Cosmology with Democratic Initial Conditions

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GGI: Gearing up for LHC13

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

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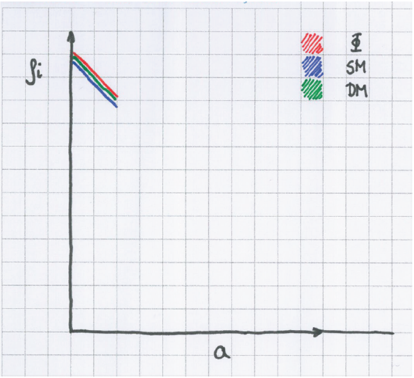
Motivation

- 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 Φ, whereas DM comes from the redshifted primordial abundance.

Cosmic history

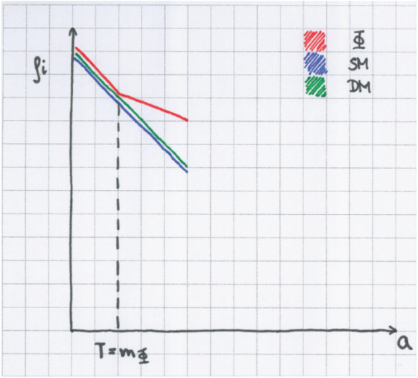
Democratic reheating following inflation:



Credit: Jakub Scholtz for hand drawn figures!

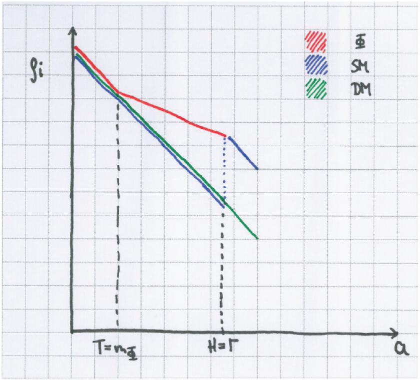
Cosmic history

Heavy state becomes non-relativistic:



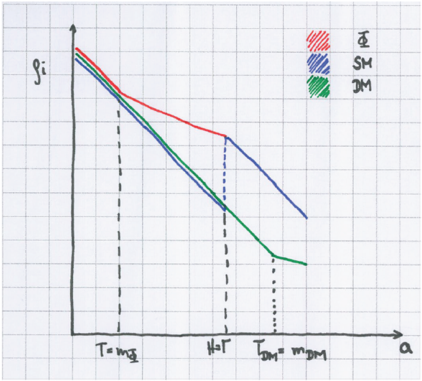
Cosmic history

Heavy state decays and repopulates the Standard Model:



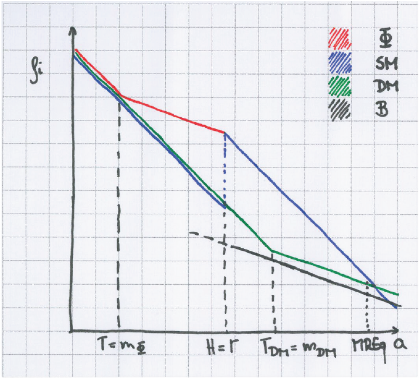
Cosmic history

Dark matter becomes non-relativistic:



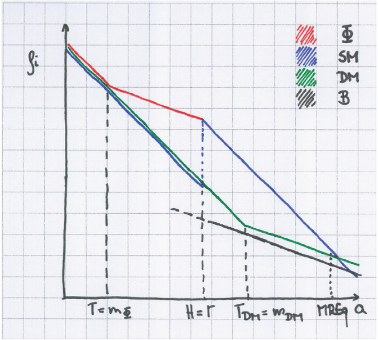
Cosmic history

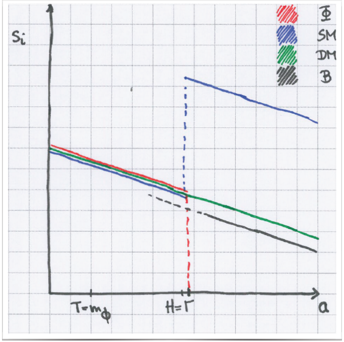
Baryogenesis occurs (at some point):



Entropy injection

This can be seen instead in terms of entropy production:





Φ decay floods the entropy and drastically reduces cosmological impact of the dark matter – "Flooded Dark Matter and S level Rise" [1509.08477].

