUSY

Typically get too much DM, but there are generic mechanisms for reducing it

- Co-annihilation region
- Degenerate $\chi$ and stau
- Excluded: Stau LSP
- Yellow: pre-WMAP
- Red: post-WMAP
- Focus point region
- Too much dark matter
- Mixed Neutralinos
- Bulk region
- Light sfermions

Feng, Matchev, Wilczek (2003)
Implications for Detection

Many diverse experiments are promising in the cosmologically preferred regions
WIMP DETECTION

Correct relic density $\rightarrow$ Efficient annihilation then
$\rightarrow$ Efficient annihilation now (indirect detection)
$\rightarrow$ Efficient scattering now (direct detection)
DIRECT DETECTION

- **WIMP essentials:**
  - $v \sim 10^{-3} \, c$
  - Kinetic energy $\sim 100$ keV
  - Local density $\sim 1 / \text{liter}$

- Detected by recoils off ultra-sensitive underground detectors
Indirect Detection

Dark Matter Fill-in-the-Blank!

Dark matter annihilates in _________________ to a place ______________, which are detected by _________________ particles an experiment.
Dark Matter annihilates in the galactic center to a place photons, which are detected by HESS, GLAST, ... .

Typically $\chi\chi \rightarrow \gamma\gamma$, so $\chi\chi \rightarrow ff \rightarrow \gamma$.
Dark Matter annihilates in the center of the Sun to a place

neutrinos, which are detected by AMANDA, IceCube. Some particles

an experiment

\[ \nu \to \mu \text{ (km}^{-2}\text{ yr}^{-1}) \]

AMANDA in the Antarctic Ice
Dark Matter annihilates in __the halo____ to a place __positrons__, which are detected by __PAMELA__. Some particles an experiment

$d\Phi_{e^+}/d\Omega dE (cm^{-2} s^{-1} sr^{-1} GeV^{-1})$

$m_{\chi}=300 \text{ GeV}

m_{\chi}=500 \text{ GeV}

m_{\chi}=750 \text{ GeV}

m_{\chi}=1000 \text{ GeV}

15 June 2006
NEUTRALINO PROSPECTS

If neutralinos contribute significantly to dark matter, we are likely to see signals before the end of the decade:

- Direct dark matter searches
- Indirect dark matter searches
- Tevatron at Fermilab
- Large Hadron Collider at CERN
What then?

- Cosmo/astro can’t discover SUSY
- Particle colliders can’t discover DM

Lifetime > $10^{-7}$ s $\rightarrow 10^{17}$ s?
THE EXAMPLE OF BBN

- Nuclear physics $\rightarrow$ light element abundance predictions
- Compare to light element abundance observations
- Agreement $\rightarrow$ we understand the universe back to $T \sim 1$ MeV, $t \sim 1$ sec
DARK MATTER ANALOGUE

- Particle physics $\rightarrow$ dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?
RELIC DENSITY DETERMINATIONS

% level comparison of predicted $\Omega_{\text{hep}}$ with observed $\Omega_{\text{cosmo}}$

LHC ("best case scenario")
ILC
WMAP (current)
Planck (~2010)
IDENTIFYING DARK MATTER

Yes

Are $\Omega_{\text{hep}}$ and $\Omega_{\text{cosmo}}$ identical?

Yes

Calculate the new $\Omega_{\text{hep}}$

No

Which is bigger?

Yes

$\Omega_{\text{hep}}$

Yes

$\Omega_{\text{cosmo}}$

No

Does it decay?

Yes

Can you identify a source of entropy production?

No

Can this be resolved with some non-standard cosmology?

Yes

Does it account for the rest of DM?

No

Think about the cosmological constant problem

No

Are you sure?

Yes

Did you make a mistake?

No

Congratulations!
You’ve discovered the identity of dark matter and extended our understanding of the Universe to $T=10$ GeV, $t=1$ ns (Cf. BBN at $T=1$ MeV, $t=1$ s)

No
DIRECT DETECTION IMPLICATIONS

Baltz, Battaglia, Peskin, Wizansky (2006)

Comparison tells us about local dark matter density and velocity profiles

Green (2007)
INDIRECT DETECTION IMPLICATIONS

\[ \frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \frac{dN_i^\gamma}{dE} \frac{1}{4\pi m_\chi^2} \int_\psi \rho^2 dl \]

Gamma ray fluxes factorize

COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS
LECTURE 2 SUMMARY

• Neutralinos emerge as excellent dark matter candidates in many supersymmetric models

• Promising prospects for direct detection, indirect detection, and colliders

• At the same time, great progress requires synergy: comparisons may lead to discovery of the identity of dark matter, require the existence of another component, tell us about the distribution of dark matter in the galaxy, structure formation
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GRAVITINO COSMOLOGY

• Neutralinos (and all WIMPs) are cold and weakly-interacting. Is this a universal prediction of SUSY DM?

