Tweaking the Dark Matter Abundance with Cosmology

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Outline

1. Diluting Dark Matter
2. Freeze-out During Matter Domination
3. Dark Matter Freeze-in
4. Freeze-in & Non-Standard Cosmology
I. Diluting Dark Matter
Tweaking the DM Abundance with Cosmology

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Current Bounds

![Graph showing current bounds on WIMP-nucleon cross sections and DM masses, highlighting Xenon1T and various experimental results.](image-url)
Cosmological Impact

After dark matter is frozen out its number does not change from interactions.

$$\Omega_{DM} \propto m_{DM} Y_{DM} \propto m_{DM} \frac{n_{DM}}{s}$$

However, decaying particles $\chi$ can heat SM bath, & dilute $Y_{DM}$ since $s \propto T^3$.

$$\Omega_{DM} \propto \zeta m_{DM} Y_{FO}$$

Dilution factor $\zeta$ from temperature after decays $T_{after}$ compared to without decays.

$\chi$ decay heats the bath, to $T_{RH} \simeq \sqrt{M_{Pl} \Gamma_{\chi}}$, any frozen-out species diluted:

$$\zeta = \left( \frac{T_{without}}{T_{after}} \right)^3 \sim 10^{-10} \left( \frac{T_{RH}}{10 \text{ MeV}} \right) \left( \frac{10^8 \text{ GeV}}{m_{\chi}} \right)$$

Because of dilution, correct relic density for weaker interactions with SM.
Cosmological Impact

Earliest cosmological evidence (known to be radiation dominated)

Non-Standard Model cosmological events?

End of Inflation (start of radiation domination?)
Changes to the Expansion Rate

Notable, expansion rate $H$ depends critically on cosmology:

$$H \propto \begin{cases} 
T^2 & \text{During radiation domination} \\
T^4 & \text{During particle decays (heating)} \\
T^{3/2} & \text{During matter domination}
\end{cases}$$

- During radiation domination
  - Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

- During particle decays (heating)
  - Hamdan & JU [1710.03758]
  - Also (in passing): Kamionkowski & Turner PRD 42 (1990) 3310

Recall $T_{\text{FO}}$ is defined $\Gamma(T_{\text{FO}}) = H(T_{\text{FO}})$, changing $H$ impacts final $Y_{\text{DM}}$. 
Decays vs Matter Domination

Matter Domination:

\[
\frac{d\rho_R}{dt} = -4H\rho_R + \langle \sigma v \rangle 2\langle E_X \rangle \left[ n_X^2 - (n_X^{eq})^2 \right]
\]

\[
\frac{dn_X}{dt} = -3H n_X - \langle \sigma v \rangle \left[ n_X^2 - (n_X^{eq})^2 \right].
\]
Decays vs Matter Domination

Point of non-negligible entropy production in bath.

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Decays vs Matter Domination

Decay Regime:

\[
\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_{\phi\rho_\phi} + \langle \sigma v \rangle 2\langle E_X \rangle \left[ n_X^2 - \left( n_X^{\text{eq}} \right)^2 \right]
\]

\[
\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[ n_X^2 - \left( n_X^{\text{eq}} \right)^2 \right].
\]

Giudice, Kolb, & Riotto, PRD 64 (2001) 023508
II. Freeze-out During Matter Domination
Changes to the Expansion Rate

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Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

Hamdan & JU [1710.03758]

Also (in passing): Kamionkowski & Turner PRD 42 (1990) 3310
Matter Dominated Freeze-out

One can emulate the standard Boltzmann treatment

$$\dot{n}_X + 3Hn_X = -\langle \sigma v \rangle [n_X^2 - (n_X^{eq})^2]$$

but with different form for $H$

$$H \simeq H_\star \left( \frac{g_\star(T)}{g_\star(T_\star)} \right)^{3/8} \left( \frac{T}{T_\star} \right)^{3/2} \left[ (1 - r) + r \left( \frac{T}{T_\star} \right) \right]^{1/2}$$

for $r = \{ 1$ \text{ RD}, 0 \text{ MD} \}$

Where $T_\star$ is temperature $\chi$ becomes matter-like and $H_\star \equiv H(T_\star)$

Radiation dominated freeze-out

$$T_{\text{FO}}^{\text{RD}} \simeq \frac{m_{\text{DM}}}{\ln [m_{\text{DM}} M_{\text{Pl}} \sigma_0]}$$

$$Y_{\text{FO}}^{\text{RD}} = 3 \sqrt{\frac{5}{\pi g_\star} \frac{(n + 1) x_F^{n+1}}{g_\star S M_{\text{Pl}} m_{\text{DM}} \sigma_0}}$$

