Dark Matter and Early Universe

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Introduction
What happened before recombination?

- Quantum gravity? Branes? Other gravitation theories?
- Inflation
- Topological defects (cosmic strings, magnetic monopoles, domain walls, ...)?
- Primordial Black Holes?
- Leptogenesis
- Baryogenesis
- Particle-antiparticle asymmetry
- QCD-dominated plasma
- Relic particle freeze-out/in
- Big-Bang nucleosynthesis
- ...

Big-Bang nucleosynthesis (BBN) is the oldest epoch which leads to direct observations.
Hypothesis: dark matter (DM) made of thermal relics.

**Thermal relics**

- Stable, massive and weakly interacting particles
- Particles in thermal equilibrium in the early Universe
- At lower temperature, suppressed interactions with the thermal bath
- Annihilation/co-annihilation of relic particles down to freeze-out temperature ($\sim 10 - 100$ GeV)
- Out-of-equilibrium description through Boltzmann equations
- Good particle physics candidates should have the observed cold dark matter density
- Standard particle physics candidates are in reach of the LHC and dark matter detection experiments

For illustrative purposes: dark matter composed of the MSSM lightest neutralinos.
MSSM neutralino

**Minimal Supersymmetric extension of the Standard Model (MSSM)**

- More than 100 free parameters
- Provided $R$-parity is conserved, SUSY particles produced in pairs
- The lightest supersymmetric particle is stable
- 4 neutralinos and 2 charginos: supersymmetric partners of the Higgs ($h, H, A, H^\pm$) and vector bosons ($\gamma, Z, W^\pm$)
- The lightest neutralino is a suitable dark matter candidate

**Lightest neutralino $\tilde{\chi}_1^0 \equiv \chi$**

- Mixed state of bino/wino/higgsino (photino/zino/higgsino)
- if mostly bino, very weakly interacting
- if mostly wino, accompanied by one chargino close in mass
- if mostly higgsino, accompanied by one chargino and another neutralino close in mass
- if mixed, more strongly interacting

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MSSM neutralino

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Relic density: standard calculation

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation
  \[ H^2 = \frac{8\pi G}{3} \times \rho_{\text{rad}} \]
- the evolution of the number density of all supersymmetric particles follows the Boltzmann equation
  \[ \frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2) \]
- the time and temperature are related through the adiabaticity condition:
  \[ \frac{ds_{\text{rad}}}{dt} = -3Hs_{\text{rad}} \]

Thermal average of effective cross section (\(k_{1,2}: \text{modified Bessel functions}\)):

\[
\langle \sigma_{\text{eff}} v \rangle = \frac{\int_0^\infty dp_{\text{eff}} p_{\text{eff}}^2 \, W_{\text{eff}} \, K_1 \left( \frac{\sqrt{s}}{T} \right)}{m_1^4 \, T \left[ \sum_i g_i \frac{m_i^2}{m_\chi^2} K_2 \left( \frac{m_\chi}{T} \right) \right]^2}
\]

where: (ij: coannihilating SUSY particles / kl: SM outgoing particles)

\[
\frac{dW_{\text{eff}}}{d \cos \theta} = \sum_{ijkl} \frac{p_{ij} p_{kl}}{32\pi p_{\text{eff}} S_{kl} \sqrt{s}} \sum_{\text{helicities}} \left| \sum_{\text{diagrams}} M(ij \rightarrow kl) \right|^2
\]
Neutralino relic density

The relic density is then obtained: (Today: $T_0 = 2.725$ K)

$$\Omega_X h^2(T_0) \equiv 2.755 \times 10^{-8} \frac{\rho_X(T_0)}{s_{rad}(T_0)}$$

with $\rho_X = m_X n(T_0)$

Very precise measurements of cold dark matter density by Planck (+ others) (2015):

$$\Omega_c h^2(T_0) = 0.1188 \pm 0.0010$$

The Planck results lead to very strong constraints on supersymmetric parameters.


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Caveat!

Many unobservable phenomena could have happened during the pre-BBN era.
For example, the expansion rate can be modified:

$$H^2 = \frac{8\pi G}{3} \times (\rho_{\text{rad}} + \rho_D)$$

The entropy content of the Universe can also be altered!

$$\frac{ds_{\text{rad}}}{dt} = -3Hs_{\text{rad}} + \Sigma_D$$

⇒ Modified relation between time, expansion rate and temperature!