• No! Here, we’ll consider the gravitino, a SUSY dark matter candidate with completely different, but equally rich, implications for particle physics and cosmology

• In some cases, the gravitino has identical motivations to neutralinos, preserving even the WIMP relic abundance “coincidence”
Gravitinos

• SUSY: graviton $G \rightarrow$ gravitino $\tilde{G}$

• Mass: in gravity-mediated SUSY breaking, expect $\sim 100$ GeV – 1 TeV

• $\tilde{G}$ interactions couple particles to their superpartners
  
  Couplings grow with energy, but are typically extremely weak
Gravitino Production 1: Thermal

- Gravitinos are the original SUSY DM. First ideas: If the universe cools from $T \sim M_{Pl}$, gravitinos decouple while relativistic, expect $n_{\tilde{G}} \sim n_{eq}$.

- Stable:
  \[ \Omega_{\tilde{G}} < 1 \Rightarrow m_{\tilde{G}} < 1 \text{ keV} \]
  (cf. neutrinos). (Current constraints $\rightarrow$ too hot.)

- Unstable:
  \[ \tau_{\tilde{G}} \sim \frac{M_{Pl}^2}{m_{\tilde{G}}^3} \sim 1 \text{ yr} \left[ \frac{100 \text{ GeV}}{m_{\tilde{G}}} \right]^3 \]
  Decay before BBN $\rightarrow$
  \[ m_{\tilde{G}} > 10-100 \text{ TeV} \]

Pagels, Primack (1982)

Weinberg (1982)

Both inconsistent with TeV mass range
Gravitino Production 2: Reheating

• More modern view: gravitino density is diluted by inflation.

• But gravitinos regenerated in reheating. What happens?

\[ \sigma_{\text{SM}} n \sim T \gg H \sim \frac{T^2}{M_{\text{Pl}}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\text{Pl}}^2} \]

SM interaction rate >> expansion rate >> $\tilde{G}$ interaction rate

• Thermal bath of SM particles and superpartners: occasionally they produce a gravitino: $ff \rightarrow f \tilde{G}$
Gravitino Production 2: Reheating

- The Boltzmann equation:
  \[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left( n^2 - n_{eq}^2 \right) \]

- Change variables:
  \[ t \rightarrow T \quad n \rightarrow Y \equiv \frac{n}{s} \]

- New Boltzmann equation:
  \[ \frac{dY}{dT} = -\frac{\langle \sigma \tilde{G} v \rangle}{HTs} n^2 \sim \langle \sigma \tilde{G} v \rangle \frac{T^3T^3}{T^2TT^3} \]

- Simple: \( Y \sim \text{reheat temperature} \)
Bounds on $T_{RH}$

- $<\sigma v>$ for important production processes:

| process $i$ | $|\mathcal{M}_i|^2/\sigma v^2 \left(1 + m^2_{\tau}/m^2_{\chi}\right)$ |
|-------------|--------------------------------------------------------------------------------------------------|
| A           | $(g^a + g^b) \to \tilde{g}^a + G$                                                             | $4(s + 2t + 2\frac{m^2_{\tau}}{m^2_{\chi}})|f^{abc}|^2$ |
| B           | $(g^a + g^b) \to g^a + G$                                                                     | $-4(t + 2s + 2\frac{m^2_{\tau}}{m^2_{\chi}})|f^{abc}|^2$ |
| C           | $\tilde{q}_i + g^a \to q_j + G$                                                               | $2s|T_{\chi}^i|^2$ |
| D           | $g^a + q_i \to q_j + G$                                                                       | $-2|T_{\chi}^i|^2$ |
| E           | $\tilde{q}_i + q_j \to g^a + G$                                                               | $-2|T_{\chi}^i|^2$ |
| F           | $(\tilde{g}^a + \tilde{g}^b) \to \tilde{g}^a + G$                                           | $-2s\sqrt{\Delta m_{\alpha+\beta}^2} |f^{abc}|^2$ |
| G           | $q_i + \tilde{g}^a \to q_j + G$                                                               | $-4(s + \frac{m^2_{\tau}}{m^2_{\chi}})|T_{\chi}^i|^2$ |
| H           | $\tilde{q}_i + g^a \to q_j + G$                                                               | $-2(t + 2s + 2\frac{m^2_{\tau}}{m^2_{\chi}})|T_{\chi}^i|^2$ |
| I           | $(q_i + \tilde{g}^a) \to g^a + G$                                                             | $-4(t + \frac{m^2_{\tau}}{2|m^2_{\chi}|})|T_{\chi}^i|^2$ |
| J           | $\tilde{q}_i + \tilde{q}_j \to g^a + G$                                                       | $2(s + 2t + 2\frac{m^2_{\tau}}{m^2_{\chi}})|T_{\chi}^i|^2$ |

