OUTLINE

LECTURE 1
The Universe Observed, WIMP Cosmology

LECTURE 2
WIMP Detection, WIMPs at Colliders

LECTURE 3
Gravitino Cosmology, SuperWIMPs at Colliders
WIMP Detection: No-Lose “Theorem”

Correct relic density $\rightarrow$ Efficient annihilation then
$\rightarrow$ Efficient scattering now
$\rightarrow$ Efficient annihilation now
Direct Detection

• Most satisfying detection: recoils from dark matter bumping into detectors

• Two strategies:
  – Few event detection (background discrimination)
  – Annual modulation (statistics, systematics)
Direct Detection: Current

- Spin-independent scattering most promising for SUSY
  
  Goodman, Witten (1984)

- Theorists: $\chi q$ scattering
- Expts: $\chi$ nucleus scattering
- Meet in middle: $\chi p$ scattering

DAMA’s Favored Region and Other’s Exclusion Contours

WIMP–nucleon cross section (cm$^2$)

WIMP mass (GeV c$^{-2}$)

CDMS (2005)
Direct Detection: Future

Current Sensitivity
Near Future
Future

Theoretical Predictions

Baer, Balazs, Belyaev, O’Farrill (2003)
Indirect Detection

Dark Matter Madlibs!

Dark matter annihilates in ______________ to
a place
___________, which are detected by ______________.
particles an experiment
Dark Matter annihilates in the center of the Sun to a place neutrinos, which are detected by **AMANDA, IceCube**. Some particles are annihilated and produce neutrinos, which are detected by AMANDA and IceCube in the Antarctic Ice.
Dark Matter annihilates in the galactic center to a place photons, which are detected by HESS, GLAST, ….

some particles

Typically $\chi \chi \rightarrow \gamma \gamma$, so $\chi \chi \rightarrow ff \rightarrow \gamma$
Dark Matter annihilates in the halo to a place

positrons, which are detected by AMS on the ISS.

some particles

an experiment
WIMPS AT COLLIDERS

What can colliders add to our understanding?

- Cosmology can’t discover SUSY
- Particle colliders can’t discover DM

Lifetime $> 10^{-7} \text{ s} \rightarrow 10^{17} \text{ s}$?
WIMPS AT COLLIDERS

• Choose a concrete example: neutralinos

• Choose a simple model framework that encompasses many qualitatively different behaviors: mSUGRA

• Relax model-dependent assumptions and determine parameters

• Identify cosmological, astrophysical implications
Neutralino DM in mSUGRA

Cosmology excludes much of parameter space ($\Omega_{\chi}$ too big)

Cosmology focuses attention on particular regions ($\Omega_{\chi}$ just right)

Choose 4 representative points for detailed study

Baer et al., ISAJET    Gondolo et al., DARKSUSY    Belanger et al., MICROMEGA
SYNERGY IN DM STUDIES

Collider Inputs

SUSY Parameters

$\chi\chi$ Annihilation

Relic Density

Indirect Detection

Direct Detection

$\chi N$ Interaction

Astrophysical and Cosmological Inputs
BULK REGION LCC1 (SPS1a)

$m_0, M_{1/2}, A_0, \tan\beta = 100, 250, -100, 10 \; [\mu > 0, m_{3/2} > m_{\text{LSP}}]$

- Correct relic density obtained if $\chi$ annihilate efficiently through light sfermions:

- Motivates SUSY with light $\chi, \tilde{f}$

Allanach et al. (2002)
PRECISION MASSES

- LHC: See below
- ILC: Exploit all properties: kinematic endpoints, threshold scans
  - variable beam energy
  - $e^-$ beam polarization
  - $e^-e^-$ option

Weiglein, Martyn et al. (2004)
Feng, Peskin (2001)

- Must also verify insensitivity to all other parameters
BULK RESULTS

- Scan over ~20 most relevant parameters
- Weight each point by Gaussian distribution for each observable
- ~50K scan points

(Preliminary) result: $\frac{\Delta \Omega_\chi}{\Omega_\chi} = 2.2\% \ (\Delta \Omega_\chi h^2 = 0.0026)$
RELIC DENSITY DETERMINATIONS

ILC

LHC ("best case scenario")

WMAP (current)

Planck (~2010)