And relics can be generated non-thermally:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}}v \rangle (n^2 - n_{eq}^2) + N_D$$

$$\rho_D, \Sigma_D \text{ and } N_D \text{ are model-dependent...}$$
Relic density: decaying scalar field

Scenario with a pressureless decaying scalar field (e.g. modulus, late inflaton, dilaton, ...) of energy density $\rho_\phi$:

$$H^2 = \frac{8\pi G}{3} (\rho_{rad} + \rho_\phi)$$

We define the scalar field decay width $\Gamma_\phi$, with a large branching fraction to radiation and a (tiny) branching ratio $b$ to neutralinos:

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$
$$\frac{ds_{rad}}{dt} = -3Hs_{rad} + \frac{\Gamma_\phi \rho_\phi}{T}$$
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle (n^2 - n_{eq}^2) + \frac{b}{m_\phi} \Gamma_\phi \rho_\phi$$

Decay width related to the reheating temperature $T_{RH}$:

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{eff} (T_{RH})}{45} \frac{T_{RH}^2}{M_P}}$$

Important parameters:

$$\eta = b \left( \frac{1 \text{ GeV}}{m_\phi} \right)$$
$$\kappa_\phi = \frac{\rho_\phi(T_{init})}{\rho_\gamma(T_{init})}$$
Relic density: decaying scalar field

Evolution of the scalar field density, neutralino density and entropy injection $\tilde{\Sigma}^* \equiv \frac{\Gamma_\phi \rho_\phi}{3HT_{rad}}$ as a function of $x = m_\chi / T$, in absence of non-thermal production of neutralinos ($\eta = 0$).

(a) $T_{RH} = 0.01$ GeV, $\kappa_{\phi}^{init} = 100$, $T_{init} = 40$ GeV

(b) $T_{RH} = 10$ GeV, $\kappa_{\phi}^{init} = 100$, $T_{init} = 40$ GeV

Complex interplay between expansion rate and entropy injection...

In absence of non-thermal neutralino production, results in a decrease of the relic density.
We consider a point with too large relic density (CMSSM point with bino-like neutralino):

\[ \Omega_{\text{standard}} h^2 = 1.27 \quad \text{to be compared to} \quad \Omega_{\text{Planck}} h^2 = 0.1188 \pm 0.0010 \]

The dark region corresponds to the Planck value \( \pm 10\% \) theoretical uncertainty.

The whole parameter region is compatible with Big-Bang nucleosynthesis constraints.

The relic density can be easily decreased by 3–4 orders of magnitude for any values of \( \eta \).
Relic density: decaying scalar field

We consider a point with too small relic density (pMSSM point with higgsino-like neutralino):

\[ \Omega_{\text{standard}} h^2 \approx 5.9 \times 10^{-3} \]

to be compared to

\[ \Omega_{\text{Planck}} h^2 = 0.1188 \pm 0.0010 \]

The dark region corresponds to the Planck value \( \pm 10\% \) theoretical uncertainty.

The whole parameter region is compatible with Big-Bang nucleosynthesis constraints

The relic density is decreased in absence of \( \eta \), but can be easily increased by 2–3 orders of magnitude for tiny values of \( \eta \).

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Conclusions

- Decaying scalar fields can increase or decrease relic density by orders of magnitude.
- Cosmological quintessence can increase relic density by orders of magnitude.
- It is not possible to exclude a new physics scenario using only relic density constraints.
- Relic density constraints can simultaneously set limits on BOTH a new physics model AND a cosmological scenario.
- If new particles are discovered, relic density will provide constraints on the early Universe properties at $T \sim \text{GeV–TeV}$.

Advertisement

  - G. Robbins’ talk tomorrow at 6:45pm!
  - [https://alterbbn.hepforge.org/](https://alterbbn.hepforge.org/)
- Open sources and user-friendly codes
- Flexible cosmological scenario implementation
Backup
Relic density: quintessence

Quintessence: cosmological scalar field giving a dynamical explanation for dark energy

\[ H^2 = \frac{8\pi G}{3} \left( \rho_{\text{rad}} + \rho_\phi \right) \]

Klein-Gordon equation:

\[ \frac{d\rho_\phi}{dt} = -3H(\rho_\phi + P_\phi) \]

\[ P_\phi = \frac{1}{2} \dot{\phi}^2 - V(\phi) \]

\[ \rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi) \]

Many possibilities for the potential, e.g. \( V(\phi) = \alpha_1 \exp(-\beta_1 \phi) + \alpha_2 \exp(-\beta_2 \phi) \)

Today: \( V(\phi) \gg \dot{\phi}^2 \iff P_\phi \approx -\rho_\phi \iff \rho_\phi \propto T^0 \)

In the very early Universe: \( \dot{\phi}^2 \gg V(\phi) \iff P_\phi \approx +\rho_\phi \iff \rho_\phi \propto T^6 \)

Different possibilities in intermediate times, depending on the choice of the potential and values of the potential parameters.
We checked that full quintessence evolution can be parametrised in the following way:

Here $\rho_\phi \propto T^n$, where $n$ can be modified at different times.

Since quintessence can only add an energy density to the Friedmann equation and therefore accelerate the expansion, the relic density can only be increased in this scenario.
Relic density: quintessence

We consider a point with too small relic density:

$$\Omega_{\text{standard}} h^2 = 5.9 \times 10^{-3}$$

to be compared to

$$\Omega_{\text{Planck}} h^2 = 0.1188 \pm 0.0010$$

Grey regions excluded by Big-Bang nucleosynthesis constraints

Dashed lines corresponds to the Planck value

The relic density can be increased by 2–3 orders of magnitude by the presence of quintessence

However, neutralinos with a standard relic density \( \lesssim 3 \times 10^{-4} \) can not be restored because of BBN constraints