Cosmology with Democratic Initial Conditions: Flooded Dark Matter

James Unwin
University of Illinois, Chicago

Work with L. Randall & J. Scholtz [1509.08477].

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WIMPs will be squeezed in the next 5-10 years...

Different Motivation: Democratic Reheating

- Typically thought that cosmic inflation occurred in the early universe.
- Democratic inflaton decay is a natural expectation.
- If there are many sectors it is surprising that at late time Standard Model has considerable fraction of energy and dominates entropy.
- Moreover, without a large injection of entropy into the Standard Model, dark sectors would typically contribute too much entropy.
- Ask: what is required to match the present Universe given a democratically decaying inflaton?
- Suppose Standard Model energy density from late decay of heavy state $\Phi$, whereas DM comes from a hidden sector primordial abundance.
Cosmic history

Denote the scale factor $\Phi$ becomes nonrelativistic by $a = a_0$ and define

$$R^{(i)} \equiv R(a_i) \equiv \frac{\rho_{DM}(a_i)}{\rho_{\Phi}(a_i)}.$$

Assuming democratic inflaton decay

$$R^{(0)} \equiv R(a_0) \simeq 1.$$

Also track other primordial populations:

$$R_{SM}^{(0)} \equiv \frac{\rho_{SM}(a_0)}{\rho_{\Phi}(a_0)}; \quad R_{DS}^{(0)} \equiv \frac{\rho_{DS}(a_0)}{\rho_{\Phi}(a_0)}.$$

*nb.* Use FRW scale factor $a$ to track time.
Cosmic history

Heavy state becomes non-relativistic. The evolution of $\rho_{\text{tot}}$ given by:

$$H^2(a) = \frac{\rho_{\text{tot}}(a)}{3M_{\text{Pl}}^2} \simeq \frac{m_\Phi^4}{M_{\text{Pl}}^2} \left[ \left( \frac{a_0}{a} \right)^3 + R^{(0)} \left( \frac{a_0}{a} \right)^4 + R_{\text{SM}}^{(0)} \left( \frac{a_0}{a} \right)^4 + R_{\text{DS}}^{(0)} \left( \frac{a_0}{a} \right)^4 \right]$$

Once $\Phi$ dominates $\rho_{\text{tot}}$ this simplifies to

$$H^2(a) \simeq \frac{\rho_{\text{tot}}(a)}{3M_{\text{Pl}}^2} \simeq \frac{m_\Phi^4}{M_{\text{Pl}}^2} \left[ \left( \frac{a_0}{a} \right)^3 \right].$$
Cosmic history

Heavy state decays at $H \simeq \Gamma$ and repopulates the Standard Model.

At the time of the $\Phi$ decay

$$\left( \frac{a_0}{a_\Gamma} \right)^3 \simeq \frac{\Gamma^2 M_{Pl}^2}{m_\Phi^4}$$

The ratio of energy densities at the time of the $\Phi$ decay

$$R^{(\Gamma)} = R^{(0)} \left( \frac{a_0}{a_\Gamma} \right) \simeq R^{(0)} \left[ \frac{\Gamma^2 M_{Pl}^2}{m_\Phi^4} \right]^{1/3}.$$
Cosmic history

Dark matter must become non-relativistic and also baryogenesis must occur.

Assuming adiabatic evolution the ratio of entropy densities is unchange after $a_\Gamma$

$$R^{(\Gamma)} \simeq \left( \frac{s^{(\Gamma)}_{DM}}{s^{(\Gamma)}_{SM}} \right)^{4/3} = \left( \frac{s^{(\infty)}_{DM}}{s^{(\infty)}_{SM}} \right)^{4/3}. $$

Can be expressed in observed quantities

$$\frac{s^{(\infty)}_{DM}}{s^{(\infty)}_{SM}} \simeq \Delta \frac{n_{DM}}{n_B} \simeq \Delta \frac{\Omega_{DM}}{\Omega_B} \frac{m_p}{m_{DM}},$$

where $\Delta = n_B/s_{SM} = 0.88 \times 10^{-10}$.
Primordial relic dark matter

We have that:

\[ R^{(\Gamma)} \simeq R^{(0)} \left[ \frac{\Gamma^2 M_{Pl}^2}{m^4_\Phi} \right]^{1/3} \quad \text{and} \quad R^{(\Gamma)} \simeq \Delta \frac{\Omega_{DM}}{\Omega_B} \frac{m_p}{m_{DM}}. \]

Thus the decay rate required to match the observed DM relic density:

\[ \Gamma \simeq \frac{m^2_\Phi}{M_{Pl}} \left( \Delta \frac{\Omega_{DM}}{\Omega_B} \frac{m_B}{m_X} \right)^2. \]

SM reheat temperature due to \( \Phi \) decay

\[ T_{RH} \simeq \sqrt{\Gamma M_{Pl}} \simeq m_\Phi \Delta \frac{\Omega_{DM}}{\Omega_B} \frac{m_B}{m_{DM}}. \]

Competition between requirement:

- phenomenologically high \( T_{RH} \)
- and small \( \Gamma \) to dilute DM
Successful models must satisfy the following general criteria:

- The **DM relic density** matches the value observed today.
- The Standard Model reheat temperature is well above **BBN**.
- **Baryogenesis** should occur (may place bounds on $T_{RH}$).
- A thermal bath of $\Phi$ is generated after inflation which implies a limit on the mass $m_\Phi \sim \rho_\Phi^{1/4}(a_0) \lesssim 10^{16}$ GeV.
- DM should be ‘warm’/‘cold’.
Relaxation of free streaming constraints

As SM dof are regenerated via decays it becomes warmer than hidden sector

\[ \frac{T_{\text{DM}}}{T_{\text{SM}}} \approx \left( \frac{s_{\text{DM}}}{s_{\text{SM}}} \right)^{1/3} \approx \left( \frac{m_{\text{DM}}\Omega_B}{\Delta m_p\Omega_{\text{DM}}} \right)^{1/3} \]

This means DM nonrelativistic earlier, and bounds on the free streaming length are weakened compared to thermal relic:

\[ \sim 5 \text{ keV} \quad \rightarrow \quad O(100) \text{ eV} \]
Contours of $\kappa$, defined $\Gamma = \kappa^2 m_\Phi / 8\pi$.

RH neutrino with mass $10^9$ GeV and $y^i_\nu \sim y^i_l$ is a nice example – see •.
Conclusion: Flooded Dark Matter

- Start from democratic inflaton decay – as how to match cosmology.
- DM largest number density but SM dominates entropy.
- Explained by late entropy injection to SM with primordial DM.
- This also explains the absence of “dark radiation”.
- The lifetime of $\Phi$ essentially determines $\Omega_{DM}/\Omega_B$.
- Weakens Lyman-$\alpha$ bound ($m_{DM} \lesssim 5$ keV) and allows $m_{DM} \sim 300$ eV
- Avoids the Griest & Kamionkowski unitarity bound: $m_{DM} \lesssim 100$ TeV
  
  Griest & Kamionkowski PRL 64, 615
- Sub-keV DM can potentially resolve the core-cusp problem.
  
  Randall, Scholtz, JU, [1608.XXXXX].

Thank you.