ILC AND NEW DEVELOPMENTS IN COSMOLOGY

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5 February 2007

BILCW07

Graphic: N. Graf
COSMOLOGICAL REVOLUTION

- Remarkable agreement
  
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  [Baryons: 4% ± 0.4%
  Neutrinos: 2% (\(\Sigma m_\nu/eV\)) ]

- Remarkable precision (~10%)

- Remarkable results
DARK MATTER QUESTIONS

• What is its mass?
• What is its spin?
• What are its other quantum numbers and interactions?
• Is it absolutely stable?
• What is the symmetry origin of the dark matter particle?
• Is dark matter composed of one particle species or many?
• How was it produced?
• When was it produced?
• Why does $\Omega_{DM}$ have the observed value?
• What was its role in structure formation?
• How is dark matter distributed now?
DARK ENERGY QUESTIONS

• What is it?
• Why not $\Omega_\Lambda \sim 10^{120}$?
• Why not $\Omega_\Lambda = 0$?
• Does it evolve?

BARYON QUESTIONS

• Why not $\Omega_B \approx 0$?
• Related to leptogenesis, leptonic CP violation?
• Where are all the baryons?

What tools do we need to answer these?
PARTICLE PHYSICS AT THE ENERGY FRONTIER
DARK MATTER

- We know how much there is:
  \[ \Omega_{\text{DM}} = 0.23 \pm 0.04 \]

- We know what it’s not:
  - Not short-lived: \( \tau > 10^{10} \) years
  - Not baryonic: \( \Omega_B = 0.04 \pm 0.004 \)
  - Not hot: must be “slow” to seed structure formation
DARK MATTER CANDIDATES

- There are many candidates
- Masses and interaction strengths span many, many orders of magnitude
- But not all are equally motivated. Focus on:
  - WIMPs
  - SuperWIMPs

WIMPS

(1) Assume a new (heavy) particle $\chi$ is initially in thermal equilibrium:

$$\chi \chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi \chi \leftrightarrow \bar{f} f$$

(3) $\chi$'s “freeze out”:

$$\chi \chi \not\leftrightarrow f f$$
• The amount of dark matter left over is inversely proportional to the annihilation cross section:

\[ \Omega_{DM} \sim \langle \sigma_A v \rangle^{-1} \]

Scherrer, Turner (1986)

• What is the constant of proportionality?

• Impose a natural relation:

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

\[ \Omega_{DM} \sim 0.1 \text{ for } m \sim 100 \text{ GeV} - 1 \text{ TeV} \]

Cosmology alone tells us we should explore the weak scale
STABILITY

• This assumes a *stable* new particle, but this is generic:

  Problems
  (proton decay, extra particles, EW precision constraints…)
  ⇧
  Discrete symmetry
  ⇧
  Stability

• Dark matter is easier to explain than no dark matter, and with the proliferation of EWSB models has come a proliferation of WIMP possibilities.
NON-DECOUPLING

- New physics does not decouple cosmologically:

  \[ \Omega \sim m^2 \]

  There are loopholes, but very heavy particles are disfavored, independent of naturalness.
WIMPS FROM SUPERSYMMETRY

Goldberg (1983); Ellis et al. (1983)

Supersymmetry: many motivations. For every known particle $X$, predicts a partner particle $\tilde{X}$

Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

In many models, $\chi$ is the lightest supersymmetric particle, stable, neutral, weakly-interacting, mass $\sim 100$ GeV. All the right properties for WIMP dark matter!
Minimal Supergravity

Cosmology excludes many possibilities, favors certain regions

Co-annihilation region

Bulk region

Focus point region

Yellow: pre-WMAP
Red: post-WMAP

Too much dark matter
WIMPS FROM EXTRA DIMENSIONS

- Extra spatial dimensions could be curled up into small circles of radius $R$
- Particles moving in extra dimensions appear as a set of copies of SM particles

$$m_{\text{KK}} = R^{-1}$$

- New particle masses are integer multiples of $m_{\text{KK}}$
  - $4m_{\text{KK}}$
  - $3m_{\text{KK}}$
  - $2m_{\text{KK}}$
  - $m_{\text{KK}}$
  - $0$

Servant, Tait (2002); Cheng, Feng, Matchev (2002)
Minimal Universal Extra Dimensions

Kakizaki, Matsumoto, Senami (2006)

Excluded
(Charged LKP)

