Implementing Asymmetric Dark Matter and Dark Electroweak Baryogenesis in a Mirror Two-Higgs-Doublet Model

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Motivation

- There is an apparent coincidence between the cosmological mass densities of visible and dark matter

$$\Omega_{\mathrm{DM}} \simeq 5\Omega_{\mathrm{VM}}$$

- Why is this a coincidence?
  - The abundance of **VM** arises from a baryon asymmetry which is generated by an unknown baryogenesis mechanism.
  - The abundance of most **DM** candidates is set by unrelated mechanisms (freeze-out, freeze-in, misalignment)

Motivation

$$\Omega_{\mathrm{DM}} \simeq 5\Omega_{\mathrm{VM}}$$

- To explain this coincidence we need to relate the following quantities for VM and DM:
  1. number densities
  2. particle masses

$$\Omega_X = n_X m_X$$

- Asymmetric Dark Matter (ADM) models relate number densities, but few address the particle mass relationship.

Relating particle masses: Mirror Matter

- The mass of **visible baryons** comes from QCD confinement energy.
- **DM** should similarly be a bound state of a 'dark QCD'.

- This can be realised in **mirror matter** models, where:
  - The dark sector is a copy of the visible sector
  - A Z_2 'mirror' symmetry exchanges visible particles with their dark counterparts

$$SU(3) \times SU(2) \times U(1) \times SU(3)' \times SU(2)' \times U(1)'$$

- The dark matter then consists of **dark baryons** whose mass depends on the dark QCD confinement scale Λ_{DM}.

Relating particle masses: Breaking the Mirror

- To allow Λ_{QCD} and Λ_{DM} to differ by a factor of a few, we must break the mirror symmetry.
- We introduce a **second Higgs doublet** in each sector and construct the scalar potential so that its minimum breaks the mirror symmetry.

$$\langle\Phi_1\rangle = \begin{bmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{bmatrix}, \quad \langle\Phi_1'\rangle = 0,$$

$$\langle\Phi_2\rangle = 0, \quad \langle\Phi_2'\rangle = \begin{bmatrix} 0 \\ \frac{w}{\sqrt{2}} \end{bmatrix}.$$

  - This allows the quark masses in each sector to differ
  - This then alters the running of the confinement scale in each sector.
  - For w >> v, the mass of the dark neutron can be greater than the visible proton by a factor of a few.

$$\Phi_1 \leftrightarrow \Phi_1'$$
$$\Phi_2 \leftrightarrow \Phi_2'$$

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Relating particle masses: Breaking the Mirror

- This minimum is the exact solution for the toy mirror 2HDM potential (bottom-right).
- For the full potential (bottom-left), we can approximately obtain the desired minimum pattern by choosing parameters that replicate the structure of the toy model.

$$\langle\Phi_1\rangle = \begin{bmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{bmatrix}, \quad \langle\Phi_1'\rangle = 0,$$

$$\langle\Phi_2\rangle = 0, \quad \langle\Phi_2'\rangle = \begin{bmatrix} 0 \\ \frac{w}{\sqrt{2}} \end{bmatrix}.$$

$$\begin{aligned}
V_{\rm M2HDM} = {} & m_{11}^2\left(\Phi_1^\dagger\Phi_1 + \Phi_1'^\dagger\Phi_1'\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2 + \Phi_2'^\dagger\Phi_2'\right) \\
& + \left(m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_1'^\dagger\Phi_2'\right) + h.c.\right) + \frac{1}{2}z_1\left(\left(\Phi_1^\dagger\Phi_1\right)^2 + \left(\Phi_1'^\dagger\Phi_1'\right)^2\right) \\
& + \frac{1}{2}z_2\left(\left(\Phi_2^\dagger\Phi_2\right)^2 + \left(\Phi_2'^\dagger\Phi_2'\right)^2\right) + z_3\left(\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \Phi_1'^\dagger\Phi_1'\Phi_2'^\dagger\Phi_2'\right) \\
& + z_4\left(\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \Phi_1'^\dagger\Phi_2'\Phi_2'^\dagger\Phi_1'\right) + \frac{1}{2}z_5\left(\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_1'^\dagger\Phi_2'\right)^2 + h.c.\right) \\
& + \left[\left(z_6\Phi_1^\dagger\Phi_1 + z_7\Phi_2^\dagger\Phi_2\right)\Phi_1^\dagger\Phi_2 + \left(z_6\Phi_1'^\dagger\Phi_1' + z_7\Phi_2'^\dagger\Phi_2'\right)\Phi_1'^\dagger\Phi_2' + h.c.\right] \\
& + z_8\Phi_1^\dagger\Phi_1\Phi_1'^\dagger\Phi_1' + z_9\Phi_2^\dagger\Phi_2\Phi_2'^\dagger\Phi_2' + \left(z_{10}\Phi_1^\dagger\Phi_2\Phi_1'^\dagger\Phi_2' + h.c.\right) \\
& + \left(z_{11}\Phi_1^\dagger\Phi_2\Phi_2'^\dagger\Phi_1' + h.c.\right) + z_{12}\left(\Phi_1^\dagger\Phi_1\Phi_2'^\dagger\Phi_2' + \Phi_1'^\dagger\Phi_1'\Phi_2^\dagger\Phi_2\right) \\
& + \left[\left(z_{13}\Phi_1^\dagger\Phi_1 + z_{14}\Phi_2^\dagger\Phi_2\right)\Phi_1'^\dagger\Phi_2' + \left(z_{13}\Phi_1'^\dagger\Phi_1' + z_{14}\Phi_2'^\dagger\Phi_2'\right)\Phi_1^\dagger\Phi_2 + h.c.\right]
\end{aligned}$$