Parts per mille agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
m_0, M_{1/2}, A_0, \tan\beta = 3280, 300, 0, 10 \ [\mu>0, m_{3/2}>m_{\text{LSP}}]

- Correct relic density obtained if \(\chi\) is mixed, has significant Higgsino component to enhance

- Motivates SUSY with light neutralinos, charginos

\[ \begin{align*}
M_N &= \begin{pmatrix}
M_1 \cos^2\theta_W + M_2 \sin^2\theta_W & (M_2 - M_1) \sin\theta_W \cos\theta_W \\
(M_2 - M_1) \sin\theta_W \cos\theta_W & M_1 \sin^2\theta_W + M_2 \cos^2\theta_W
\end{pmatrix} \\
M_C &= \begin{pmatrix}
M_2 \\
\sqrt{2}m_W \sin\beta \\
\mu
\end{pmatrix}
\]
FOCUS POINT RESULTS

- $\Omega_\chi$ sensitive to Higgsino mixing, chargino-neutralino degeneracy

Alexander, Birkedal, Ecklund, Matchev et al. (2005)

(Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi = 2.4\%$ ($\Delta\Omega_\chi h^2 = 0.0029$)
RELIC DENSITY DETERMINATIONS

Parts per mille agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
CO-ANNIHILATION REGION LCC3

\[ m_0, \, M_{1/2}, \, A_0, \, \tan \beta = 210, \, 360, \, 0, \, 40 \quad [\mu > 0, \, m_{3/2} > m_{\text{LSP}}] \]

• If other superpartners are nearly degenerate with the \( \chi \) LSP, they can help it annihilate

\[
\begin{array}{c}
\chi \\
\tau \\
\tilde{\tau} \\
\gamma
\end{array}
\]

Griest, Seckel (1986)

• Requires similar \( e^{-m/T} \) for \( \chi \) and \( \tilde{\tau} \), so (roughly)

\[ \Delta m < T \sim m_\chi/25 \]

• Motivates SUSY with \( \tilde{\tau} \rightarrow \tau \chi \) with \( \Delta m \sim \text{few GeV} \)
CO-ANNIHILATION RESULTS

Dutta, Kamon; Nauenberg et al.; Battaglia (2005)

(Preliminary) result: $\Delta \Omega_{\chi}/\Omega_{\chi} = 7.0\%$ ($\Delta \Omega_{\chi} h^2 = 0.0084$)
RELIC DENSITY DETERMINATIONS

% level agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
• The bottom line: LHC and International Linear Collider can discover WIMPs and determine their properties at the % level.

• These allow precise predictions of relic densities from high energy physics, which we can compare to cosmological data.

• What do we learn?
IDENTIFYING DARK MATTER

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).

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

Yes

Did you make a mistake?

No

Which is bigger?

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

Yes

Yes

No

No

Yes

Which is bigger?

$\Omega_{\text{cosmo}}$

$\Omega_{\text{hep}}$

Yes

No

Can you discover another particle that contributes to DM?

Yes

No

Can you identify a source of entropy production?

Yes

No

Can this be resolved with some wacky cosmology?

Yes

Think about the cosmological constant problem

Yes

No

No

Yes

Does it decay?

Yes

No

No

Does it account for the rest of DM?

No

Yes

No
SYNERGY IN DM STUDIES

Collider Inputs

SUSY Parameters

\( \chi \chi \) Annihilation

Relic Density

Indirect Detection

Direct Detection

\( \chi N \) Interaction

Astrophysical and Cosmological Inputs
ILC IMPLICATIONS

ILC $\Rightarrow \Delta m < 1$ GeV, $\Delta \sigma/\sigma < 10\%$

Comparison tells us about local dark matter density and velocity profiles
Dark Matter annihilates in the galactic center to a place photons, which are detected by GLAST, HESS, … .

Halo profiles are poorly understood, controversial near the galactic center.
LECTURE 2 SUMMARY

• If a WIMP is part of dark matter, the LHC and the ILC together can measure its properties precisely.

• Comparison of predicted and observed relic density can lead to discovery (finally!) of the identity of dark matter, or require the existence of another component.

• Comparison of predicted and observed detection rates will tell us about the distribution of dark matter in the galaxy, structure formation.