IMPLICATIONS OF PARTICLE PHYSICS FOR COSMOLOGY

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Graphic: N. Graf
OUTLINE

LECTURE 1
The Universe Observed, WIMP Cosmology

LECTURE 2
WIMP Detection, WIMPs at Colliders

LECTURE 3
Gravitino Cosmology, SuperWIMPs at Colliders
GRAVITINO COSMOLOGY

• Let’s consider a dark matter candidate with completely different, but equally rich, implications for particle physics and cosmology.

• There is one other class of particles with all the virtues of WIMPs: SuperWIMPs
  Well-motivated stable particle
  Present in “½” of parameter space
  Naturally correct relic density

• …and more
  Spectacular collider signals
  There is already cosmological evidence for it (BBN, small scale structure, …)

  The prototypical superWIMP is the gravitino (also axinos, quintessino, other similar candidates)
Gravitinos

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

- Mass: expect $\sim 100$ GeV – 1 TeV (high-scale SUSY breaking)

- $\tilde{G}$ interactions:
  \[ -\frac{i}{8M_{Pl}} \tilde{G}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \tilde{B} F_{\nu\rho} \]

  Couplings grow with energy, but are typically extremely weak
GRAVITINOS: THE FIRST SUSY DM

Pagels, Primack (1982)
Weinberg (1982)
Krauss (1983)
Nanopoulos, Olive, Srednicki (1983)

Moroi, Murayama, Yamaguchi (1993)
Bolz, Buchmuller, Plumacher (1998)

• Original 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)

Pagels, Primack (1982)

Unstable:

$$\tau_{\tilde{G}} \sim \frac{M_{Pl}^2}{m_{\tilde{G}}^3} \sim 1 \text{ yr} \left[ \frac{100 \text{ GeV}}{m_{\tilde{G}}} \right]^3$$

BBN $\Rightarrow m_{\tilde{G}} > 10$-100 TeV

Weinberg (1982)

Both inconsistent with TeV mass range.
Gravitino Production: Reheating

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

- But gravitinos regenerated in reheating. What happens?

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

SM interaction rate >> expansion rate >> \( \tilde{G} \) interaction rate

- Thermal bath of SM particles: occasionally they interact to produce a gravitino: \( ff \rightarrow f \tilde{G} \)
Gravitino Production: Reheating

• The Boltzmann equation:

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

Dilution from expansion
\[ f \tilde{G} \rightarrow f \bar{f} \quad f \bar{f} \rightarrow f \tilde{G} \]

• Change variables:

\[ t \rightarrow T \quad n \rightarrow Y \equiv \frac{n}{s} \]

• New Boltzmann equation:

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

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

- $\langle \sigma v \rangle$ for important production processes:

| Process $i$ | $|\langle MA_i \rangle|^2 / x_{\text{eff}}^2 \left(1 + \frac{m^2}{s_{\text{eff}}} \right)$ |
|-------------|--------------------------------------------------------------------------------|
| A           | $g^a + g^b \to \tilde{g}^a + \tilde{G}$                                    |
| B           | $g^a + g^b \to g^a + G$                                                     |
| C           | $\tilde{q}_i + g^a \to q_i + G$                                            |
| D           | $g^a + q_i \to \tilde{q}_i + G$                                            |
| E           | $\tilde{q}_i + q_i \to g^a + G$                                            |
| F           | $\tilde{g}^a + g^b \to \tilde{g}^a + \tilde{G}$                           |
| G           | $q_i + \tilde{g}^a \to q_i + G$                                            |
| H           | $\tilde{q}_i + g^a \to \tilde{q}_i + G$                                    |
| I           | $q_i + q_i \to \tilde{g}^a + G$                                            |
| J           | $\tilde{q}_i + q_i \to \tilde{g}^a + G$                                    |

- $T_{\text{RH}} < 10^8 - 10^{10}$ GeV; constrains inflation, leptogenesis

- $\tilde{G}$ DM if bound saturated (introduce new scale).