$$\begin{aligned}
V_{\rm ASB} = {} & \lambda_1\left(\Phi_1^\dagger\Phi_1 + \Phi_1'^\dagger\Phi_1' - \frac{v^2}{2}\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2 + \Phi_2'^\dagger\Phi_2' - \frac{w^2}{2}\right)^2 \\
& + \kappa_1\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1'^\dagger\Phi_1'\right) + \kappa_2\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_2'^\dagger\Phi_2'\right) \\
& + \sigma_1\left(\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \left(\Phi_1'^\dagger\Phi_1'\right)\left(\Phi_2'^\dagger\Phi_2'\right)\right) \\
& + \sigma_2\left(\Phi_1^\dagger\Phi_1 + \Phi_1'^\dagger\Phi_1' + \Phi_2^\dagger\Phi_2 + \Phi_2'^\dagger\Phi_2' - \frac{v^2}{2} - \frac{w^2}{2}\right)^2
\end{aligned}$$

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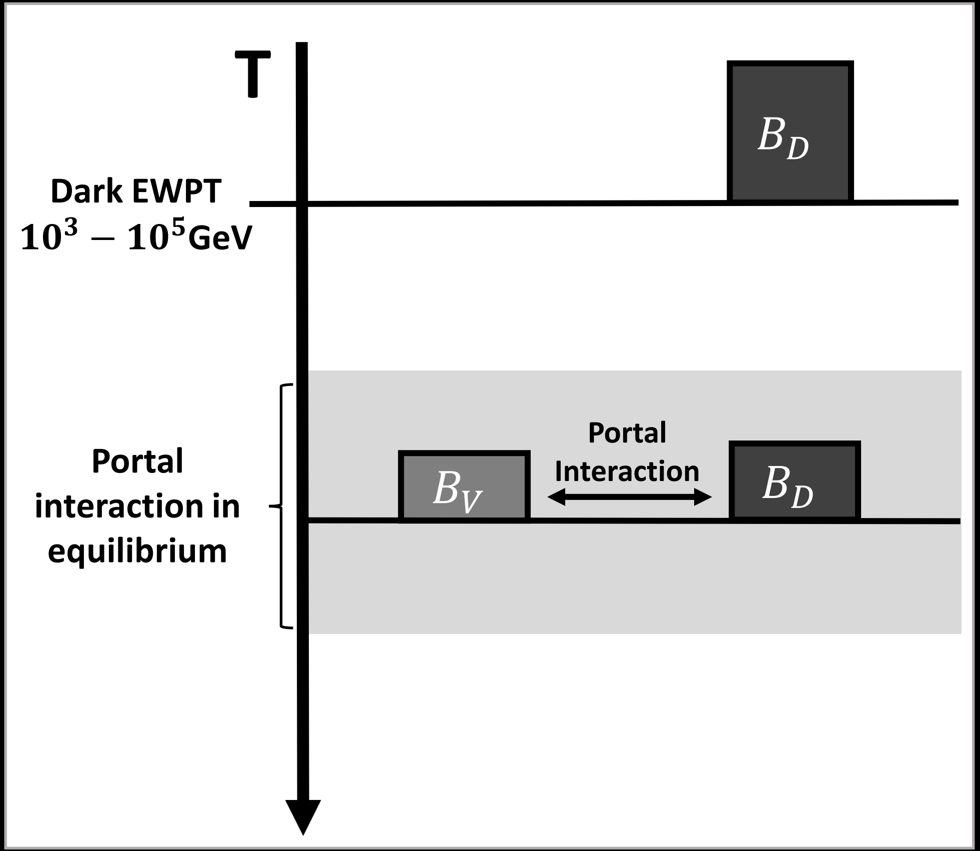
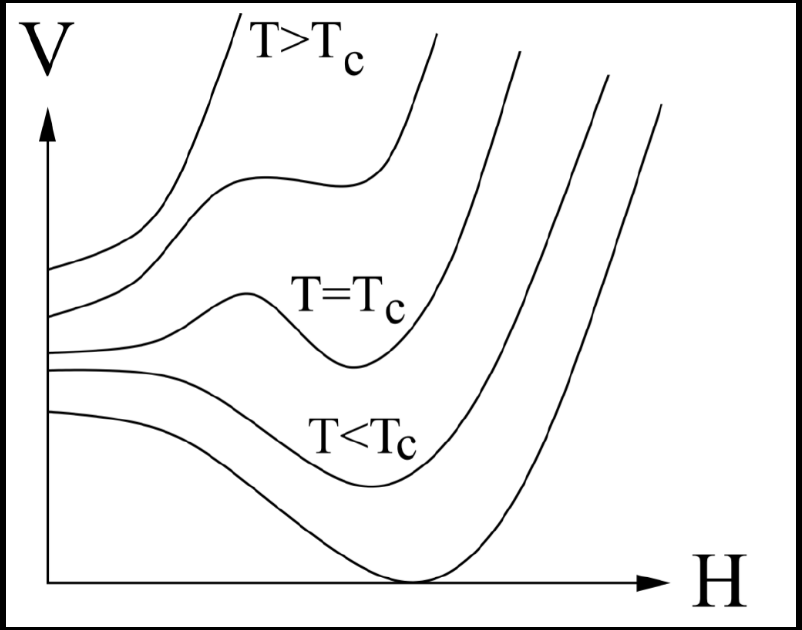
Relating number densities: Electroweak baryogenesis