- $T_{RH} < 10^8 - 10^{10}$ GeV; constrains inflation

- $\tilde{G}$ can be DM if bound saturated

Bolz, Brandenburg, Buchmuller (2001)
Gravitino Production 3: Late Decay

- What if gravitinos are diluted by inflation, and the universe reheats to low temperature?

- $\tilde{G}$ not LSP

- $\tilde{G}$ LSP

- No impact – assumption of Lectures 1 and 2

- A new source of gravitinos

Feng, Rajaraman, Takayama (2003)
Gravitino Production 3: Late Decay

- Suppose gravitinos $\tilde{G}$ are the LSP
- WIMPs freeze out as usual
- But then all WIMPs decay to gravitinos after $M_{\text{Pl}}^2/M_W^3 \sim$ hours to month

Gravitinos naturally inherit the right density from WIMPs, but interact only gravitationally – they are superWIMPs
SuperWIMP Detection

• SuperWIMPs evade all direct, indirect dark matter searches

• But cosmology is complementary: Superweak interactions $\rightarrow$ very late decays to gravitinos $\rightarrow$ observable consequences

• Signals
  – Small scale structure
  – Big Bang nucleosynthesis
  – CMB $\mu$ distortions
SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by $\lambda_{FS}$, $Q$
- Warm DM with cold DM pedigree
- SUSY does not predict only CDM; small scale structure constrains SUSY

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)
Kaplinghat (2005)
BIG BANG NUCLEOSYNTHESIS

Late decays may modify light element abundances

After WMAP

- $\eta_D = \eta_{\text{CMB}}$

- Independent $^7\text{Li}$ measurements are all low by factor of 3:

\[
^7\text{Li}/H = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\% \text{ CL}) [27]
\]
\[
^7\text{Li}/H = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \text{sys}) [28]
\]
\[
^7\text{Li}/H = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\text{stat + sys, 95\% CL}) [29]
\]

Fields, Sarkar, PDG (2002)
BBN EM PREDICTIONS

- Consider $\tilde{\tau} \rightarrow \tilde{G} \tau$

- Grid: Predictions for
  
  $m_{\tilde{G}} = 100 \text{ GeV} - 3 \text{ TeV}$ (top to bottom)
  
  $\Delta m = 600 \text{ GeV} - 100 \text{ GeV}$ (left to right)

- Some parameter space excluded, but much survives

- SuperWIMP DM naturally explains $^7\text{Li}$!
BBN RECENT DEVELOPMENTS

• Much recent progress, results depend sensitively on what particle decays to gravitino.

• Hadronic decays are important
  – constrain $\chi \rightarrow Z \tilde{G} \rightarrow q \bar{q} \tilde{G}$
  – Slepton, sneutrino decays ok

  Kawasaki, Kohri, Moroi (2004); Jedamzik (2004); Feng, Su, Takayama (2004);
  Jedamzik, Choi, Roszkowski, Ruiz de Austri (2005)

• Charged particles catalyze BBN: $^4\text{He} X^- + d \rightarrow ^6\text{Li} + X^-$
  – Constrain $\tilde{\tau} \rightarrow \tilde{G} \tau$ to lifetimes < $10^4$ s, or maybe $10^6$ s ok
  – Neutralino, sneutrino decays ok