Bolz, Brandenburg, Buchmüller (2001)
Gravitino Production: Late Decay

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

- $\tilde{G}$ not LSP

- No impact – implicit assumption of Lectures 1 and 2

- $\tilde{G}$ LSP

- A new source of gravitinos
SuperWIMPs

- Early universe behaves as usual, WIMP freezes out with desired thermal relic density
- A long time later...
  - \( M_{Pl}^2/M_W^3 \sim \text{month} \)
  - all WIMPs decay to gravitinos
- Gravitinos inherit WIMP density, but are superweakly interacting – superWIMPs

Gravitino naturally have right relic density
SuperWIMP Signals

- SuperWIMPs escape all conventional DM searches
- But late decays $\tilde{\tau} \rightarrow \tau \tilde{G}, \tilde{B} \rightarrow \gamma \tilde{G}, \ldots,$ have cosmological consequences
- Assuming $\Omega_{\tilde{G}} = \Omega_{\text{DM}}$, signals determined by 2 parameters:
  
  $$m_{\tilde{G}}, \ m_{\text{NLSP}}$$

**Lifetime**

\[
\Gamma(\ell \rightarrow \ell \tilde{G}) = \frac{1}{48\pi M_*^2 m_{\ell}^5} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_{\ell}^2} \right]^4
\]

\[
\Gamma(\tilde{B} \rightarrow \gamma \tilde{G}) = \frac{\cos^2 \theta_W}{48\pi M_*^2 m_{\tilde{G}}^2} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2} \right]^3 \left[ 1 + 3 \frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2} \right]
\]

**Energy release**

$$\zeta_i = \epsilon_i \ B_i \ Y_{\text{NLSP}}$$

$i = \text{EM, had}$

$$Y_{\text{NLSP}} = n_{\text{NLSP}} / n_{\gamma}^{\text{BG}}$$
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:

  $^7\text{Li}/H = 1.5^{+0.9}_{-0.5} \times 10^{-10}$ (95\% CL) [27]

  $^7\text{Li}/H = 1.72^{+0.28}_{-0.22} \times 10^{-10}$ (1\sigma + sys) [28]

  $^7\text{Li}/H = 1.23^{+0.68}_{-0.32} \times 10^{-10}$ (stat + sys, 95\% CL) [29]

- $^7\text{Li}$ is now a problem

Fields, Sarkar, PDG (2002)  
Jedamzik (2004)
BBN EM Constraints

• NLSP = WIMP $\rightarrow$ Energy release is dominantly EM (even mesons decay first)

• EM energy quickly thermalized, so BBN constrains ($\tau, \zeta_{EM}$)

• BBN constraints weak for early decays: hard $\gamma, e^-$ thermalized in hot universe

• Best fit reduces $^7$Li:

Cyburt, Ellis, Fields, Olive (2002)
BBN EM Predictions

• Consider $\tilde{\tau} \rightarrow \tilde{G} \tau$ (others similar)

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

• Some parameter space excluded, but much survives

• SuperWIMP DM naturally explains $^7$Li!

Feng, Rajaraman, Takayama (2003)
BBN Hadronic Constraints

• BBN constraints on hadronic energy release are severe.

Dimopoulos, Esmailzadeh, Hall, Starkman (1988)  
Jedamzik (2004)
Reno, Seckel (1988)  
Kawasaki, Kohri, Moroi (2004)

• Neutralino NLSPs highly disfavored: hadrons from  
  \[ \chi \rightarrow Z\tilde{G}, \, h\tilde{G} \]
  destroy BBN. Possible ways out:
  - Kinematic suppression? No, \( \Delta m < m_Z \) \( \Rightarrow \) BBN EM violated.
  - Dynamical suppression? \( \chi = \tilde{\gamma} \) ok, but unmotivated.

• For sleptons, cannot neglect subleading decays:
  \[ \tilde{l} \rightarrow lZ\tilde{G}, \, \nu W\tilde{G} \quad \tilde{\nu} \rightarrow \nu Z\tilde{G}, \, lW\tilde{G} \]
BBN Hadronic Predictions

Despite $B_{\text{had}} \sim 10^{-5} - 10^{-3}$, hadronic constraints are leading for $\tau \sim 10^5 - 10^6$, must be included.

