Non-thermal WIMPS

or

WIMPs in low reheating temperature cosmological models

Dark Matter-Colliders, June 11, 2006
Within the standard cosmology neutralinos in CMSSM are the CDM only in the blue narrow bands (e.g. J. Ellis et.al.2005)
\( T_{RH} \): highest temperature of the most recent radiation dominated epoch of the Universe

**Standard cosmological assumptions:** \( T_{RH} \) is large,

- neutralinos are produced thermally and reach equilibrium before decoupling
- the entropy of matter and radiation is conserved

**Well motivated alternative: moduli decay**

Moduli fields: pervasive in SUSY models, \( m_\phi = O(10-100) \) TeV - gravitational strength couplings....thus,

\[
T_{RH} \simeq 10 \text{ MeV} \left( \frac{m_\phi}{100 \text{ TeV}} \right)^{3/2} \left( \frac{M_P}{\Lambda_{\text{eff}}} \right)
\]
Low $T_{RH}$ cosmological scenarios: $T_{RH} \geq 5$ MeV

non-standard cosmological models with a late episode of entropy production: moduli decay, Q-ball decay, thermal inflation......

- $T_{RH} <$ standard freeze-out temperature: thermal production suppressed
- $\phi$-decays produce entropy, which dilutes the neutralino abundance
- $\phi$ can decay into SUSY particles producing $b$ neutralinos per decay

G.G. and P. Gondolo, hep-ph/0602230 and G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, hep-ph/0605016: **Only two parameters** $T_{RH}$ and $b/m_\phi$ ($\eta = b(100\text{TeV}/m_\phi)$)
Thermal and non-thermal production mechanisms have been considered many times


but coherent overview was missing.........
In non-standard cosmologies (with two more parameters determined by the physics at the high scale: $T_{RH}, \eta$) the narrow bands can be anywhere in the parameter space: in all models the neutralino can have the CDM density!
**Standard cosmology:**

$T_{RH}$ is very large, neutralino production is thermal, and ceases when $\Gamma < H$ (freeze-out) at $T \simeq m_\chi/20$ yielding $\Omega_{\text{std}} \simeq 2 \times 10^{-10} \text{GeV}^{-2}/<\sigma v>$

**Low $T_{RH}$ cosmologies:**

Neutralino thermal production is suppressed, non-thermal production due to the decay of the entropy-producing scalar field may be important.

**With the right combination of $T_{RH}$ and $\eta$ any neutralino with standard density $\Omega_{\text{std}} > 10^{-5}(100\text{GeV}/m_\chi)$ can have the right density to be the dark matter**

(We assumed $m_\phi < 2m_{3/2}$ to avoid the gravitino problem)
Range of $\Omega_{\text{std}} h^2$ for millions of points in mSUGRA

Ted Baltz
Late decaying scalar scenario

G.G. and P. Gondolo
hep-ph/0602230

Two additional parameters: $T_{RH}$ and $\eta = b \frac{100\text{TeV}}{m_\phi}$

Four different cases for $\Omega h^2$ vs $T_{RH}$
Graciela Gelmini - UCLA

MSSM

Standard cosmology

G.G., Gondolo, Soldatenko and Yaguna, hep-ph, 0605016

Neutralino mass (GeV)

$\Omega h^2$

$10^{-4}$

$10^{-2}$

$10^{0}$

$10^{2}$

$10^{4}$

$10^{6}$

Neutralino mass (GeV)

$100$

$1000$

$10000$

Wmap

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MSSM


All points can be brought to cross the WMAP red line with suited $T_{RH}$, $\eta$. 

Neutralino Mass (GeV) vs. $\Omega h^2$ for different $T_{RH}$ and $\eta$.
For neutralinos to be the CDM anywhere in the parameter space we need, $b/m_{\phi} \approx (10^{-8} - 10^{-2})$ neut./100 TeV.
Neutralino warm dark matter
Lin, Huang, Zhang and Brandenberger (2001); Hisano, Kohri and Nojiri (2001)

Cold dark matter may have problems with structure at small scales.

Dark matter may be warm.....

Warm dark matter requires speed now (if $p_\chi$ only redshifts):

$$v_0 = \frac{T_0}{T_{RH}} \frac{E_I}{m_\chi} \simeq 10^{-7},$$

$E_I$: energy at production at $T_{RH}$

Thus:

$\chi$ must be produced hot +late+ must not lose energy in interactions with thermal bath, i.e. must not interact $\Gamma_{\text{scat.}} < H$
Neutralino warm dark matter

Late decaying scalar scenario G.G. and C. Yaguna (in preparation)

\[ b \simeq N 10^{-4} \left( N = \frac{m_\phi}{E_I} \right) \]

\[ m_\phi \simeq N 10^3 \text{TeV} \times \left( \frac{100 \text{GeV}}{m_\chi} \right) \left( \frac{T_{RH}}{10 \text{MeV}} \right) \]

\( \chi \) is a Bino in Split-SUSY type model:

\[ \mu(m_\tilde{\nu}) > 5(20) \text{TeV} \times \left( \frac{100 \text{GeV}}{m_\chi} \right)^{1/4} \left( \frac{T_{RH}}{10 \text{MeV}} \right)^{3/4} \]

Difficult for DM searches!
CONCLUSIONS

• Low-$T_{RH}$ cosmologies are more complicated than the standard one, this does not mean nature did not choose one of them....

• Different aspects of low-$T_{RH}$ models have been studied with interesting results, but no consistent all encompassing scenario yet...

• Many string (or plain supersymmetric) and other models predict a late episode of entropy production...

• Any neutralino with standard density $\Omega_{\text{std}} > 10^{-5}(100\text{GeV}/m_\chi)$ can have the right density to be the dark matter

• If the LHC pinpoints a model rejected by the dark matter constraint within the standard cosmology, we may have discovered something important about cosmology before Big-Bang Nucleosynthesis, such as low-$T_{RH}$, and constrain the physics at the Planck scale!
MSSM + mSUGRA
Standard cosmology
G.G., Gondolo, Soldatenko and Yaguna,
MSSM$^+$
mSUGRA

$T_{RH} = 10$ GeV

$\eta = 0$

G.G., Gondolo, Soldatenko and Yaguna,
**MSSM + mSUGRA**

\[ T_{RH} = 10 \text{ GeV} \]

\[ \eta = \frac{10^{-9}}{100 \text{ TeV}} \]

G. G. Gondolo, Soldatenko and Yaguna,
MSSM + mSUGRA

\[ T_{RH} = 10 \text{GeV} \]
\[ \eta = \frac{10^{-6}}{100 \text{TeV}} \]

G.G., Gondolo, Soldatenko and Yaguna,
MSSM + mSUGRA

\[ T_{RH} = 1 \text{ GeV} \]

\[ \eta = \frac{10^{-6}}{100 \text{ TeV}} \]

G.G., Gondolo, Soldatenko and Yaguna,
MSSM + mSUGRA

\[ T_{RH} = 100 \text{MeV} \]

\[ \eta = \frac{10^{-6}}{100 \text{TeV}} \]

G.G., Gondolo, Soldatenko and Yaguna,

\[ \Omega h^2 \]

G.G., Gondolo, Soldatenko and Yaguna,

\[ T_{RH} = 100 \text{MeV}, \ \eta = 1 \times 10^{-6} \]

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**MSSM** + **mSUGRA**

\[ T_{RH} = 10 \text{MeV} \]

\[ \eta = \frac{10^{-6}}{100 \text{TeV}} \]

G.G., Gondolo, Soldatenko and Yaguna,