# Cosmology with Democratic Initial Conditions: Flooded Dark Matter

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

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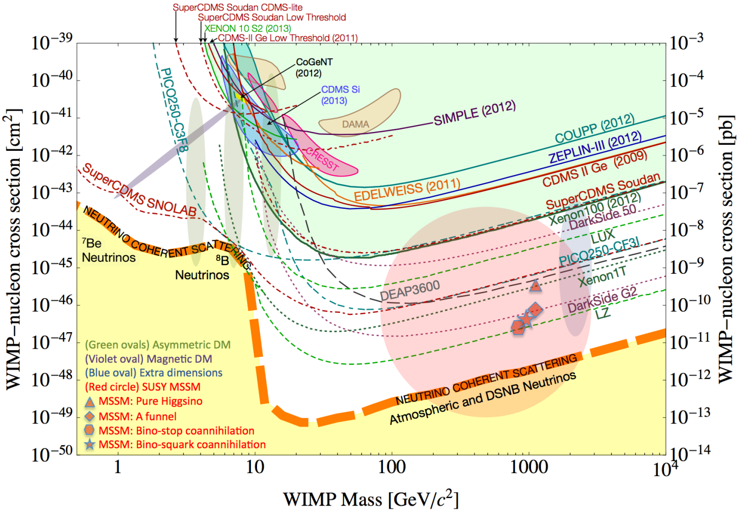
# WIMPs will be squeezed in the next 5-10 years...




Snowmass report (2013): [arXiv:1310.8327]

# 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

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

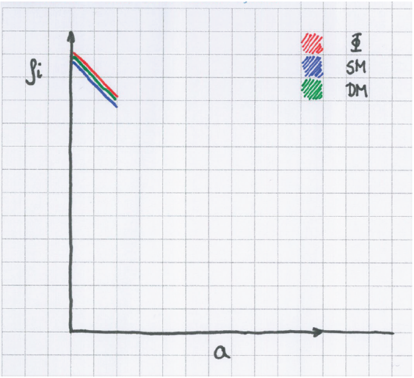
Assuming democratic inflaton decay

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

Also track other primordial populations:

$$R^{(0)}_{\rm SM} \equiv \frac{\rho_{\rm SM}(a_0)}{\rho_\Phi(a_0)}; \qquad R^{(0)}_{\rm DS} \equiv \frac{\rho_{\rm DS}(a_0)}{\rho_\Phi(a_0)} .$$

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



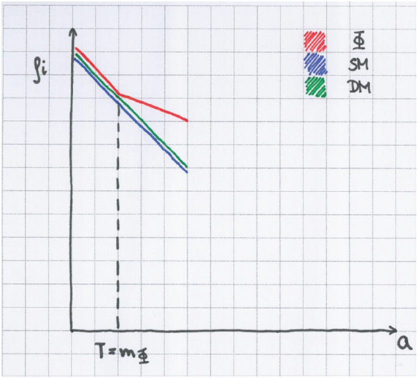
# Cosmic history

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

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

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

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



# Cosmic history

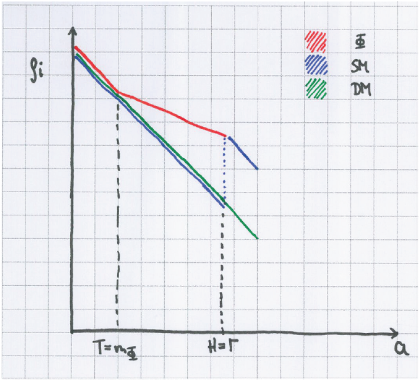
Heavy state decays at $H \simeq \Gamma$ and repopulates the Standard Model.