Feng, Su, Takayama (2004)
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): $|\mu| \sim 2 \times 10^{-6}$
GRAVITINOS AT COLLIDERS

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

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

Tevatron Run II reach: $m_{\tilde{\chi}} \sim 180$ GeV for 10 fb$^{-1}$

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)
...
Guaranteed Rates from Cosmology

- Cosmology implies model-independent guaranteed rates for collider signals
- WIMPs

Birkedal, Matchev, Perelstein (2004)

Pair production invisible $\rightarrow$ radiate jet or photon

\[
\sigma(ij \rightarrow X\bar{X}; \hat{s}) = \frac{\eta_{ij} v_X^2 (2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \sigma(X\bar{X} \rightarrow ij; \hat{s}) = \frac{\eta_{ij} (2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \kappa_{ij} \tan^2 \theta_{W} \varepsilon_{X}^{2n+1} \\
\kappa_{ij} = \frac{\sigma(X\bar{X} \rightarrow ij; \hat{s})}{\sigma_{\text{tot}}} 
\]
WIMP guaranteed rates not promising

The Reach of a 500 GeV LC

Dash – stat. only \((\mathcal{L} = 500 \text{ fb}^{-1})\), Solid – stat. + 0.3% syst.

Cuts: \(\sin \theta > 0.1, \ p_T^\gamma > 7.5 \text{ GeV}, \ x_\gamma \in [1 - 8M_\chi^2/s, 1 - 4M_\chi^2/s]\)
Guaranteed Rates from Cosmology

- SuperWIMPs

Feng, Su, Takayama (2004)

Stau pair production visible and spectacular!

\[ \text{WMAP } \Omega_{\text{dm}} \Rightarrow \quad \tilde{\tau} \quad \tilde{\tau} \quad \tilde{\tau} \quad \tilde{\tau} \quad e^- \quad e^+ \quad e^- \quad e^+ \]

LHC sensitive to many annihilation channels: u, d, s, c, b
SuperWIMP guaranteed rates much more promising

10 event discovery contours:
P-wave, $S_x=0$
$m_{SWIMP}/m_{WIMP}=0.6$

Scale as
$(2S_x+1)^{-2}$ and
$(m_{SWIMP}/m_{WIMP})^{-1}$
Slepton Trapping

• Cosmological constraints
  – Charged slepton NLSP
  – $\tau_{\text{NLSP}} < \text{year}$

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

  Feng, Smith (2004)
  Nojiri et al. (2004)

• Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?
To optimize trap shape and placement:

- Consider parts of spherical shells centered on $\cos \theta = 0$ and placed against detector
- Fix volume $V$ (ktons)
- Vary $(\Delta (\cos \theta), \Delta \phi)$

$r_{in} = 10$ m, 10 mwe
Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

\[
\frac{dE}{dx} = K z^2 Z \frac{1}{A} \beta^2 \left[ \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I \sqrt{1 + \frac{2m_e c^2}{M^2} + \frac{m_e^2}{M^2}}} \right) - \beta^2 - \frac{\beta}{2} \right]
\]

- Use "continuous slowing down approximation" down to \( \beta = 0.05 \)

\[ m_\gamma = 219 \text{ GeV} \]
Model Framework

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

Of the sleptons produced, $O(1)\%$ are caught in 10 kton trap

10 to $10^4$ trapped sleptons in 10 kton trap (1 m thick)
International Linear Collider

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

\{ \text{NLSP only} \}

Sleptons are slow, most can be caught in 10 kton trap
Factor of \sim 10 improvement over LHC
What we learn from slepton decays

- Gravitational decays are simple:

$$\Gamma (\tilde{\ell} \rightarrow \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2} \right]^4$$

- Measurement of $\Gamma \rightarrow m_{\tilde{G}}$
  - $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - $F$. Supersymmetry breaking scale
  - BBN in the lab

- Measurement of $\Gamma$ and $E_l \rightarrow m_{\tilde{G}}$ and $M_*$
  - Precise test of supergravity: gravitino is graviton partner
  - Measurement of $G_{\text{Newton}}$ on fundamental particle scale
  - Probes gravitational interaction in particle experiment
LECTURE 3 SUMMARY

• There are two classes of DM candidates that naturally give the correct relic density: WIMPs and SuperWIMPs

• SuperWIMPs have spectacular, but completely different implications for cosmology, colliders

• If any of this is right, there will be a rich program of cosmology at colliders

• Is any of this right? We’ll see – soon!