Particle Dark Matter: Production Mechanisms

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PHYS 792

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Feb. 4, 2014 (W4-1)
1. Standard Cosmology & Particle Physics
2. Thermal Production, Standard Cosmology
3. Non-Thermal Production, Standard Cosmology
4. Non-Standard Cosmology
5. Reminders
Standard Cosmological Model

- Multiple Epochs \((t = 0 - t \sim 10^{-36} \text{ s})\): the earliest stage of the Universe, about which we know very little.

- Inflation Epoch \((t \sim 10^{-36} \text{ s} - t \sim 10^{-32} \text{ s})\): A hypothetical period of rapid expansion in which the Universe increased in volume by a factor on the order of \(10^{77}\).

- Radiation Dominated Epoch (ended at \(t \sim 47000 \text{ yr}\)): Period during which the expansion of the Universe was driven primarily by radiation.

- Big Bang Nucleosynthesis \((t \sim \text{minutes})\): The temperature of the Universe fell to the point that atomic nuclei (e.g. He and Li) could form. The remaining abundances of these elements make this the earliest time in the Universe from which we have any data.
Matter Dominated Epoch ($t \sim 47000 \text{ yr} - t \approx 5 \times 10^9 \text{ yr}$): The period when expansion was decelerating due to the gravitational influence of matter, including dark matter.

(Re)combination ($t \approx 375000 \text{ yr}$): The point at which the Universe was cool enough for electrons to stay bound to protons, forming the first atoms. This is the period from which the cosmic microwave background was emitted.

Dark Energy Dominated Epoch ($t \approx 5 \times 10^9 \text{ yr} - \text{ present}$): The $\Lambda$ parameter, usually called dark energy, is causing the expansion of the Universe to accelerate.
What are the most important properties of a particle?
Particle Properties

- Mass
- Cross sections ($\sigma$) for various reactions and interactions
- Electric Charge
- Spin
- Interactions (weak, strong, electromagnetic, gravitational)

Particle Production
If dark matter is composed of unknown particles, then those particles must have been made at some point before Big Bang Nucleosythesis. That fact, combined with the data we have from BBN and other cosmological evidence we have discussed, places constraints on potential dark matter candidates.
Assumptions with Standard Cosmology

- We have no data from the pre-BBN epoch, when dark matter particles would have been created and their present densities established.
- The entropy of matter and radiation were conserved in the radiation-dominated epoch.
- Dark matter particles were produced during the radiation-dominated epoch.
- Dark matter particles were produced thermally, that is by interactions with particles in the plasma composing the early Universe.
- They “decoupled” from the plasma. In other words, they stopped interacting with the temperature and density of the early Universe fell to sufficiently low levels.
Standard Thermal Production Mechanism$^1$

We denote the dark matter particle $\chi$. For some period in the early Universe, these particles were in equilibrium through annihilation reactions

$$\chi\bar{\chi} \leftrightarrow e^+e^-, q\bar{q}, W^+W^-, Z^0\bar{Z}^0, HH, \ldots$$  \hspace{1cm} (1)

The rate of annihilation/creation is given by

$$\Gamma = \langle \sigma_{\text{ann}} v \rangle n_{\text{eq}},$$  \hspace{1cm} (2)

where $\sigma_{\text{ann}}$ is the annihilation cross section of the DM particle, $v$ is the particle’s relative velocity, and $n_{\text{eq}}$ is the number density while in equilibrium.

$^1$This and following slides are largely taken from Bertone, Ch. 7 (arXiv:1002.3828)
Determining the Relic Density

By **relic** we mean a particle that was created in the early Universe and is stable (or has a lifetime significantly longer than the age of the Universe) and is thus still present. The relic density can be computed using the equation for the dark matter number density:

\[
\frac{dY}{dx} = \frac{1}{3H} \frac{ds}{dx} \langle \sigma v \rangle (Y^2 - Y_{eq}^2). \tag{3}
\]

where \( Y = n/s \), \( x = m/T \), and \( T \) the photon temperature; \( n \) is the number density of DM particles, \( s \) is the entropy density, \( H \) is the Hubble parameter, and \( m \) is mass of the particle.

...Skipping a whole bunch of theory that you can read in arXiv:1002.3828 at your convenience...
Equation 3 can be rewritten as

$$\frac{dY}{dx} = - \left( \frac{45}{\pi M_P^2} \right)^{-1/2} \frac{g_*^{1/2} m}{x^2} \langle \sigma v \rangle (Y^2 - Y_{eq}^2).$$

(4)

where $M_P = 1.22 \times 10^{19}$ GeV is the Planck mass and

$$g_*^{1/2} = \frac{h_{\text{eff}}}{g_{\text{eff}}^{1/2}} \left( 1 + \frac{1}{3} \frac{T}{h_{\text{eff}}} \frac{dh_{\text{eff}}}{dT} \right).$$

(5)

This single equation is then numerically solved with the initial condition $Y = Y_{eq}$ at $x \simeq 1$ to obtain the present dark matter abundance $Y_0$. 
From it, the dark matter relic density can be computed as

$$\Omega_\chi h^2 = \frac{\rho^0_\chi h^2}{\rho^0_c} = \frac{m_\chi s_0 Y_0 h^2}{\rho^0_c} = 2.755 \times 10^8 Y_0 m_\chi / \text{GeV}, \tag{6}$$

where, $\rho^0_c$ and $s_0$ are the present critical density and entropy density respectively. In obtaining the numerical value in Eq. (6) we used $T_0 = 2.726$ K for the present background radiation temperature and $h_{\text{eff}}(T_0) = 3.91$ corresponding to photons and three species of neutrinos.
Gravitational Production

- A class of candidates, known as WIMPZILLAs, resulting from the gravitational creation of matter in an accelerating Universe.
- WIMPZILLAs are very massive relics from the Big Bang: they can be the dark matter in the universe if their mass is $\approx 10^{13}$ GeV. They might be produced at the end of inflation through a variety of possible mechanisms: gravitationally, during preheating, during reheating, in bubble collisions.
- We will discuss these in a later class.
Decays

Dark matter may be produced in the decay of other particles. If the DM particles are non-interacting when the decay occurs, they inherit (except for some entropy dilution factor) the density of the parent particle $P$

$$\Omega_{\text{DM}} \ h^2 \simeq \frac{m_{\text{DM}}}{m_P} \Omega_P \ h^2.$$  \hspace{1cm} (7)

This is the case of superWIMPs (see the assigned reading), extremely weakly interacting particles produced in the late decays of certain particles (e.g. axinos or gravitinos from the decay of neutralinos or sleptons) which practically only interact gravitationally and cannot be directly detected.
Non-Standard Cosmology

- A vast proliferation of models exists that produce dark matter particles while violating some of the assumptions made earlier.
- We will cover some of these in classes on specific candidates.
- Since we are focusing on dark matter from an experimental perspective and this is not a Cosmology class, most of these models are beyond our scope.
- If you are interested, you can read about them in §7.4 of Bertone (arXiv:1009.3690) and references therein.
Reminders

- **Assigned Reading for Feb. 11:** Bertone, Ch. 10 (available at arXiv:1002.3828)
- All midterm presentation topics have been chosen.
  - Doug Tiedt: MaCHOs (Feb. 27)
  - Dan Rederth: Sterile Neutrinos
  - Tyler Bogwardt: Modified Gravity
  - Hari Chapagain: Axions
- Choose your topic for final presentation on or before Feb. 20
- Since we have no USD students, for most of the rest of the semester we will be in CB 110, except February 27 and April 3, when we will be back in CB 108.