Big-Bang nucleosynthesis, early Universe and relic particles

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Introduction

History of the Universe

Key:
- q: quark
- g: gluon
- e: electron
- m: muon
- n: neutrino
- W, Z: bosons
- photon
- meson
- baryon
- ion
- atom
- star
- galaxy
- black hole

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
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 is the oldest epoch which leads to direct observations.
Hypothesis: dark matter made of thermal relics.

**Thermal relics**

- Stable, massive and weakly interacting particles
- Particles in thermal equilibrium in the early Universe
- Below the freeze-out temperature ($\sim 10 - 100 \text{ GeV}$), suppressed interactions with the thermal bath
- Annihilation/co-annihilation of the relic particles
- 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, sparticles produced in pairs
- The lightest sparticle 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 very mixed, more strongly interacting
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:
  \[ \frac{ds_{\text{rad}}}{dt} = -3Hs_{\text{rad}} \]

Thermal average of effective cross section \((\kappa_1, 2: \text{modified Bessel functions})\):

\[
\langle \sigma_{\text{eff}}v \rangle = \frac{\int_{0}^{\infty} dp_{\text{eff}} p_{\text{eff}}^2 W_{\text{eff}} K_1 \left( \frac{\sqrt{s}}{T} \right)}{m_1^4 T \left[ \sum_i g_i \frac{m_i^2}{m_1^2} K_2 \left( \frac{m_i}{T} \right) \right]^2}
\]

where: \((ij: \text{coannihilating SUSY particles} / kl: \text{SM outgoing particles})\)

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

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

$$\Omega_c h^2 = 0.1188 \pm 0.0010$$

Binos generally have a too large relic density, except when close in mass to other (co-annihilating) sparticles.
Heavy winos and higgsinos can have naturally a correct relic density.

The Planck results lead to very strong constraints on supersymmetry.
Caveat!

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

We can parametrize the modification by adding a “dark density” $\rho_D$:

$$H^2 = \frac{8\pi G}{3} \times (\rho_{\text{rad}} + \rho_D) \text{ with } \rho_D(T) = \rho_D(T_{\text{BBN}})(T/T_{\text{BBN}})^{n_D}$$

- $n_D = 4$: radiation-like behaviour
- $n_D = 6$: behaviour of a scalar field dominated by its kinetic term
- $n_D > 6$: decaying scalar field

where

$$\kappa_D = \rho_D(T_{\text{BBN}})/\rho_\gamma(T_{\text{BBN}})$$

Big-Bang Nucleosynthesis (BBN) occurs at $T \sim \text{MeV}$ and can impose strong limits on this kind of models, since it may be affected by the presence of a dark density.
Deuterium fraction

Helium fraction

Accepted regions below the lines.

Observationally: \( Y_p = 0.2449 \pm 0.0040, \ 2^\text{H}/H = (2.527 \pm 0.030) \times 10^{-5}. \)
Relic density: influence of a modified expansion rate

Pure bino (667 GeV, $\Omega_{\text{std}} h^2 = 22.5$)  
Pure higgsino (510 GeV, $\Omega_{\text{std}} h^2 = 0.0174$)

Relic density mainly increased, possibly by several orders of magnitude.

Planck 2015: $\Omega_c h^2 = 0.1188 \pm 0.0010$
The entropy content of the Universe can also be altered!

⇒ Modified relation between time, expansion rate and temperature!

Possible parametrisation:

\[
\frac{ds_{\text{rad}}}{dT} = -3Hs_{\text{rad}} + \Sigma_D
\]

\[
\Sigma_D(T) = \Sigma_D(T_{\text{BBN}})(T/T_{\text{BBN}})^{n_D}
\]

- \( n_D \sim 5 - 7 \): entropy evolution of a decaying scalar field

where

\[
\kappa_D = \Sigma_D(T_{\text{BBN}})/\Sigma^\text{eff}_\gamma(T_{\text{BBN}})
\]

with

\[
\Sigma^\text{eff}_\gamma(T_{\text{BBN}}) = \frac{1}{M_P} \sqrt{\frac{8\pi^3}{5}} T_{\text{BBN}}^2 s_\gamma(T_{\text{BBN}})
\]

This modification can push the relic density in the other direction!
Big-Bang Nucleosynthesis: influence of entropy injection

Deuterium fraction

Helium fraction

Accepted regions below the lines.

Observationally: $Y_p = 0.2449 \pm 0.0040$, $^2H/H = (2.527 \pm 0.030) \times 10^{-5}$. 
Relic density: influence of entropy injection

Pure bino (667 GeV, $\Omega_{\text{std}}h^2 = 22.5$)

Pure higgsino (510 GeV, $\Omega_{\text{std}}h^2 = 0.0174$)

Relic density decreased or increased, possibly by several orders of magnitude.

Planck 2015: $\Omega_c h^2 = 0.1188 \pm 0.0010$
Calculation of BBN abundances in alternative cosmologies

Authors: Alexandre Arbey, Kevin Hickerson and Espen Jenssen

Website: https://alterbbn.hepforge.org/

Features of AlterBBN

- Open source code written in C.
- High readability, user friendly.
- Fast calculation of the abundance of the elements.
- 26 elements, nuclear network of 100 processes.
- Different cosmological scenarios (reheating, dark energy, WIMP, ...).
- Automatic calculation of the errors and correlations.
- Parallel routines for faster correlation calculation.
- New manual to be released soon!
SuperIso Relic v4.0 (beta1)

Calculation of flavour physics and dark matter observables

Authors: Alexandre Arbey, Farvah Nazila Mahmoudi and Glenn Robbins

Website: http://superiso.in2p3.fr/relic/

Features of SuperIso Relic

- Open source code written in C (particle physics amplitudes in Fortran).
- Calculation of relic density, and direct and indirect detection observables and observability
- Particle physics models: MSSM and NMSSM currently included
- Generalisation towards other models ongoing: link with FeynRules and automatical calculation of the amplitudes.
- Different cosmological scenarios.
- Linked with AlterBBN.
- Contains SuperIso, for the calculation of flavour physics observables.
- New manual to be released soon!

Conclusions

- Dark matter particles may be strongly affected by the possible phenomena in the early Universe.
- Big-Bang Nucleosynthesis can help setting limits on the possible deviations.
- If dark matter particles are discovered, scenarios leading to too large or too small relic densities should not be disregarded.
- Results rather general, valid also for non-SUSY scenarios and non-WIMPs.

Perspectives

- Further improvements in AlterBBN v2.0 and SuperIso Relic v4.0.
- Detailed manuals will appear soon.
- Other cosmological scenarios can be implemented.
- Generic version of SuperIso Relic will be released soon.
- Do not hesitate to suggest new features, scenarios, ...
- Feedback is welcome if you use the codes!