The LC and the Cosmos: Connections in Supersymmetry

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The Particle/Cosmo Interface

Many Grand Questions:

• **Baryogenesis**
  – Why is there more matter than anti-matter?

• **Ultra-high Energy Cosmic Rays**
  – What are the highest energy particles detected?

…

• **Dark Matter**
  – What is most of the matter in the universe made of?
Dark Matter

• The dawn of precision cosmology:

\[ t_0 = 13.7 \pm 0.2 \text{ Gyr} \]
\[ \Omega_{\text{total}} = 1.02 \pm 0.02 \]
\[ \Omega_{\text{DM}} = 0.23 \pm 0.04 \]
\[ \Omega_{\text{baryon}} = 0.044 \pm 0.004 \]
\[ \Omega_\nu < 0.015 \left( m_\nu < 0.23 \text{ eV for degenerate case} \right) \]

WMAP (2003)

• We live in interesting times:
  – We know how much dark matter there is
  – We have no idea what it is
WIMPs

- Weakly-interacting particles with weak-scale masses naturally provide $\Omega_{DM}$

- Either
  - a devious coincidence,
  or
  - a strong, fundamental, and completely independent motivation for new physics at the electroweak scale

Jungman, Kamionkowski, Griest (1995)
Limitations of Separate Approaches

- Dark matter experiments cannot discover SUSY
  - can only provide rough constraints on mass, interaction strengths

- Colliders cannot discover dark matter
  - can only verify $\tau > 10^{-7}$ s, 24 orders of magnitude short of the age of the universe
Synergy

Feng, Nojiri (2002)

Collider Inputs

SUSY Parameters

\( \chi \chi \) Annihilation

Relic Density

\( \chi N \) Interaction

Indirect Detection

Direct Detection

Astrophysical and Cosmological Inputs
\( \chi \chi \) Annihilation

- Neutralino annihilation: sensitive to most SUSY parameters
  - Top diagram vanishes for heavy scalar superpartners
  - Bottom diagram vanishes for \( \chi = \) pure Bino

\[ \begin{aligned}
\chi \quad & \quad \bar{f} \\
\chi \quad & \quad \tilde{f} \\
\chi \quad & \quad f \\
\chi \quad & \quad W^- \\
\chi \quad & \quad \chi_i^+ \\
\chi \quad & \quad W^+ 
\end{aligned} \]

- \( \Omega_\chi < 0.3 \) requires
  - Light scalars, or
  - Mixed neutralinos, light Higgsinos
  \( \Rightarrow \) typically, rich LC physics
Relic Density

• Extreme sensitivity to neutralino mixing

• Extreme sensitivity to degeneracies

E.g., $\chi - \tau$ co-annihilation requires mass measurements much better than

$$\Delta m \sim T \sim m_\chi/25$$

Accurate $\Omega_\chi$ determination requires full capabilities of the Linear Collider
Many handles at colliders. E.g., gaugino-ness measurements:

- LHC/LC: Mass measurements of all charginos and neutralinos
- LC: Polarized measurements of lighter chargino pair production

LC500 Right-polarized chargino pair production cross sections (fb)

Feng, Murayama, Peskin, Tata (1995)
Dark Matter Detection

- Direct detection depends on $\chi N$ scattering

- Indirect detection depends on $\chi \chi$ annihilation

  $\chi \chi \rightarrow \gamma$ in galactic center
  $\chi \chi \rightarrow e^+$ in halo

  or both

  $\chi \chi \rightarrow \nu$ in centers of the Sun and Earth
Indirect Detection Experiments

TABLE I. Current and planned neutrino experiments. We list also each experiment’s (expected) start date, physical dimensions (or approximate effective area), muon threshold energy \(E_{\mu}^{\text{thr}}\) in GeV, and 90\% CL flux limits for the Earth \(\Phi_\mu\) and Sun \(\Phi_{\odot}\) in km\(^{-2}\) yr\(^{-1}\) for half-cone angle \(\theta \approx 15^\circ\) when available.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Dimensions</th>
<th>(E_{\mu}^{\text{thr}})</th>
<th>(\Phi_\mu)</th>
<th>(\Phi_{\odot})</th>
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<tbody>
<tr>
<td>Baksan [65]</td>
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<td>Kamiokande [66]</td>
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<td>MACRO [67]</td>
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<td>Super-Kamiokande</td>
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<td>Baikal NT-96 [6]</td>
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<td>AMANDA B-10</td>
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<td>Baikal NT-200</td>
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<td>AMANDA II [7]</td>
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<td>NESTOR [72]</td>
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<td>ANTARES [73]</td>
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<td>IceCube [71]</td>
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</table>