Matter dominated freeze-out

$$T_{\text{FO}}^{\text{MD}} \simeq \frac{m_{\text{DM}}}{\ln [m_{\text{DM}}^{3/2} M_{\text{Pl}} \sigma_0 / \sqrt{T_\star}]}$$

$$Y_{\text{FO}}^{\text{MD}} = 3 \sqrt{\frac{5}{\pi g_\star} \frac{(n + 3/2) x_F^{n+3/2}}{g_\star S M_{\text{Pl}} m_X \sigma_0 \sqrt{x_\star}}}$$

Scherrer and Turner, PRD 33 (1986) 1585

Hamdan & JU [1710.03758]
Matter Dominated Freeze-out

$Y_{DM}$ in matter dominated FO *different to radiation dominated* case.

Radiation domination restored after freeze-out as *“matter” decays* to SM.

Required because *observations imply* radiation domination prior to current epoch.

This *leads to dilution* $\zeta$ of the dark matter abundance:

$$\Omega_{DM} = \zeta \times \frac{s_0 m_X Y_{FO}}{\rho_c}$$

This leads to dilution $\zeta$ of the dark matter abundance:

Weakening search limits compared to radiation dominated FO.

[Hamdan & JU [1710.03758]

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Matter Dominated Freeze-out

For DM freeze-out during matter domination, whilst avoiding cosmological constraints:

a). Universe matter dominated during freeze-out

b). Matter domination ends after dark matter freeze-out

c). Reheat temperature above few MeV for BBN

d). $\phi$ decays negligible during dark matter freeze-out

  o.w./ similar to Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

e). Cold dark matter: $x_f > 3$
Application: Scalar Higgs Portal

Annihilation cross section
units of thermal relic cross section.

$$\langle \sigma v \rangle_0 = 3 \times 10^{-26} \text{cm}^3/\text{s}$$

Classic Ref: Cline, Kainulainen, Scott, Weniger [1306.4710]

Tweaking the DM Abundance with Cosmology
Scalar Higgs Portal assuming Standard Cosmology is **experimentally excluded** away from region of resonant annihilation via the Higgs.

Escudero-Berlin-Hooper-Lin [1609.09079]
MDFO via Scalar Higgs Portal

In MDFO classic **Higgs Portal revived** as a viable model.

See also: Bernal, Cosme & Tenkanen [1803.08064], Hardy [1804.06783]
MDFO via Fermion Higgs Portal

\[ \mathcal{L} \supset \frac{1}{\Lambda} H^\dagger H \bar{\chi} \chi \] define an effective coupling \( \kappa = v_0/\Lambda \)

Chanda, Hamdan, & JU [1911.02616]

Tweaking the DM Abundance with Cosmology
MDFO via Z Portal

\[ \mathcal{L} \supset \frac{g}{4 \cos \theta_W} (\bar{\chi} \gamma^\mu (V_\chi - A_\chi \gamma^5) \chi Z_\mu) \]

define \( \kappa := V_\chi = A_\chi \)

Chanda, Hamdan, & JU [1911.02616]
Beyond Matter and Radiation Domination

If the early universe is dominated by field evolving as:

\[ \rho_\phi(t) = \rho_\phi(t_I) a^{-(4+m)} \]

The equation of state for \( \phi \) is \( \omega = \frac{p_\phi}{\rho_\phi} = \frac{m + 1}{3} \)

For \( m = -1 \) implies \( \omega = 0 \) and recovers matter dominated early universe.

\( \omega \) different to zero implies expansion rate \( H \propto T^{2+ml/2} \) can impact DM evolution.

If \( m > 0 \) (i.e. \( \omega > 1 \)) the field will redshift faster than radiation - no need for \( \phi \) decays.

Scenario can arise from scalar with potential

\[ V(\phi) = \frac{4 - 2n}{(4 + m)^2 t_I^2} \exp \left[ (\phi(t_I) - \phi) \sqrt{m + 4} \right] \]

D’Eramo, Fernandez, & Profumo [1703.04793]
Beyond Matter and Radiation Domination

Impact on the dark matter relic density for $\textbf{FO while } H \propto T^{2+m/2}$

\[ Y_{\chi}(r) \]

\[ Y_{\chi}(r) \]

- Equil.
- Rad
- $m = 1$
- $m = 2$
- $m = 3$
- $m = 4$

D’Eramo, Fernandez, & Profumo [1703.04793]
III. Dark Matter Freeze-in
Freeze-in assumes dark matter initially has negligible abundance.

