Dark matter relic density from observations of supersymmetry at the ILC

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DESY

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Dark matter experiments

Indirect detection

Production at colliders

Direct detection

DM

SM

DM

SM
Measurements at the ILC

Production at the ILC

$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$ $e^-$ $e^+$

SUSY

Production at the ILC
Cosmological vs. collider precision

\[ \Omega_{CDM} h^2 = 0.1197 \pm 0.0022 \]

\[ \Rightarrow \Delta = 2\% \]

\[ \Omega_{CDM} h^2 = ? \pm ? \]

\[ \Rightarrow \Delta = ?\% \]
How is DM relic density determined

- relic density $\propto$ present day abundance $Y(T_0)$
- $\frac{dY}{ds} \propto \langle \sigma v \rangle (Y^2 - Y_{eq}(T)^2)$
- Full model $\Rightarrow$ prediction for relic density
- micrOMEGAs a code to calculate relic density
  arXiv:1305.0237
Dark matter mechanisms in SUSY

Stau coannihilation is one of the preferred mechanisms to explain dark matter in SUSY

Mastercode arXiv:1508.01173v1
Processes in stau coannihilation

- Pair annihilation depends on LSP mixing and sfermion mass

- Coannihilation depends strongly on the stau-LSP mass difference
Variation of dark matter with masses

- Typical variations in a scenario with many light sparticles

| Observable | $\pm$ variation | $\pm$ change in $\Omega$ |
|------------|-----------------|-------------------------|
| $m_{\tilde{\chi}^0_1}$ | 1% | 5% |
| $m_{\tilde{\tau}_1}$ | 1% | 5% |
| $m_{\tilde{l}_R}$ | 1% | < 0.5% |
| $m_{\tilde{l}_L}$ | 1% | < 0.01% |
| $m_{\tilde{\nu}}$ | 10% | < 0.1% |
| $m_{H,A_0}$ | 10% | < 0.1% |
| $m_{\tilde{\chi}_i}$ | 10% | < 0.1% |
| $m_{\tilde{q}}$ | 10% | < 0.01% |

- LSP and stau1 mass crucial, others much less important

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Variation of dark matter with mixings

- Typical variations in a scenario with many light sparticles

| "observable"                        | ± variation | ± change in $\Omega$ |
|-------------------------------------|-------------|----------------------|
| stau mixing angle $\theta_\tau$     | 1%          | 1%                   |
| binoness of LSP $N_{11}$            | 1%          | 3.5%                 |
| other neutralino mixings            | 100%        | $\sim 1 - 4\%$      |
| Higgs mixing                        | 50%         | 2%                   |
| other mixings                       | 50%         | $< 0.1\%$            |

- Stau and LSP mixing also crucial, Higgs and other neutralino mixings needed to $\sim 10\%$

- What can the ILC give? Study a concrete example
Stau coannihilation observable at the ILC

- pMSSM point with 12 parameters ”STC8” (arXiv:1307.0782)
- $m_{\tilde{\chi}_1^0} = 96$ GeV (bino), $m_{\tilde{\tau}_1} = 107$ GeV (RH)
- True relic density value 0.113
Stau coannihilation observable at the ILC

- pMSSM point with 12 parameters "STC8" (arXiv:1307.0782)
- \( m_{\tilde{\chi}_1^0} = 96 \text{ GeV (bino)},\ m_{\tilde{\tau}_1} = 107 \text{ GeV (RH)} \)
- True relic density value 0.113
SGV analysis of STC8 done by Berggren (arXiv:1508.04383v1)

More details tomorrow early afternoon BSM

$\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ endpoint $\Rightarrow \Delta m_{\tilde{\tau}_1} = 0.15\%$
500GeV measurements

- Can discover all sleptons, sneutrinos, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$
- Precisions on masses and mixings:

| Parameter              | Value 1 | Value 2 |
|------------------------|---------|---------|
| $m_{\tilde{\chi}_1^0}$| 0.15%   | 0.5%    |
| $m_{\tilde{\tau}_1}$  | 0.16%   | 2.5%    |
| $m_{\tilde{\nu}_{eR}}$| 0.17%   | 0.40%   |
| $m_{\tilde{e}_L}$     | 1%      | 1%      |
| $m_{\tilde{\nu}_{e,\mu,\tau}}$ | 1% | 1% |
| $\theta_{\tau}$       | 1%      | 20%     |
| $N_{11,12,13,14}$     | 1% each | $U_{mix}$, $V_{mix}$ 20% each |
Stau1 and LSP mass vs mixings

- **Red**: LSP mass and stau1 mass varied 0.15%
- **Blue**: LSP mixings and stau1 mixing varied 1%
- With these assumptions, mixings dominate uncertainty on relic density $\Omega$

The graph shows the distribution of relic density $\Omega$ with and without mass variations. The blue line represents the case where mixings and stau1 mixing are varied by 1%, while the red line shows the case with mass variations for LSP and stau1. The table below provides summary statistics for the relic density distribution:

| Distribution | Entries | Mean | RMS |
|--------------|---------|------|-----|
| $\Omega$     | 10000   | 1    | 0.002928 |
| $\Omega_2$   | 10000   | 1.001| 0.0334 |

- Precisions of stau mixing and LSP mixings need to be studied.
Important to measure: binoness of LSP

- **Blue**: LSP and stau1 mass 0.15%, LSP, stau1 mixings 1%
- **Red**: same but N11 (binoness) fixed

![Histogram of Omega and Omega2](image)