* 2 GeV for Sun

TABLE II. Some of the current and planned \(\gamma\) ray detector experiments with sensitivity to photon energies 10 GeV \(\lesssim E_\gamma \lesssim 300\) GeV. We list each experiment’s (proposed) start date and expected \(E_\gamma\) coverage in GeV. The energy ranges are approximate. For experiments constructed in stages, the listed threshold energies will not be realized initially. See the references for details.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>(E_\gamma) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGRET [88]</td>
<td>Satellite</td>
<td>1991-2000</td>
<td>0.02-30</td>
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<tr>
<td>STACEE [89]</td>
<td>ACT array</td>
<td>1998</td>
<td>20-300</td>
</tr>
<tr>
<td>CELESTE [90]</td>
<td>ACT array</td>
<td>1998</td>
<td>20-300</td>
</tr>
<tr>
<td>ARGO-YBJ [91]</td>
<td>Air shower</td>
<td>2001</td>
<td>100-2,000</td>
</tr>
<tr>
<td>MAGIC [92]</td>
<td>ACT</td>
<td>2001</td>
<td>10-1000</td>
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<tr>
<td>AGILE [93]</td>
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<tr>
<td>HESS [94]</td>
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<tr>
<td>AMS/(\gamma) [95]</td>
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<tr>
<td>CANGARO</td>
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<td>VERITAS [8]</td>
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<td>GLAST [98]</td>
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</table>

TABLE III. Recent and planned \(e^+\) detector experiments. We list each experiment’s (expected) start date, duration, geometrical acceptance in cm\(^2\) sr, maximal \(E_{e^+}\) sensitivity in GeV, and (expected) total number of \(e^+\) detected per GeV at \(E_{e^+} = 50\) and 100 GeV.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Duration</th>
<th>Acceptance</th>
<th>(E_{e^+}^{\text{max}})</th>
<th>(dN/dE) (50)</th>
<th>(dN/dE) (100)</th>
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<tbody>
<tr>
<td>HEAT94/95 [114]</td>
<td>Balloon</td>
<td>1994/95</td>
<td>29/26 hr</td>
<td>495</td>
<td>50</td>
<td></td>
<td></td>
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<tr>
<td>CAPRICE94/98 [115]</td>
<td>Balloon</td>
<td>1994/98</td>
<td>18/21 hr</td>
<td>163</td>
<td>10/30</td>
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<td></td>
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<tr>
<td>PAMELA [116]</td>
<td>Satelite</td>
<td>2002-5</td>
<td>3 yr</td>
<td>20</td>
<td>200</td>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>AMS-02 [117]</td>
<td>Space station</td>
<td>2003-6</td>
<td>3 yr</td>
<td>6500</td>
<td>1000</td>
<td>2300</td>
<td>250</td>
</tr>
</tbody>
</table>
Dark Matter Detection

- Particle probes
  - Direct DM detection
  - Indirect DM detection

- Astrophysical and particle searches are complementary
- SUSY at LC500 → dark matter signal before ~2007 (in mSUGRA)
Particle/Cosmo Interface

- Particle Physics + standard cosmology $\rightarrow$ predictions for $\Omega_\chi$
  - Direct detection rates
  - Indirect detection rates

- If consistent with observations and experiments, we understand the universe back to $10^{-8}$ sec ($T \sim 10$ GeV)

[Cf. Big Bang nucleosynthesis at 1 sec ($T \sim 1$ MeV)]
What if there are discrepancies?

- Thermal relic density need not be the actual relic density – late decays, …
  - The mismatch tells us about the history of the universe between $10^{-8} \, \text{s} < t < 1 \, \text{s}$

- The detection rate need not be the actual detection rate
  - the mismatch tells us about halo profiles, dark matter velocity distributions, …

- LHC/LC will not only identify DM as SUSY, but also may shed light on “astrophysical” problems
Example: Halo profile at the galactic center

• Halo profiles are currently not well-known (cuspy, clumpy, …)

• An indirect dark matter signal is photons from the galactic center:

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \frac{dN^i_\gamma}{dE} \sigma_i v \frac{1}{4\pi m^2_\chi} \int \rho^2 dl$$

Buckley et al. (1999)

Feng, Matchev, Wilczek (2000)
superWIMPs

- WIMP motivations are strong, suggest optimism for detection: weaker interactions $\rightarrow$ too much relic density

- But this relation may be broken:
  - E.g., gravitino LSP, WIMP NLSP
    - WIMP freezes out as usual, but then decays to gravitino
    - gravitino inherits the desired $\Omega$
    - Gravitino interacts only gravitationally, is a superWIMP

\[ \tau_{\text{Bino}} \text{ for } m_{\text{gravitino}} = 0.1, 0.3, 1, 3 \text{ TeV from below} \]
Implications

- Gravitino dark matter escapes all dark matter experiments

- Astrophysical superWIMP detection depends on NLSP:

  \( \gamma \) superWIMP
  - diffuse \( \gamma \) signature
  - CMB deviations from black-body

  \( \nu \) superWIMP
  - CMB anisotropy

  e superWIMPs, q superWIMPs, …

- Colliders may see meta-stable massive charged particles, provide valuable information
Conclusions

• Dark matter and EWSB are independent motivations for new physics; both point to the weak scale

• Both collider and astrophysical/cosmological data are required to get anywhere

• High sensitivity to SUSY parameters – LC inputs are likely to be extremely valuable