Not enough DM

Too much DM

WMAP preferred
WIMP DETECTION

Correct relic density $\rightarrow$ Efficient annihilation then
$\rightarrow$ Efficient annihilation now
$\rightarrow$ Efficient scattering now
DIRECT DETECTION

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

- (Coherent) spin-independent scattering most promising for most WIMP candidates

- Theorists: \( \chi q \) scattering
  Expts: \( \chi \) nucleus scattering
  Compromise: \( \chi p \) scattering
Indirect Detection

Dark matter annihilates in ________________ to a place
____________ , which are detected by ________________ .

particles an experiment
Dark Matter annihilates in the halo to a place, which are detected by PAMELA. Some particles annihilate in a place, which are detected by PAMELA. An experiment.
PROSPECTS

If the relic density “coincidence” is no coincidence and DM is WIMPs, the new physics behind DM will very likely be discovered in the next few years:

- Direct dark matter searches
- Indirect dark matter searches

The Tevatron at Fermilab
The Large Hadron Collider at CERN
What then?

- Cosmology 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?
Contributions to Neutralino WIMP Annihilation

Jungman, Kamionkowski, Griest (1995)
The Approach of the ALCPG Cosmology Group:

- 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, astroparticle 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
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 \( \chi, \tilde{\ell} \)

Allanach et al. (2002)
PRECISION SUSY @ LHC

- LHC produces strongly-interacting superpartners, which cascade decay

\[
\begin{align*}
(m^2_{q_i})_{\text{edge}} &= \frac{(m^2_{\tilde{q}_2} - m^2_{\tilde{q}_2}) (m^2_{\tilde{t}} - m^2_{\tilde{t}^0})}{m^2_{\tilde{q}_2}} \\
(m^2_{q_{til}})_{\text{edge}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_L}) (m^2_{\tilde{t}_1} - m^2_{\tilde{t}_1})}{m^2_{\tilde{q}_L}} \\
(m^2_{q_{til}})_{\text{min}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_L}) (m^2_{\tilde{t}_1} - m^2_{\tilde{t}_1})}{m^2_{\tilde{q}_L}} \\
(m^2_{q_{til}})_{\text{max}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_L}) (m^2_{\tilde{t}_1} - m^2_{\tilde{t}_1})}{m^2_{\tilde{q}_L}} \\
(m^2_{q_{til}})_{\text{thres}} &= \frac{[(m^2_{\tilde{q}_L} + m^2_{\tilde{q}_L}) (m^2_{\tilde{t}_1} + m^2_{\tilde{t}_1}) (m^2_{\tilde{t}_1} - m^2_{\tilde{t}_1}) - (m^2_{\tilde{q}_L} - m^2_{\tilde{q}_L}) \sqrt{(m^2_{\tilde{q}_L} + m^2_{\tilde{q}_L})^2 (m^2_{\tilde{t}_1} + m^2_{\tilde{t}_1})^2 - 16m^2_{\tilde{q}_2} m^2_{\tilde{q}_2} m^2_{\tilde{t}_1}}}{4m^2_{\tilde{q}_2}}
\end{align*}
\]
**PRECISION SUSY @ ILC**

- Exploit all properties
  - kinematic endpoints
  - threshold scans
  - $e^-$ beam polarization
  - $e^-e^-$ option

- Must also verify insensitivity to all other parameters

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Diagram showing $e^-e^-$ and $e^+e^-$ interactions with kinematic endpoints and energy spectra.

Table:

<table>
<thead>
<tr>
<th>$m$ [GeV]</th>
<th>$\Delta m$ [GeV]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_1^\pm$</td>
<td>176.4</td>
<td>0.55</td>
</tr>
<tr>
<td>$m_1$</td>
<td>378.2</td>
<td>3</td>
</tr>
<tr>
<td>$\chi_2^0$</td>
<td>96.1</td>
<td>0.05</td>
</tr>
<tr>
<td>$\chi_3^0$</td>
<td>176.8</td>
<td>1.2</td>
</tr>
<tr>
<td>$\chi_4^0$</td>
<td>358.8</td>
<td>3 – 5</td>
</tr>
<tr>
<td>$e_R$</td>
<td>143.0</td>
<td>0.05</td>
</tr>
<tr>
<td>$e_L$</td>
<td>202.1</td>
<td>0.2</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>186.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$\mu_R$</td>
<td>143.0</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu_L$</td>
<td>202.1</td>
<td>0.5</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>120.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>206.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$t_1$</td>
<td>379.1</td>
<td>2</td>
</tr>
</tbody>
</table>
RELIC DENSITY DETERMINATIONS