One field model

The period for which the energy density of DM redshifts relative to Φ energy density is controlled by the Φ lifetime.

We derive the required Φ decay rate Γ to match the observed relic density.

Denote the scale factor Φ 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 $R^{(0)} \equiv R(a_0) \simeq 1$.

We might also wish to keep track of other primordial populations:

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

One field model

The evolution of $\rho_{\rm tot}$ can be described as

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

The decays of Φ become important when $3H(a_\Gamma) = \Gamma$. Assume here that prior to decay Φ dominates the energy density and DM is relativistic.

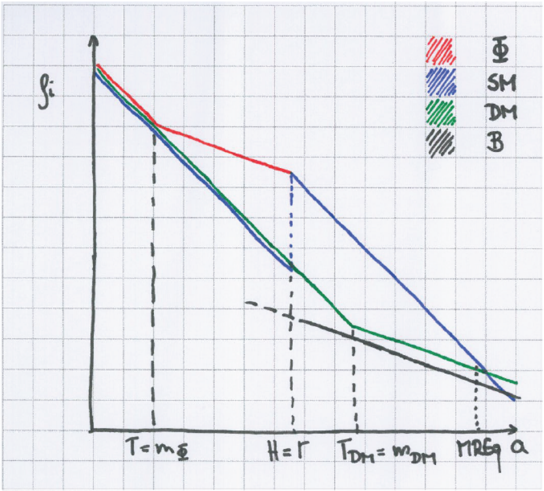
Then at time of Φ decay the scale factor is

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

and the ratio of energy densities at the time of the Φ decay

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

One field model



One field model

Assuming adiabatic evolution of the Universe after Φ decays.

The ratio of entropy densities does not change from a_Γ to present

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

The ratio of DM to SM entropies can be expressed in observed quantities

$$\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}} = \frac{2\pi^4}{45\zeta(3)}\Delta\frac{n_{\rm DM}}{n_B} = \frac{2\pi^4}{45\zeta(3)}\Delta\frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_p}{m_{\rm DM}},$$

where $\Delta = n_B/s_{\rm SM} = 0.88 \times 10^{-10}$ and m_p is the proton mass.

One field model

Putting this together the Γ required to match the observed DM relic density:

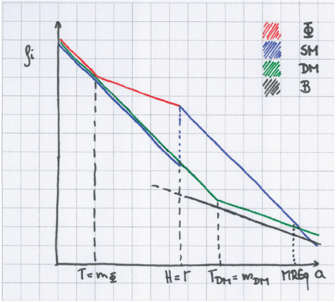
$$\Gamma \simeq \frac{m_\Phi^2}{M_{\rm Pl}}\left(\frac{s_{\rm DM}}{s_{\rm DM}}\right)^2 \simeq \frac{m_\Phi^2}{M_{\rm Pl}}\left(\Delta\frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_p}{m_{\rm DM}}\right)^2$$

SM reheat temperature due to Φ decay

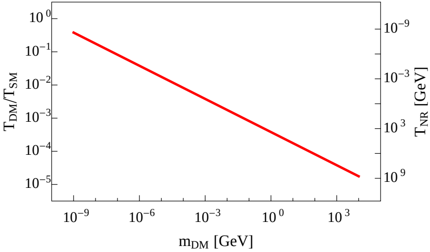
$$T_{\rm RH} \simeq \sqrt{\Gamma M_{\rm Pl}} \simeq m_\Phi \Delta\frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_p}{m_{\rm DM}}$$

Competition between requirement:

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



One field model



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

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

The temperature of hidden sector colder than visible sector Model bath $T_{\rm NR}$ at point DM nonrelativistic is

$$T_{\rm NR} = m_{\rm DM}\left(\frac{s_{\rm SM}}{s_{\rm DM}}\right)^{1/3}$$

One field model

Successful models must satisfy the following general criteria:

