The LC and the Cosmos: Connections in Supersymmetry

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Many Big 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 matter made of?
Dark Matter

- We live in interesting times
  - We know how much dark matter there is
    \( \Omega_{DM} = 0.24 \pm 0.05 \)
  - We have no idea what it is

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

- This is either a devious coincidence, or dark matter provides a strong, fundamental, and completely independent motivation for new particles at the electroweak scale
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

Collider Inputs → SUSY Parameters

\( \chi \chi \) Annihilation \( \chi N \) Interaction

Relic Density \( \rightarrow \) Indirect Detection \( \rightarrow \) Direct Detection

Astrophysical and Cosmological Inputs

Feng, Nojiri (2002)
Relic Density

- Neutralino freeze out: sensitive to most SUSY parameters
- Co-annihilations $\rightarrow$ Extreme sensitivity to degeneracies
- E.g., $\chi - \tau$ co-annihilation requires mass measurements much better than $\Delta m \sim T \sim m/25$
- Requires full capabilities of LC (see Dutta’s talk)
Relic Density

- Extreme sensitivity to neutralino mixing:

\[ \chi \rightarrow W^- \chi_i \]

vanishes for pure Bino, even 10% gaugino-ness changes $\Omega_{DM}$ drastically.

Feng, Matchev, Wilczek (2000)
• Many handles at colliders

  – LC: Polarized measurements of chargino pair production

  – LHC/LC: Mass measurements of all charginos and neutralinos
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
  $\chi \chi \rightarrow$ anti-protons

- or both
  
  $\chi \chi \rightarrow \nu$ in centers of the Earth and Sun
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 $\Phi_{\mu}^\oplus$ and Sun $\Phi_{\mu}^\odot$ in $\text{km}^{-2} \text{ yr}^{-1}$ 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>$\Phi_{\mu}^\oplus$</th>
<th>$\Phi_{\mu}^\odot$</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-Kamiokante</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$^\dagger$ [72]</td>
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<td>ANTARES [73]</td>
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<td>IceCube [71]</td>
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<td>* 2 GeV for $\Sigma$</td>
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TABLE II. Some of the current and planned $\gamma$ ray detector experiments with sensitivity to photon energies $10 \text{ GeV} \lesssim E_{\gamma} \lesssim 300 \text{ GeV}$. 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>
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<tbody>
<tr>
<td>EGRET [88]</td>
<td>Satellite</td>
<td>1991-2000</td>
<td>0.02-30</td>
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<td>STACEE [89]</td>
<td>ACT array</td>
<td>1998</td>
<td>20-300</td>
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<td>CELESTE [90]</td>
<td>ACT array</td>
<td>1998</td>
<td>20-300</td>
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<tr>
<td>ARGO-YBJ [91]</td>
<td>Air shower</td>
<td>2001</td>
<td>100-2,000</td>
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<tr>
<td>MAGIC [92]</td>
<td>ACT</td>
<td>2001</td>
<td>10-1000</td>
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<td>AGILE [93]</td>
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<td>HESS [94]</td>
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<td>AMS/\gamma [95]</td>
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<tr>
<td>CANGARO</td>
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<td>VERITAS [7]</td>
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<td>GLAST [98]</td>
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</table>

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Duration</th>
<th>Acceptance</th>
<th>$E_{e^{\pm}}$ Sensitivity</th>
<th>$\frac{dN}{dE}(50)$</th>
<th>$\frac{dN}{dE}(100)$</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>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>PAMELA [116]</td>
<td>Satellite</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

- Astrophysical and particle searches are complementary

- SUSY at LC500 requires some dark matter signal before ~2007 (in mSUGRA)

- Relic Density →
  - scalars light or
  - Higgsinos light (neutralinos mixed)

Rich physics at LC

Feng, Matchev, Wilczek (2000)
Cosmo/Astro Inputs/Outputs

• Thermal relic density need not be the actual relic density – late decays, etc.
  – The mismatch tells us about the history of the universe between $10 \text{ GeV} > T > 1 \text{ MeV}$ or $10^{-8} \text{ s} < t < 1 \text{ s}$

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

• LHC/LC not only required to identify SUSY, but also sheds light on “astrophysical” problems
Example: Halo profile at the galactic center

- Halo profiles are extremely poorly known (cuspy, clumpy, …)

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

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

Particle Physics

Astro-Physics

Buckley et al. (1999)

Feng, Matchev, Wilczek (2000)
superWIMPs

• WIMP motivations are strong, and suggest optimism for detection: weaker interactions \(\rightarrow\) too much relic density

• But one can break this relation:

  E.g., gravitino LSP, sneutrino NLSP
  – Sneutrino freezes out to WIMP density, then decays to roughly degenerate gravitino
  – gravitino is a superWIMP, interacts only gravitationally

Feng, Rajaraman, Takayama (2003)
Implications

• Dark matter escapes all dark matter experiments

• Astrophysical superWIMP detection depends on character of NLSP

\[ \nu \text{ superWIMP} \]
  – CMB signature

\[ \gamma \text{ superWIMP} \]
  – diffuse \( \gamma \) signature
  – BBN signature

\[ e \text{ superWIMPs, } q \text{ superWIMPs, …} \]

• Colliders see meta-stable massive charged particles, etc. provide invaluable information
Conclusions

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

• Both colliders and dark matter experiments are required to get anywhere

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