Cosmological Production of Dark Matter

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&
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1. Introduction

- Cold and hot thermal relic
  - How heavy/light can a dark matter particle be?
- WIMP miracle

2. Production Mechanisms

- Thermal freeze-out
  - Annihilation $2 \leftrightarrow 2$ Processes
  - Resonances
  - Threshold
  - Co-annihilation
  - Semi-annihilation
- Non-thermal freeze-in
  - FIMP Miracle
  - Late time decays
- Asymmetric production
  - Matter-dark matter coincidence
  - Matter-antimatter
- Modified cosmological history
  - Late time decays
ZOO OF DARK MATTER CANDIDATES

- **WIMPzila**: I'm super heavy
- **SIMPs**: I exist in QCD so why can't I be dark?
- **FIMP**: I do not like to interact with anyone
- **asymmetric**: I'm still in the pic you know...

**Sterile neutrinos**

**WIMP**

**AXION**: I am still the king

**If he dies it's my turn**

**Well..we never know..**

**BLACK HOLES**

**GRAVITINO**: bad luck... nightmare scenario

**I have to freeze-in to survive**

**dark photon**
Our current knowledge of elementary particles is summarized by the so-called Standard Model.

It includes all the known elementary particles.

It correctly predicts their interactions.

Does it account for all there is?

No! There is Dark Matter!
In 1933 Fritz Zwick used the virial theorem to infer the existence of unseen matter in the Coma galaxy cluster. In 1970s Vera Rubin, established the existence of dark matter in galaxies by studying galaxy rotation curves. In 2003 the observation of the bullet cluster by Maxim Markevitch confirmed the existence of dark matter using CMB data.

COBE (1990s), WMAP (2000s), PLANCK (2013) confirmed the existence of dark matter using CMB data. Without dark matter, the power fluctuations peak at different angles across the sky compared to with dark matter. With dark matter, the power fluctuations peak at 27% lower angles across the sky.
**Cold and hot thermal relic: thermal decoupling**

\[ \rho_{\text{crit}} = \frac{3H_0^2}{8\pi G_N} \approx 10^{-29} \text{g/cm}^3 \]

\[ \rho_{DM} = \Omega_{DM} \rho_{\text{crit}} \approx \rho_{\text{crit}} \]

**Numbers to remember**

\[ \rho_{\text{crit}} = 10^{-6} \text{GeV/cm}^3 \]

\[ \rho_\odot = \Omega_{DM} \rho_{\text{crit}} \approx 0.3 \rho_{\text{crit}} \]

\[ \Gamma = n\sigma v \]
The temperature is slightly less than the neutron-proton mass difference; these weak reactions become slower than the expansion rate of the Universe, and the neutron:proton ratio freezes out at about 1:6.
Thermal Photons - CMB

Temperature of 2.725 ± 0.002 Kelvin

The early Universe
Evidence for Dark Matter

Thermal Equilibrium - BBN

Thermal Equilibrium - CMB

Thermal Production of Dark Matter

27% of dark matter

Arxiv: 1703.07364

Very good guess
Evidence for Dark Matter

Are you a WIMP?

Very good guess
**Cold and hot thermal relic: thermal decoupling**

**Hot Relic**

*Interaction Rate x Expansion Rate*

\[ \Gamma = n \sigma v \quad \quad H^2 = \frac{8\pi G_N}{3} \rho \]

**Expansion Rate**

\[ H \sim T^2 / M_p \]

**Reduced Planck Mass**

\[ M_p = 1/\sqrt{8\pi G_N} = 2.435 \times 10^{18} \text{ GeV} \]

**Decoupling condition**

\[ n(T_\nu) \sigma(T_\nu) = H(T_\nu) \]

\[ n_{rel} \sim T^3, \quad m \ll T \]

\[ T_\nu^3 G_F^2 T_\nu = T_\nu / M_p \]

**Neutrino decoupling temperature**

\[ T_\nu = (G_F^2 M_p)^{-1/3} \sim 1 \text{ MeV} \]
**Cold and hot thermal relic: thermal decoupling**

*Interaction Rate x Expansion Rate*

\[ \Gamma = n\sigma v \quad \text{and} \quad H^2 = \frac{8\pi G_N}{3} \rho \]

\[ H \sim T^2 / M_p \]

**Hot Relic**

**Expansion Rate**

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**Neutrino decoupling temperature**

\[ T_\nu = (G_F^2 M_p)^{-1/3} \sim 1 \text{MeV} \]

For \( T > 1 \text{eV} \)

\[ \rho = \rho_{rad} = \frac{\pi^2}{30} g T^4 \]
# Cold and hot thermal relic: thermal decoupling