- As in ADM models, we wish to generate related visible and dark baryon asymmetries.
  - The original paper considered thermal leptogenesis.
  - We explored electroweak baryogenesis at the dark electroweak phase transition.
- The idea:
  - Generate a dark baryon asymmetry at the dark EWPT.
  - Partially transfer this asymmetry to the visible sector through portal interactions



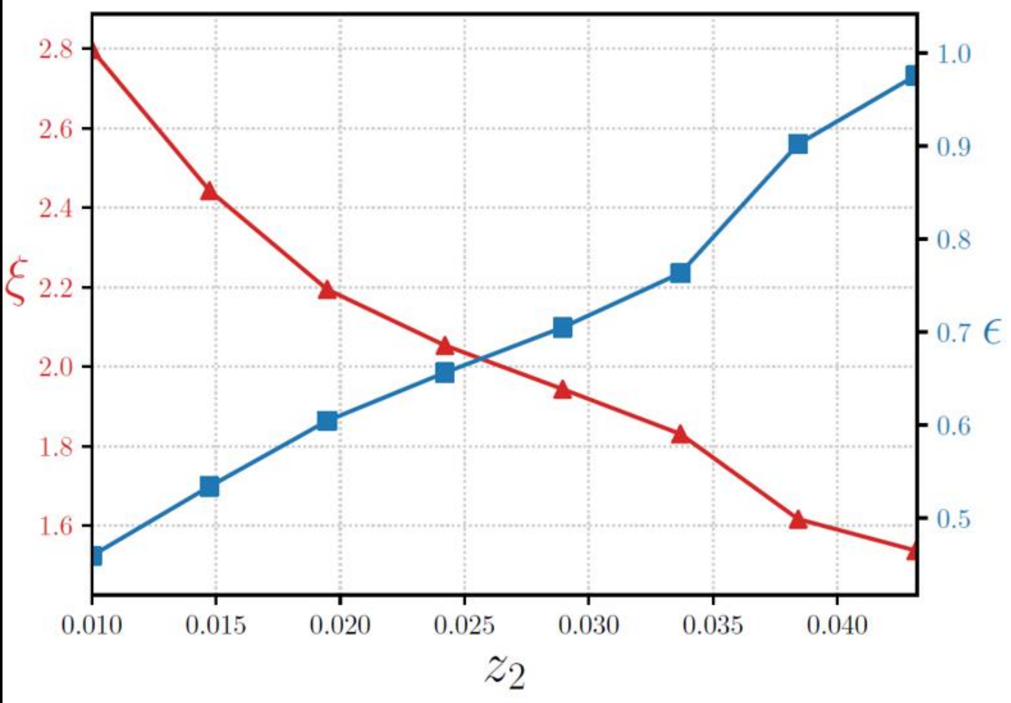
1. Strength of the Dark Electroweak Phase Transition

- EWBG requires the EWPT to be strongly first-order, so that the transition proceeds by bubble nucleation.
  - This corresponds to a barrier in the Finite Temperature Effective Potential.
- We constructed the FTEP in order to find regions of parameter space for which the dark EWPT was strongly first-order.