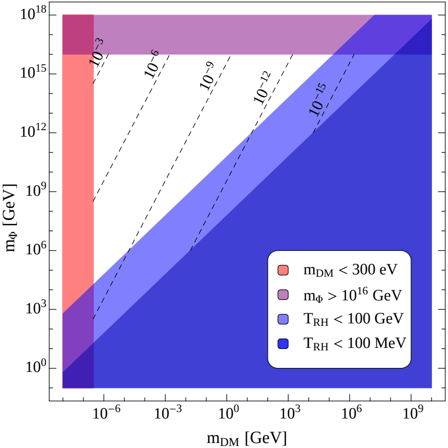
A. A thermal bath of Φ is generated after inflation which implies a limit on the mass $m_\Phi \sim \rho_\Phi^{1/4}(a_0) \lesssim 10^{16}$ GeV.

B. The Standard Model reheat temperature is well above BBN.

C. The DM relic density matches the value observed today.

D. Baryogenesis should occur (may place bounds on $T_{\rm RH}$).

One field model



Defining $\Gamma = \kappa^2 m_\Phi / 8\pi$ we show contours of κ that give correct DM relic.

Two field model

Consider two heavy fields: $\Phi_{\rm DM}$ and $\Phi_{\rm SM}$ associated with the DM and SM.

Assume $\Phi_{\rm DM}$ that decays primarily to dark matter, and $\Phi_{\rm SM}$ is longer-lived.

Hence $s_{\rm SM}$ will dominate over $s_{\rm DM}$, as DM redshifts prior to $\Phi_{\rm DM}$ decays.

This differs from one field case since the relative redshifting no longer starts right after Φ becomes nonrelativistic, but after $\Phi_{\rm DM}$ decays.

We derive relationship between $\Gamma_{\Phi_{\rm SM}}$ and $\Gamma_{\Phi_{\rm DM}}$ to get the correct DM relic for the degenerate case $m_{\Phi_{\rm SM}} = m_{\Phi_{\rm DM}} = m_\Phi$, and initial conditions

$$\rho_i(a_0) = R_i^{(0)} m_\Phi^4 \ , \qquad\qquad (a_0 : \ T \sim m_\Phi)$$

Two field model

The energy densities are evolved to $H \simeq \Gamma_{\rm DM}$ to obtain

$$\rho_i(a_{\Gamma_{\rm DM}}) = R_i^{(0)} m_\Phi^4 \left(\frac{a_0}{a_{\Gamma_{\rm DM}}}\right)^3 , \qquad (i = \Phi_{\rm DM}, \Phi_{\rm SM}) .$$

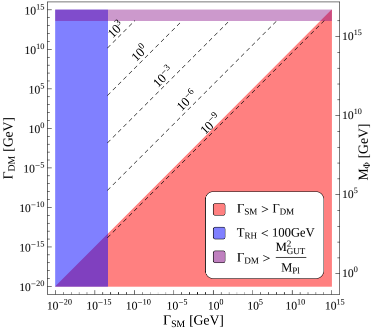
As the DM redshifts like radiation between the first decay and the second, and this era is matter dominated, after the second field has decayed

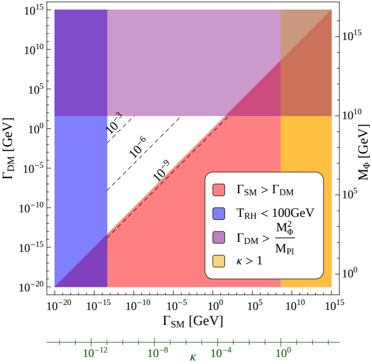
$$\frac{\rho_{\rm DM}(a_{\Gamma_{\rm SM}})}{\rho_{\rm SM}(a_{\Gamma_{\rm SM}})} = \frac{R^{(0)}_{\Phi_{\rm DM}}}{R^{(0)}_{\Phi_{\rm SM}}} \left[\frac{R^{(0)}_{\Phi_{\rm DM}} + R^{(0)}_{\Phi_{\rm SM}}}{R^{(0)}_{\Phi_{\rm SM}}} \left(\frac{\Gamma_{\rm SM}}{\Gamma_{\rm DM}}\right)^2\right]^{1/3} ,$$