\( Y_{\text{DM}} \)

\( x \equiv \frac{m_{\text{DM}}}{T} \propto t. \)

Hall, Jedamzik, March-Russell, West [0911.1120]

Tweaking the DM Abundance with Cosmology

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Freeze-in assumes dark matter initially has negligible abundance.

\[ Y_{\text{DM}} \]

\[ Y_{\text{IR}} \]

\[ x \equiv m_{\text{DM}}/T \propto t. \]
Freeze-in assumes dark matter initially has negligible abundance.
Freeze-in vs Freeze-out

\[ Y_{\text{FO}} \sim 1/(\sigma_0 M_{\text{Pl}} m_{\text{DM}}) \]

\[ Y_{\text{IR}} \propto \sigma_0 M_{\text{Pl}} m_{\text{DM}} \]

\[ Y_{\text{eq}} \]

- \( x \)
- \( Y_{\text{DM}} \)
Freeze-in vs Freeze-out

Parameter depends very different in Freeze-out, IR Freeze-in & UV Freeze-in.

Hall, Jedamzik, March-Russell, West [0911.1120]
Elahi, Kolda & JU [1410.6157]
Equilibration and FIMPS

If energy exchange is too large, risk dark matter equilibration with thermal bath.

![Equilibration and Freeze-out Diagram]

Equilibration and freeze-out as a function of $x \equiv m_{DM}/T \propto t$. The graph shows the evolution of $Y_{eq}$, $Y_{FI/FO}$, and $Y_{IR}$ with $x$. The graph indicates the critical points of equilibration and freeze-out, with $Y_{eq}$ peaking and then declining, while $Y_{IR}$ rises sharply after a certain value of $x$. The diagram also highlights the importance of $x$ in understanding the evolution of dark matter abundance.
Equilibration and FIMPS

If energy exchange is too large, risk dark matter equilibration with thermal bath.

For IR Freeze-in with GeV DM this require couplings: $\lambda \lesssim 10^{-7}$

Avoiding equilibration requires very `feeble' couplings: **FIMP Dark Matter.**

Requires dedicated experiments for light dark matter or long lived states.
IV. UV Freeze-in & Non-Standard Cosmology
Enhancements during UV Freeze-in

**UV freeze-in:** The production cross section of DM from thermal bath is:

\[ \langle \sigma v \rangle \sim \frac{T^n}{\Lambda^{2+n}} \]

Corresponding to Freeze-in operator of **mass dimension** \(5 + n/2\).

The **DM abundance** is expected to be

\[ Y \sim \int_0^{T_{RH}} \frac{M_{Pl} T^n}{\Lambda^{n+2}} \sim \frac{M_{Pl} T_{RH}^{n+1}}{\Lambda^{n+2}}. \]

\(T_{RH}\) is reheat temperature assuming instantaneous decay of inflaton.

Assuming universe **initially matter dominated** before reheating then for \(n>6\) then DM abundance **enhanced** relative to sudden decay approx.

Garcia, Mambrini, Olive, Peloso, [1709.01549].
For increasing operator dimension the production becomes **more UV dominated**.
Transition from non-standard cosmology

If the early universe is dominated by field $\phi$ with equation of state $\omega$

And the state $\phi$ is **decaying** to Standard Model radiation then the evolution follows

\[
\frac{d\rho_\phi}{dt} + 3(1 + \omega) H \rho_\phi = -\Gamma_\phi \rho_\phi
\]
\[
\frac{d\rho_R}{dt} + 4 H \rho_R = +\Gamma_\phi \rho_\phi
\]

It follows the **energy densities evolve** as

\[
\rho_\phi(a) = \rho_\phi(a_{\text{in}}) \left(\frac{a_{\text{in}}}{a}\right)^{3(1+\omega)} = 3 M_{\text{Pl}}^2 H_{\text{in}}^2 \left(\frac{a_{\text{in}}}{a}\right)^{3(1+\omega)}
\]
\[
\rho_R(a) = \frac{6}{5 - 3\omega} M_{\text{Pl}}^2 H_{\text{in}} \Gamma_\phi \frac{a_{\text{in}}^{3(1+\omega)}}{a^4} \left[a^{5-3\omega/2} - a_{\text{in}}^{5-3\omega/2}\right]
\]

where $a = a_{\text{in}}$ is the scale factor at some arbitrary initial point, we take the initial condition $\rho_R(a_{\text{in}}) = 0$ and thus $H_{\text{in}} \equiv H(a_{\text{in}}) = \sqrt{\rho_\phi(a_{\text{in}})/(3 M_{\text{Pl}}^2)}$. 