1. Strength of the Dark Electroweak Phase Transition

- We readily found areas of parameter space for which the dark EWPT was strongly first-order.
  - These regions corresponded to the dark Higgs boson being relatively light.
- The example plot shows the strength of the phase transition (strong = >1) and a perturbative expansion parameter that ensures we can trust the perturbative calculation of the FTEP at the phase transition.
- z_2 is a parameter of the scalar potential that controls the mass of the dark Higgs boson.
- In general, the transition is sufficiently strong for small values of z_2.



ξ – strength of phase transition
ϵ – perturbative expansion parameter

2. Asymmetry Transfer

- We analysed two cross-sector effective operators as 'portal interactions' to share the dark asymmetry with the visible sector:
  - The neutron portal: $$\frac{1}{M^5}\bar{u}\bar{d}\bar{d}u'd's' + h.c.$$ This interaction is motivated by the problem of BBN bounds on dark radiation
  - The lepton portal: $$\frac{1}{M_{ab}}\bar{l}_{iL}\Phi_a^c l'_{jR}\Phi'_b + h.c.$$ This interaction can also be responsible for generating neutrino masses

2. Asymmetry Transfer

- Both portals successfully produced similar number densities of VM and DM.
  - For a neutron portal in equilibrium between the dark and visible EWPTs, with $M \sim 10^3 - 10^4$ GeV, the final ratio of baryon numbers is:

$$\frac{B_D}{B_V} = 1.3$$

The lepton portal transfer depends on the initial conditions for the dark lepton and baryon asymmetries generated during dark EWBG. For equal initial asymmetries, the final baryon number ratio is:

$$\frac{B_D}{B_V} = 1.7$$

Dark Radiation and the Neutron Portal

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- A generic issue with mirror matter models is the additional **dark radiation** they introduce (dark photons and neutrinos).
- This is strongly bounded by BBN measurements of the effective number of neutrino species:

$$N_{\text{eff}} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4 + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{g_D^*}{2}\left(\frac{T_D}{T_\gamma}\right)^4$$

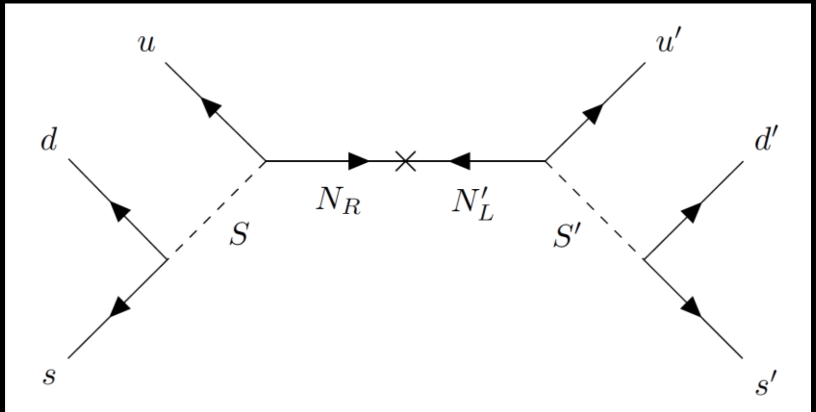
- To avoid this bound, the dark sector needs to be at a sufficiently **lower temperature** than the visible sector during BBN.
  - This can be achieved if the sectors thermally decouple between the visible and dark quark-hadron phase transitions.
  - This requires a portal interaction to maintain thermal equilibrium to this point.

Dark Radiation and the Neutron Portal

- The neutron portal can now serve a dual role:
  - It naturally decouples between the QHPTs as the dark quarks bind into hadrons.
  - The neutron portal can thus maintain thermal equilibrium to help avoid dark radiation bounds while also transferring asymmetries between the sectors.
- However, the dark QHPT temperature is quite low (~1 GeV) – below the UV scale of the effective operator – and so we need to provide a UV-completion of the neutron portal.

Dark Radiation and the Neutron Portal

- The following UV completion is feasible given pheno constraints on the mass of the diquark scalar S
- However, this is only for a very specific mass range of the gauge singlet mediator $N_R/N_{L'}$.



- Given that this UV completion is valid, the asymmetry transfer still produces similar asymmetries in each sector, with a final baryon ratio:

$$\frac{B_D}{B_V} = 1.1$$

Concluding Remarks

- The coincidence in VM and DM energy densities is a mystery that must be explained.
- A Mirror Two-Higgs-Doublet Model allows for baryonic DM with a mass related to the visible proton.
- Electroweak baryogenesis looks to be feasible in this model.
  - The dark EWPT can be strongly first-order.
  - Portal interactions can share the dark baryon asymmetry roughly equally between the visible and dark sectors.
- The neutron portal may also help avoid stringent BBN bounds on dark radiation.