Given $\Gamma_{\Phi_{\rm DM}}$ decay rate, the required $\Gamma_{\Phi_{\rm SM}}$ for the observed relic density is

$$\Gamma_{\rm SM} \simeq \Gamma_{\rm DM} \left(\Delta \frac{\Omega_{\rm DM}}{\Omega_B} \frac{m_p}{m_{\rm DM}}\right)^2 \left[\left(\frac{R^{(0)}_{\Phi_{\rm SM}}}{R^{(0)}_{\Phi_{\rm DM}}}\right)^3 \frac{R^{(0)}_{\Phi_{\rm SM}}}{R^{(0)}_{\Phi_{\rm DM}} + R^{(0)}_{\Phi_{\rm SM}}}\right]^{1/2} .$$

Two field model





Parameter space in the $\Gamma_{\rm SM}$–$\Gamma_{\rm DM}$ plane. Contours of $m_{\rm DM}$ to obtain the correct relic density. Right axis: m_Φ in 1-field models that gives same result.

RH plot we fix $m_\Phi = 10^{10}$ GeV and assume $\Gamma_{\rm SM} = \kappa^2 m_\Phi / 8\pi$.

Baryogenesis

Baryogenesis must occur and there are a number of possibilities

- A particle asymmetry comes either from inflaton decays or from dynamics in the early Universe s.t. it is initially present in both the visible and dark matter sector. cf. Asymmetric Dark Matter.
- CP violating decays of Φ to the Standard Model generate an asymmetry in B or L. cf. Leptogenesis via RH neutrinos.
- Baryon asymmetry generated by dynamics in the visible sector. e.g. Electroweak Baryogenesis.

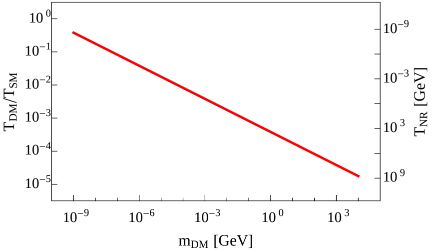
Note that scenarios that make use of sphalerons require that Φ decays reheat the visible sector above $T_{\rm RH} \gtrsim 100$ GeV.

Maximal Baroqueness

- Present-day $\Omega_{\text{DM}}/\Omega_B$ is controlled by lifetimes of the heavy states Φ.
- Typically, final heavy species to decay dominates the energy & entropy.
- Earlier energy dumps are diluted relative to the energy.
- The last state to decay will typically be the state that is most weakly coupled to its associated sector.
- i.e. the longest lived state, but small couplings appear baroque.
- Specifically, Standard Model sector is reheated preferentially because it has hierarchically small couplings to the heavy states Φ.
- Conceivable selection based on maximum baroqueness connected with choosing sector with $v \ll \Lambda$ – links into Arkani-Hamed et al.'s NNaturalness proposal.

Core-Cusp Problem

Recall from earlier:



The temperature of Standard Model bath $T_{\rm NR}$ at point DM nonrelativistic is

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

Because DM nonrelativistic earlier, free streaming bounds are weakened:

$$\sim 5 \text{ keV} \;\; \rightarrow \; \sim 300 \text{ eV}$$

Core-Cusp Problem

If in the central region the occupation levels are saturated, the Fermi gas becomes degenerate and gradient of the density profile vanishes near centre.

Thus for a self gravitating fermion gas the density distribution can be altered due to Pauli blocking if the gas is degenerate in an appreciable region.

A fermion gas is degenerate in the high density, low temperature limit; for

$$T < T_{\text{Deg}} = \frac{h^2}{2\pi m k_B}\left(\frac{\rho}{2m}\right)^{2/3} \simeq 10^{-3}\left(\frac{\rho}{10^{-27}\text{kg cm}^{-3}}\right)^{2/3}\left(\frac{200\text{ eV}}{m}\right)^{5/3}.$$

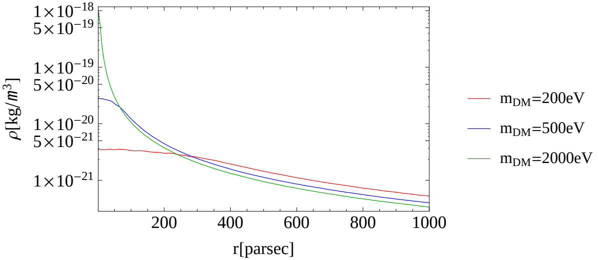
Domcke & Urbano, [1409.3167].