- Omega
  - Entries: 10000
  - Mean: 1
  - RMS: 0.008752

- Omega2
  - Entries: 10000
  - Mean: 1.001
  - RMS: 0.03355

**Note:**
- N11 fixed
- N11 varied
500 GeV measurements

- **Red**: all sleptons, sneutrinos, $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ varied, rest fixed. 
  $\Delta \Omega = 3.5\%$ (fix $N11 \implies \Delta \Omega = 2\%$)

- **Blue**: same but squarks uniformly varied 1 - 50 TeV, 
higgses 0.4 - 2 TeV and $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\pm$ 0.25 TeV - 2 TeV

- Unobserved sector causes $\sim 1\sigma$ shift of the mean

![Histogram of Omega](image)
Assumptions for 1TeV measurements

- Assume no further improvement on light sparticle measurements (over-conservative)
- Extended Higgs masses: $\Delta = 1\%$
- $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\pm$: $\Delta = 1\%$

- Red: unobservables fixed
- Blue: unobservables free
- No shift from unobservables, width is similar
Not considered

- MicrOMEGAs $\rightarrow$ tree-level SUSY cross-sections
- SUSY loop corrections can give $\sim 10\%$ (e.g. arXiv:0710.1821v3)
- This probably just a shift of the mean predicted $\Omega$ (for other coannihilation scenarios arXiv:1510.0629v1)
MicrOMEGAs → tree-level SUSY cross-sections
SUSY loop corrections can give ≈ 10%
(e.g. arXiv:0710.1821v3)
This probably just a shift of the mean predicted Ω
(for other coannihilation scenarios arXiv:1510.0629v1)

$h_0 - H_0$ mixing angle ignored
Related to couplings of light Higgs
In stau-coannihilation: if sleptons, sneutrinos and light gauginos discovered and if mixings measured to 1% 

⇒ ILC precision on relic density $\sim 2 \times$ Planck precision

With current assumptions, uncertainties on mixing properties dominate over mass uncertainties

Need a more reliable estimate of the ILC capabilities e.g. from tau polarisation and polarised cross sections

With real discoveries would need to consider loop corrections
Backup: 500 GeV assumptions

500 GeV discoveries
black=estimate, blue=analysis
(arXiv:1508.04383v1)

|                  | 0.15% | 0.5% |
|------------------|-------|------|
| $m_{\chi_1^0}$  |       |      |
| $m_{\tau_1}$    | 0.16% | 2.5% |
| $m_{e_R}$       | 0.17% | 0.40%|
| $m_{\tilde{e}_L}$ | 1%    |      |
| $m_{\tilde{\nu}_e,\tilde{\nu}_\mu,\tilde{\nu}_\tau}$ | 1%    |      |
| $\theta_{\tau}$ | 1%    | 20%  |

$N_{11,12,13,14}$ 1% each $U_{mix}, V_{mix}$ 20% each

Unobservables at 500 GeV - uniform variations

|                  | 0.25 – 2 TeV | 0.25 – 2 TeV |
|------------------|--------------|--------------|
| $m_{\chi_3^0,\chi_4^0}$ |              |              |
| $m_{H_0,A_0,H^\pm}$   | 0.4 – 2 TeV  |              |
| $m_{\tilde{d}_L,\tilde{u}_L,\tilde{s}_L,\tilde{c}_L}$ all equal | 1 – 50 TeV | $m_{\tilde{d}_R,\tilde{u}_R,\tilde{s}_R,\tilde{c}_R} = m_{\tilde{d}_L} - 100$ GeV |
| $m_{\tilde{t}_1,\tilde{t}_2,\tilde{b}_1,\tilde{b}_2}$ independent | 0.6 – 50 TeV | $m_{\tilde{g}}$ 1 – 50 TeV |
| $\theta_{t,b}$ | $-\pi/2 \rightarrow \pi/2$ | $A_{t,b}$ $-5000 \rightarrow 5000$ |
Backup: 1 TeV assumptions

1 TeV observations

| Particle  | 0.17% | 0.40% |
|-----------|-------|-------|
| $m_{\tilde{e}_R}$ |       |       |
| $m_{\tilde{e}_L}$ | 1%    |       |
| $m_{\tilde{\tau}_1}$ | 0.16% |       |
| $m_{\tilde{\tau}_2}$ |       | 2.5%  |
| $\theta_T$ | 1%    |       |
| $A_T$ |       | 20%   |
| $m_{\tilde{\nu}_e,\tilde{\nu}_\mu,\tilde{\nu}_\tau}$ | 1%    |       |
| $m_{\chi_{1,2}^0}$ | 0.15% | 0.5%  |
| $N_{12,13,14}$ | 1% each |       |
| $m_{\chi_{3,4}^0}$ | 1%    |       |
| $m_{\tilde{H}_0,A_0,H^\pm}$ | 1%    |       |

Unobserved at 1 TeV

| Parameter             | Mass     |
|-----------------------|----------|
| $m_{\tilde{d}_L,\tilde{u}_L,\tilde{s}_L,\tilde{c}_L}$ | all equal 1 – 50 TeV |
| $m_{\tilde{t}_1,\tilde{t}_2,\tilde{b}_1,\tilde{b}_2}$ | independent 0.6 – 50 TeV |
| $\theta_{t,b}$ | 0 → $\pi/2$ |
| $m_{\tilde{g}}$ | 1 – 50 TeV |
| $A_{t,b}$ | 0 → −5000 |