## Hot Relic

### Abundance of a hot relic

\[ Y_{\text{freeze-out}} = \frac{n(T)}{s(T)} = \frac{\rho_\nu(T_\nu)}{m_\nu s(T_\nu)} \]

For \( T > 1\text{eV} \)

\[ \rho = \rho_{\text{rad}} = \frac{\pi^2}{30} g T^4 \]

entropy density = \( s \)

### Expansion Rate

\[ H \sim T^2 / M_p \]

### Reduced Planck Mass

\[ M_p = 1 / \sqrt{8\pi G_N} = 2.435 \times 10^{18} \text{GeV} \]

Iso-entropic universe

\[ s a^3 = \text{constant} \]

\[ n_{\text{rel}} \sim T^3, m \ll T \]

### Abundance of neutrinos

\[ \Omega_\nu h^2 \sim \frac{m_\nu}{92\text{eV}} \]

read S. Dodelson Book- “section about neutrinos”
Cold and hot thermal relic: thermal decoupling

Cold Relic

Interaction Rate x Expansion Rate

\[ \Gamma = H \]

Expansion Rate

\[ H \sim T^2/M_p \]

\[ n_{f.o.} \sim \frac{T_{f.o}^2}{M_p \sigma} \]

\[ n_{non-rel} \sim (mT)^{3/2} \exp^{m/T}, m \gg T \]

\[ x = m_\chi/T. \]

Cold relic condition \( x \gg 1 \)

Decoupling condition:

\[ \frac{m_\chi^3}{x^{3/2}} \exp^{-x} = \frac{m_\chi^2}{x^2 M_p \sigma} \]

\[ \sqrt{x} \exp^{-x} = \frac{1}{m_\chi M_p \sigma} \]

Assuming

\[ \sigma \sim G_F^2 m_\chi^2 \quad m_\chi = 100 GeV \]

\[ \sqrt{x} \exp^{-x} \sim 10^{-14} \]
Cold and hot thermal relic: thermal decoupling

Assuming

\[ \sigma \sim G_F^2 m_X^2 \quad m_X = 100 GeV \]

freeze-out \( \rightarrow \) \( x = 20-50 \) for several cold relic models
Cold and hot thermal relic: thermal decoupling

**Cold Relic**

Going back to the relic density

\[
\Omega_\chi = \frac{m_\chi n_\chi(T = T_0)}{\rho_c} = \frac{m_\chi T_0^3 n_0}{\rho_c T_0^3} \quad \Omega_\chi = \frac{m_\chi T_0^3 n_{f.o}}{\rho_c T_{f.o}^3} = \frac{T_0^3}{\rho_c} x_{f.o} \left( \frac{n_{f.o}}{T_{f.o}^2} \right) = \frac{T_0^3}{\rho_c M_p} \frac{x_{f.o}}{\sigma}
\]

Cold relic abundance:

\[
\frac{\Omega_\chi}{0.2} \simeq \frac{x_{f.o}}{20} \left( \frac{10^{-8} \text{GeV}^{-2}}{\sigma} \right)
\]

Changing units

\[
\sigma v \sim 10^{-8} \text{GeV}^{-2} \times 10^{10} \text{cm/s}
\]

\[
\sigma v \sim 3 \times 10^{-26} \text{cm}^3/\text{s}
\]

*let's see if we can find a similar cross section in nature*

Modified cosmological history
# Cold and hot thermal relic: thermal decoupling

## Cold Relic

Going back to the relic density

\[
\Omega_\chi = \frac{m_\chi n_\chi(T = T_0)}{\rho_c} = \frac{m_\chi T_0^3}{\rho_c} \frac{n_0}{T_0^3}
\]

\[
\Omega_\chi = \frac{m_\chi T_0^3}{\rho_c} \frac{n_{f.o}}{T_{f.o}^3} = \frac{T_0^3}{\rho_c} x_{f.o} \left( \frac{n_{f.o}}{T_{f.o}^2} \right) = \frac{T_0^3}{\rho_c M_p} \frac{x_{f.o}}{\sigma}
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### Cold relic abundance:

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\frac{\Omega_\chi}{0.2} \simeq \frac{x_{f.o}}{20} \left( \frac{10^{-8} \text{GeV}^{-2}}{\sigma} \right)
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### Changing units

\[
\sigma v \sim 10^{-8} \text{GeV}^{-2} \times 10^{10} \text{cm/s}
\]

### Let's see if we can find a similar cross section in nature

\[
\sigma_{EW} \sim G_F^2 E^2 \sim G_F^2 T^2 \sim G_F^2 \left( \frac{m_\chi}{x} \right)^2 \sim G_F^2 \left( \frac{m_\chi}{20} \right)^2 \sim 10^{-8} \text{GeV}^{-2}
\]