  Pospelov (2006); Kaplinghat, Rajaraman (2006); Kohri, Takayama (2006);
  Cyburt, Ellis, Fields, Olive, Spanos (2006); Hamaguchi, Hatsuda, Kamimura, Kino, Yanagida (2007);
  Bird, Koopmans, Pospelov (2007); Takayama (2007); Jedamzik (2007)
Cosmic Microwave Background

- Late decays may also distort the CMB spectrum

- For $10^5 \, \text{s} < \tau < 10^7 \, \text{s}$, get “$\mu$ distortions”:
  \[
  \frac{1}{e^{E/(kT)+\mu} - 1}
  \]

  $\mu=0$: Planckian spectrum
  $\mu\neq 0$: Bose-Einstein spectrum

  Hu, Silk (1993)

- Current bound: $|\mu| < 9 \times 10^{-5}$
  Future (DIMES): $|\mu| \sim 2 \times 10^{-6}$
SUPERWIMPS AT COLLIDERS

- Each SUSY event may produce 2 metastable sleptons
  Spectacular signature: slow, highly-ionizing charged tracks

  Current bound (LEP): $m_{\tilde{\chi}} > 99$ GeV

  Tevatron reach: $m_{\tilde{\chi}} \sim 180$ GeV for 10 fb$^{-1}$ (now?)

  LHC reach: $m_{\tilde{\chi}} \sim 700$ GeV for 100 fb$^{-1}$

  Drees, Tata (1990)
  Goity, Kossler, Sher (1993)
  Feng, Moroi (1996)

  Hoffman, Stuart et al. (1997)
  Acosta (2002)
  ...
Slepton Trapping

- Sleptons can be trapped and moved to a quiet environment to study their decays.

- Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?

Feng, Smith (2004)
De Roeck et al. (2005)
Slepton Range

• Ionization energy loss described by Bethe-Bloch equation:

$$\frac{dE}{dx} = K \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \ln \left( \frac{2m_ec^2\beta^2\gamma^2}{I \sqrt{1 + \frac{2m_ec^2}{M^2} + \frac{w^2}{M^2}}} \right) - \beta^2 - \frac{\delta}{2} \right]$$

$$m_\gamma = 219 \text{ GeV}$$
Model Framework

- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0=A_0=0$, $\tan \beta = 10$, $\mu > 0$
  
  $M_{1/2} = 300, 400, \ldots, 900$ GeV
Large Hadron Collider

Assume 1 m thick shell of water (10 kton)  
Sleptons trapped: ~1%, or 10 to 10^4 sleptons
International Linear Collider

\[ \begin{align*}
  m_\chi & \quad 242.9 \text{ GeV} \\
  m_{\tilde{e}_R}, m_{\tilde{\mu}_R} & \quad 227.2 \text{ GeV} \\
  m_{\tilde{\tau}_R} & \quad 219.3 \text{ GeV}
\end{align*} \]

\{ \text{mSUGRA} \}

\{ \text{NLSP only} \}

Sleptons are slow, most can be caught in 10 kton trap

Factor of \( \sim 10 \) improvement over LHC
IMPLICATIONS FROM DECAYS TO GRAVITINOS

\[ \tau(\tilde{l} \rightarrow l \tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_l^5} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_l^2} \right]^{-4} \]

- Measurement of \( \tau \), \( m_l \) and \( E_l \rightarrow m_{\tilde{G}} \) and \( G_N \)
  - Probes gravity in a particle physics experiment!
  - Measurement of \( G_N \) on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines \( \Omega_{\tilde{G}} \): SuperWIMP contribution to dark matter
  - Determines \( F \): supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)
ARE WIMPS STABLE?

- Not necessarily. In fact, they can be decaying now:
  \[ \chi \rightarrow \gamma \tilde{G} \]
- Signals in the diffuse photon flux, completely determined by 1 parameter:
  \[ \tau \simeq \frac{3\pi}{b \cos^2 \theta_W} \frac{M_P^2}{(\Delta m)^3} \simeq \frac{4.7 \times 10^{22}}{b} \frac{s}{[\text{MeV}]^3} \]
LECTURE 3 SUMMARY

• Gravitinos are excellent SUSY dark matter candidates

• Many new astrophysical implications for small scale structure, BBN, CMB, colliders

• If dark matter is at the weak scale, we are likely to make great progress in identifying it in the coming years
RECENT BOOKS