% level agreement → Identity of dark matter

<table>
<thead>
<tr>
<th>Experiment</th>
<th>m_χ (GeV)</th>
<th>Δ(Ω_χ h^2)/Ω_χ h^2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMAP (current)</td>
<td>90-110</td>
<td>-20 to 20</td>
</tr>
<tr>
<td>LHC (&quot;best case scenario&quot;)</td>
<td>&gt;100</td>
<td>-10 to 10</td>
</tr>
<tr>
<td>Planck (~2010)</td>
<td>&gt;100</td>
<td>-10 to 10</td>
</tr>
<tr>
<td>LCC1</td>
<td>&gt;100</td>
<td>-10 to 10</td>
</tr>
</tbody>
</table>

ALCPG Cosmology Subgroup
MODEL DEPENDENCE

- LHC/ILC determination of relic densities has now been studied by many groups.
  Allanach, Belanger, Boudjema, Pukhov (2004)
  Moroi, Shimizu, Yotsuyanagi (2005)
  Baltz, Battaglia, Peskin, Wizansky (2006)

- Bottom line: LHC results are not always good, but ILC removes degeneracies

Baltz, Battaglia, Peskin, Wizansky (2006)
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

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

No

Which is bigger?

Yes

Did you make a mistake?

No

Can you discover another particle that contributes to DM?

Yes

Does it decay?

No

Can you identify a source of entropy production?

Yes

Can this be resolved with some non-standard cosmology?

No

Does it account for the rest of DM?

Yes

Think about the cosmological constant problem

No

No

No

No
DIRECT DETECTION IMPLICATIONS

\[ \text{LHC + ILC} \rightarrow \Delta m < 1 \text{ GeV, } \Delta \sigma/\sigma < 20\% \]

Comparison tells us about local dark matter density and velocity profiles
INDIRECT DETECTION IMPLICATIONS

Very sensitive to halo profiles near the galactic center

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

Particle Physics  Astro-Physics
SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

• Consider gravitinos (also KK gravitons, axinos, quintessinos, …):
  spin 3/2, mass $\sim M_W$, couplings $\sim M_W/M^*$.  

Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Roszkowski et al. (2004); …

• $G$ not LSP

• $G$ LSP

• Assumption of most of literature

• Completely different cosmology and physics
SUPERWIMP RELICS

- Suppose gravitinos $\tilde{G}$ are the LSP.

- WIMPs freeze out as usual

- But then all WIMPs decay to gravitinos after $M_{Pl}^2/M_W^3 \sim$ hours to month

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs, impossible to detect directly
WORST CASE SCENARIO?

Looks bad – dark matter couplings suppressed by $10^{-16}$

But, cosmology $\rightarrow$ decaying WIMPs are sleptons: heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

How many can be trapped?

Feng, Smith (2004)
De Roeck et al. (2005)
Martyn (2006)
Large Hadron Collider

If squarks, gluinos light, many sleptons, but most are fast:
\( O(1)\% \) are caught in 10 kton trap

\( M_{1/2} = 600 \text{ GeV} \)
\( m_{\tilde{l}} = 219 \text{ GeV} \)

\( L = 100 \text{ fb}^{-1}/\text{yr} \)
International Linear Collider

$m_{\tilde{\tau}_R} \ 219.3 \text{ GeV } \quad \{ \text{NLSP only} \}

Novel use of tunable beam energy: adjust to produce slow sleptons, 75% are caught in 10 kton trap

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IMPLICATIONS FROM SLEPTON DECAYS

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

- Measurement of \( \Gamma \) and \( E_\ell \to m_{\tilde{G}} \) and \( M_* \)
  - Probes gravity in a particle physics experiment!
  - Measurement of \( G_{\text{Newton}} \) 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
  - Early universe cosmology in the lab
Resolve cosmological discrepancies?

**BBN \(^7\)Li problem:** Late decays can modify BBN

**CDM is too cold:** Late decays warm up DM

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Discrepancies resolved in bands

Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Takayama et al. (2005)
Bringmann, Borzumati, Ullio (2006)
CONCLUSIONS

• Cosmology now provides sharp problems that are among the most outstanding in basic science today.

• They require new particle physics, cannot be solved by cosmological tools alone.

• In many cases, the quantitative precision of ILC is essential to determine qualitative answers.