At the time of the $\Phi$ decay

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

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

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



# Cosmic history

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

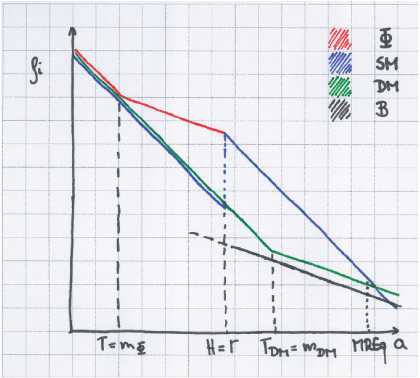
Assuming adiabatic evolution the ratio of entropy densities is unchange after $a_\Gamma$

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

Can be expressed in observed quantities

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

where $\Delta = n_B/s_{\rm SM} = 0.88 \times 10^{-10}$.



# Primordial relic dark matter

We have that:

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

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

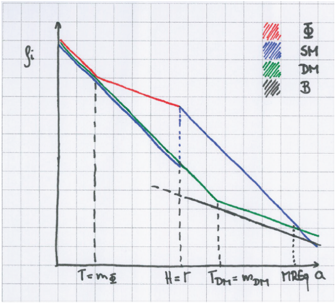
$$\Gamma \simeq \frac{m_\Phi^2}{M_{\rm Pl}}\left(\Delta \frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_B}{m_X}\right)^2$$

SM reheat temperature due to $\Phi$ decay

$$T_{\rm RH} \simeq \sqrt{\Gamma M_{\rm Pl}} \simeq m_\Phi \Delta \frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_B}{m_{\rm DM}}$$

Competition between requirement:

- phenomenologically high $T_{\rm RH}$
- and small $\Gamma$ to dilute DM

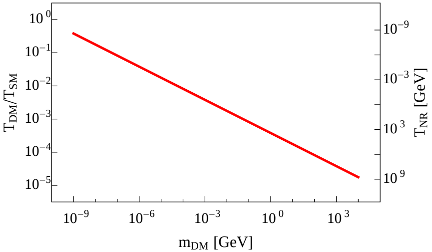


# Constraining the parameter space

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 $T_{\rm RH}$).
- 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

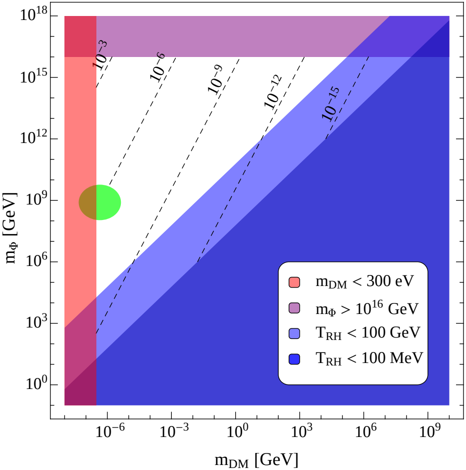



As SM dof are regenerated via decays it becomes warmer than hidden sector

$$T_{\rm DM}/T_{\rm SM} \simeq \left(\frac{s_{\rm DM}}{s_{\rm SM}}\right)^{1/3} \simeq \left(\frac{m_{\rm DM}\Omega_B}{\Delta m_p \Omega_{\rm DM}}\right)^{1/3}$$

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

$$\sim 5\text{ keV} \;\rightarrow\; \mathcal{O}(100)\text{ eV}$$




Contours of $\kappa$, defined $\Gamma = \kappa^2 m_\Phi / 8\pi$.

RH neutrino with mass $10^9$ GeV and $y_\nu^i \sim y_l^i$ 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 $\Omega_{\rm DM}/\Omega_B$.
- Weakens Lyman-$\alpha$ bound ($m_{\rm DM} \lesssim 5$ keV) and allows $m_{\rm DM} \sim 300$ eV
- Avoids the Griest & Kamionkowski unitarity bound: $m_{\rm DM} \lesssim 100$ TeV

  Griest & Kamionkowski PRL 64, 615
- Sub-keV DM can potentially resolve the core-cusp problem.

  Randall, Scholtz, JU, [1608.XXXXX].

Thank you.