Core-Cusp Problem

Fermi core where pressure is $p = \frac{h^2}{5}\left(\frac{\rho^5}{m_f^8}\right)^{1/3}$.

In the outer regions a thermal envelope $p = k\rho T/m_f$.

Compute the density profile by assuming hydrostatic equilibrium:

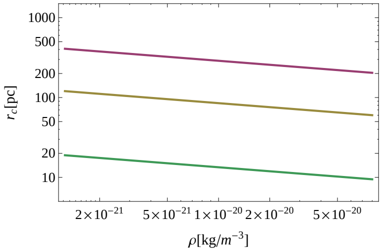


Density profile of a quasi-degenerate Fermi gas for different masses.

Randall, Scholtz, JU – Preliminary.

Core-Cusp Problem

For fermion DM of mass 200 eV (RED), 0.5 keV (YELLOW), 2 keV (GREEN) we show the expected core radius r_c as a function of the central density.



Evidence suggests the presence of constant density cores which constitute the central few hundred parsecs, Walker & Penarrubia, [1108.2404].

Randall, Scholtz, JU – Preliminary.

RH neutrino implementation

Consider neutrinos seesaw mechanism and we identify $\Phi \equiv N$

$$\mathcal{L}_\nu = y_{ij} H \bar{L}_i N_j + M_{ij} N_i N_j \ .$$

For satisfactory model of masses and mixing can take all $y_{ij} \sim \mathcal{O}(1)$.

Then $m_\nu \sim y^2 v^2 / m_N$ and $\Gamma = y^2 m_N$, but Γ sets DM relic via

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

and this fixes $m_{\rm DM}$. But implied value falls below Lyman-α bound.

RH neutrino implementation

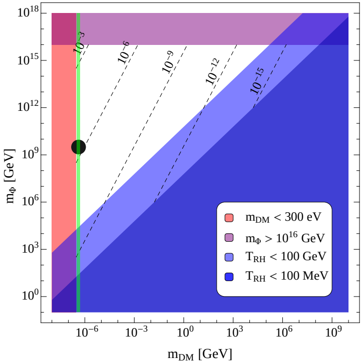
The previous analysis assumed similar Yukawa entries; rather consider

$$y_{ij} \sim \frac{m_\tau}{v} \times \begin{array}{cc} \begin{array}{ccc} N_1 & N_2 & N_3 \end{array} & \\ \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \end{pmatrix} & \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \end{array}$$

- Suppose the larger entries of the Yukawa matrix of order the y_τ.
- Matching $m_\nu \sim 0.1$ eV implies Majorana masses $M \sim 10^9$ GeV.
- Take the Yukawas of N_3 much smaller, of order m_e/m_τ.
- Parameters give ideal Γ for both DM relic density and high $T_{\rm RH}$.
- Baryogensis can proceed through nonthermal leptogenesis.
- Predicts one light neutrino is hierarchically lighter: $m_{\nu_1} \ll m_{\nu_2}, m_{\nu_3}$.

RH neutrino implementation

We can compare this to the earlier result:



We mark • the point motivated by RH neutrino model.
Highlighted in green is the mass range motivated by core-cusp.

Summary and Remarks

- Started from premise of democratic inflaton decay.
- Outlined a scenario which matches known cosmology.
- DM largest number density but SM dominates entropy.
- Explained by late time entropy injection to SM whereas primordial DM.
- Also explains the absence of "dark radiation".

- The lifetime of Φ essentially determines $\Omega_{\rm DM}/\Omega_B$.
- Natural extension is to multiple Φ, eg. $\Phi_{\rm SM}$ & $\Phi_{\rm DM}$.
- Many possibilities for model building, eg. RH neutrino.
- Weakens Lyman-α bounds and allows $m_{\rm DM} \gtrsim 300$ eV
- Sub-keV DM can resolve the core-cusp problem.