**WEAK SCALE!**
How light/heavy can a thermal relic be?

### Lower Limit

Decoupling condition:

\[
\sqrt{x} \exp^{-x} = \frac{1}{m_\chi M_p \sigma}
\]

\[
m_\chi M_p \sigma \gg 1
\]

Cold relic condition:

\[
x \gg 1
\]

**remember** \( \sigma \sim 10^{-8} \text{GeV}^{-2} \)

\[
m_\chi \gg 0.1 \text{eV}
\]

*There are bounds from structure formation \( m > \text{KeV} \)*

### Upper Limit

Write pair-annihilation cross section in partial waves and use the optical theorem

\[
\sigma < \frac{4\pi}{m_\chi^2}
\]

\[
\frac{\Omega_\chi}{0.3} > 10^{-8} \text{GeV}^{-2} \frac{m_\chi^2}{4\pi}
\]

\[
m_\chi < 100 \text{TeV}
\]
How light/heavy can a thermal relic be?

Is that all? NO!

We have assumed an iso-entropic universe. If entropy is injected after the thermal relic has frozen-out the abundance can change!

\[ s \rightarrow \gamma s \]
\[ \Omega_{\chi} \rightarrow \Omega_{\chi}/\gamma \]

Overabundance thermal relic can be diluted to the right relic density, but….

Be careful

The entropy injection has to occur before BBN
Thermal freeze-out

Boltzmann Equation

\[ \dot{L}[f] = \dot{C}[f] \]

\[ f \equiv f(p, x, t) \]

\[ \int L[f] g \frac{d^3p}{(2\pi)^3} = \frac{dn}{dt} + 3Hn \]

\[ \int C[f] g \frac{d^3p}{(2\pi)^3} = -\langle \sigma v \rangle (n_{1eq} n_{2eq} - n_1^2 n_2^2) \]

\[ \dot{n} + 3Hn = \langle \sigma v \rangle (n_{1eq}^2 - n^2) \]

\[ v \equiv \frac{\sqrt{(p_1 p_2)^2 - m_1^2 m_2^2}}{E_1 E_2} \]

\[ \langle \sigma v \rangle = \frac{\int \sigma v \exp^{-E_1/T} \exp^{-E_2/T} d^3p_1 d^3p_2}{\int \exp^{-E_1/T} \exp^{-E_2/T} d^3p_1 d^3p_2} \]

defining \( Y = \frac{n}{s} \)

\[ \frac{x}{Y_{eq}} \frac{dY}{dx} = -\frac{\Gamma}{H} \left[ \left( \frac{Y}{Y_{eq}} \right)^2 - 1 \right] \]
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Production mechanism

Dark Matter

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WIMP freeze-out
Production mechanism

Asymmetric

WIMP freeze-out
Production mechanism

Non-thermal/Modified Cosmological history + WIMP

Asymmetric

Non-thermal/Modified Cosmological history + WIMP

WIMP mass (GeV/c²)
Production mechanism

Asymmetric

Freeze-in

Non-thermal/Modified
Cosmological history

WIMP

Non-thermal/Modified
Cosmological history + WIMP

Non-thermal/Modified
Cosmological history + WIMP

Non-thermal/Modified
Cosmological history + WIMP
Production mechanism

Thermal freeze-out

Annihilation 2 ↔ 2 Processes
- Resonances
- Threshold
- Co-annihilation
- Semi-annihilation
Production mechanism

Non-thermal freeze-in

The coupling between the visible sector and DM particles is very small

Freeze-out

Freeze-in

$\log_{10} Y$ vs $\log_{10} x$
**Modified Cosmological History**

Consider a scalar field Lagrangian

\[ \rho_\phi = \frac{1}{2} \left( \frac{d\phi}{dt} \right)^2 + V(\phi) \]

\[ P_\phi = \frac{1}{2} \left( \frac{d\phi}{dt} \right)^2 - V(\phi) \]

\[ V(\phi) = M_p^4 \exp^{-\lambda\phi/M_p} \]

There's no WIMP miracle here!

**Change in the expansion rate**

\[ H \sim \frac{T^2}{M_p} \frac{T}{T_{dec}} \]

\[ \frac{\Omega_\phi}{\Omega_\chi} \sim \frac{T_{f.o}}{T_{dec}} \sim \frac{m_\chi}{20} \frac{1}{T_{BBN}} \sim 10^4 \frac{m_\chi}{100 GeV} \]

With a modified expansion history the connection to weak scale might be lost!
Modified Cosmological History

Pandora’s box

With a modified expansion history the connection to weak scale might be lost!