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Transition from non-standard cosmology

The temperature, related via \( \rho_R = \frac{\pi^2 g_*(T)}{30} T^4 \), evolves according to

\[
T = \left( \frac{45}{4\pi^3} \frac{g_*(T_{RH})}{g^2_*(T)} \right)^{1/8} \left( H_I M_{Pl} T_{RH}^2 \right)^{1/4} \left( \frac{A^{-(2+m/2)} - A^{-4}}{2 - m/2} \right)^{-4}
\]

where \( A \equiv \frac{a}{a_I} = a T_{RH} \)

Define

\[
T_{\max} \geq T_{RH}
\]

\[
H_I = 1 \text{ eV, } T_{RH} = 100 \text{ GeV}
\]

\[
\rho_\phi(t) = \rho_\phi(t_I) a^{a+m}
\]
Dark Matter and Non-Standard Cosmology

This change in cosmological evolution impacts the dark matter.

The comoving number density \( N \equiv n \times a^3 \) evolving according to

\[
\frac{dN}{da} = -\frac{\langle \sigma v \rangle}{a^4 H} (N^2 - N_{\text{eq}}^2)
\]

Implying at temperature \( T \)

\[
N(T) = \frac{8 \zeta(3)^2 g^2}{3\pi^4(n - n_c)(1 + \omega)} \left[ \frac{a_{\text{RH}}^{3+\omega}}{a_{\text{in}}^{1+\omega}} \right]^{\frac{3}{2}} \frac{T_{\text{RH}}^{4+\omega}}{\Lambda^{n+2} H_{\text{in}}} \left[ T_{\text{max}}^{n-n_c} - T^{n-n_c} \right]
\]

This can be converted into a yield \( Y(T) = \frac{N(T)}{s(T) a^3} \)

And integrating to the ‘end’ of \( \phi \) decays give the relic abundance

\[
Y(T_{\text{RH}}) \sim \frac{1}{(n - n_c)(1 + \omega)} \frac{M_{\text{Pl}} T_{\text{RH}}^{1+\omega}}{\Lambda^{n+2}} \left[ T_{\text{max}}^{n-n_c} - T_{\text{RH}}^{n-n_c} \right]
\]
Enhancements during UV Freeze-in

For a fixed $\omega$ then there is a boost relative to sudden decay approx

$$B \simeq \begin{cases} \frac{1}{3} \frac{(1+n)(2+n_c)}{n_c-n} & \text{for } n < n_c, \\ \frac{(1+n)(2+n)}{3} \ln \frac{T_{\text{max}}}{T_{\text{RH}}} & \text{for } n = n_c, \\ \frac{1}{3} \frac{(1+n)(2+n_c)}{n-n_c} \left[ \frac{T_{\text{max}}}{T_{\text{RH}}} \right]^{n-n_c} & \text{for } n > n_c. \end{cases}$$

Critical value: $n_c \equiv 2 \times \left( \frac{3-\omega}{1+\omega} \right)$

Recast as a fixed operator dimension $n$ (varying $\omega$) the boost is

$$B \simeq \begin{cases} \frac{1}{3} \frac{7-\omega_c}{\omega_c-\omega} & \text{for } \omega < \omega_c, \\ \frac{8}{3} \frac{7-\omega}{(1+\omega)^2} \ln \frac{T_{\text{max}}}{T_{\text{RH}}} & \text{for } \omega = \omega_c, \\ \frac{1}{3} \frac{7-\omega_c}{\omega-\omega_c} \left[ \frac{T_{\text{max}}}{T_{\text{RH}}} \right]^{\frac{8(\omega-\omega_c)}{(1+\omega)(1+\omega_c)}} & \text{for } \omega > \omega_c, \end{cases}$$

Critical value: $\omega_c \equiv \frac{6-n}{2+n}$
Boosting to large abundance

Useful for motivated dark matter candidates which are underproduced. For example gravitino dark matter in high scale supersymmetry scenarios.

Bernal, Elahi, Maldonado, & JU [1909.07992]
Conclusion

- **Cosmological events** and can drastically alter expectations for DM.

- Dilution permit correct relic density for **heavier DM** or **smaller couplings**.

- This can **revive the Higgs portal** (and other excluded classic models).

- Conversely, **underproduced DM** can be enhanced via reheating effects.

- Non standard cosmology occurs in many **motivated BSM scenarios**.

Thank you.