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Dark matter from a broken mirror symmetry.

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Outline

- Asymmetric Dark Matter and Mirror matter
- Dark QCD
- Asymmetric symmetry breaking
- Mirror 2HDM (Two Higgs Doublet Model)
- Leptogenesis
- Interactions between sectors
- Constraints
- Summary

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Mass content of the universe

- Latest Planck data reveals $\Omega_{DM} = 5.4 \times \Omega_{VM}$
- How do we explain the similar abundance of mass in the visible sector (VS) and dark sector (DS)?
- Asymmetric Dark matter models connect the baryon number with a dark analogue. The conservation of a global symmetry across sectors gives a connection in particle number density.
- However one must also explain the similar mass of dark matter and ordinary baryons. Past work on asymmetric dark matter have almost exclusively dealt with explaining the abundance of dark matter particles.
- One particular class of models that does both is mirror matter. Posits a copy of the SM under a discrete symmetry. $p \leftrightarrow p'$

  Add a mirror Gauge symmetry $G' = SU(3)' \times SU(2)' \times U(1)'$

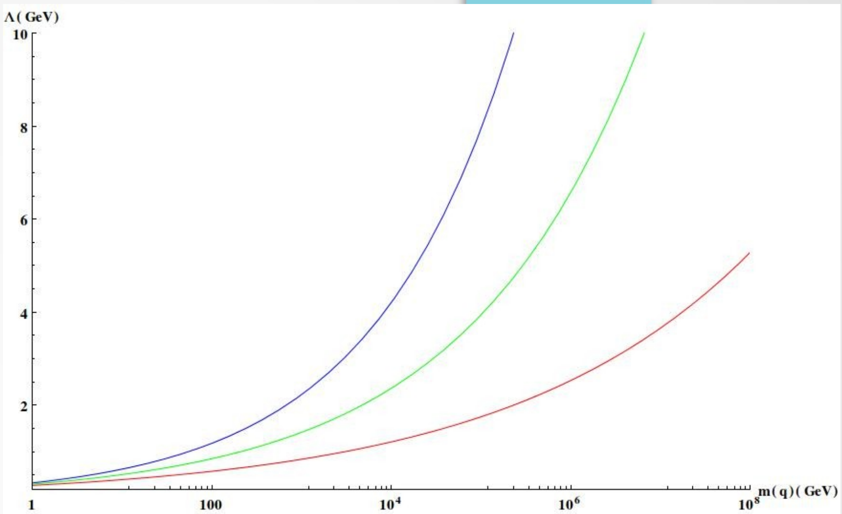
  Left handed exchanged with right handed fermions- parity is conserved!

  Mirror matter models are one of many ways of introducing a dark sector, largely disconnected with our own. These models can provide a dark matter candidate in the form of dark baryons- confined states of a dark QCD.

Dark QCD

The mass of the vast majority of the observable universe results from dimensional transmutation- the confinement scale of QCD where the coupling diverges and the theory becomes non-perturbative at low energy.

Assume Dark matter gains mass
In a similar way.



- In a model with a dark QCD, where $\alpha_3' = \alpha_3$ at a high energy scale, the two SU(3) theories can both be asymptotically free.

At low energy, the strong coupling becomes large, and each QCD gains a confinement scale

$$\Lambda_{QCD}, \Lambda'_{QCD}$$

If dark baryons produced in similar number to visible baryons then need a ratio of ~5 in confinement scales.

The scale of confinement is dependent on the number of quarks in the loop corrections. As we move the mass thresholds of a dark QCD higher, we see only *minor* increases in the confinement scale.

Asymmetric symmetry breaking

- We can generate differences between sectors in a high energy mirror matter model by breaking the mirror symmetry.
- One way of doing this is 'Asymmetric Symmetry breaking' which gives the task of spontaneous symmetry breaking in each sector to different varieties of Higgs multiplets in a mirror symmetric potential.

$$V = \lambda_1 (H_1^\dagger H_1) + ({H'}_1^\dagger {H'}_1) - v^2)^2 +$$
$$\lambda_2 (H_2^\dagger H_2) + ({H'}_2^\dagger {H'}_2) - w^2)^2 +$$
$$\kappa_1 (H_1^\dagger H_1)({H'}_1^\dagger {H'}_1) +$$
$$\kappa_2 (H_2^\dagger H_2)({H'}_2^\dagger {H'}_2) +$$
$$\sigma((H_1^\dagger H_1)(H_2^\dagger H_2) + ({H'}_1^\dagger {H'}_1)({H'}_2^\dagger {H'}_2)) +$$
$$\rho((H_1^\dagger H_1) + (H_2^\dagger H_2) + ({H'}_1^\dagger {H'}_1) + ({H'}_2^\dagger {H'}_2) - v^2 - w^2)^2.$$

In this way, we can set the mass scale of fermions in the dark sector large, while the visible sector appears as the standard model.

Absolute minima of is given by degenerate vacua of the form:

$$H_1 = (0, v), \qquad H'_1 = 0,$$
$$H_2 = 0, \qquad H'_2 = (0, w).$$

We consider the case where w >> v.

Asymmetric symmetry breaking

- Past work has used asymmetric symmetry breaking to break mirror GUT models.
- SU(5)XSU(5) Mirror model. Spontaneously break the two sectors to different gauge groups with dark SU(3) confined states forming dark matter. [arxiv:hep-ph/ 1407.4192]

$$SU(5)_v \rightarrow SU(3) \times SU(2) \times U(1).$$
$$SU(5)_d \rightarrow SU(3) \times SU(2)$$

- SO(10)XSO(10). Take a multi-step approach to symmetry breaking in each sector. Different breaking chains lead to the running of gauge couplings in the two sectors being different over intermediate energy ranges. Small differences in the mass scale of dark and visible baryons.[arxiv:hep-ph/ 1412.1894]

In this model we take a simpler model of the SM gauge group at high energy with a mirror partner. SU(3) couplings converge by mirror symmetry.
By adding singlet Majorana neutrinos, we can develop the baryon asymmetry of each sector by thermal leptogenesis.

Mirror 2HDM

Model can be seen as a mirror type III 2HDM. In this case however the asymmetric potential sets the role of the Higgs in each sector.
Visible sector has an additional heavy (5000+ TeV scale) decoupled second higgs doublet with zero VEV.
In the mirror sector, its large VEV sets a high mass scale of EW symmetry breaking and the mass of mirror quarks and leptons.

$L_L^i \sim (1,2,-\frac{1}{2})(1,1,0)$	$(L_R^i)' \sim (1,1,0)(1,2,-\frac{1}{2})$
$e_R^i \sim (1,1,-1)(1,1,0)$	$(e_L^i)' \sim (1,1,0)(1,1,-1)$
$Q_L^i \sim (3,2,\frac{1}{6})(1,1,0)$	$(Q_R^i)' \sim (1,1,0)(3,2,\frac{1}{6})$
$u_R^i \sim (3,1,\frac{2}{3})(1,1,0)$	$(u_L^i)' \sim (1,1,0)(3,1,\frac{2}{3})$
$d_R^i \sim (3,1,-\frac{1}{3})(1,1,0)$	$(d_L^i)' \sim (1,1,0)(3,1,-\frac{1}{3})$
$N_R^i \sim (1,1,0)(1,1,0)$	$(N_L^i)' \sim (1,1,0)(1,1,0)$
$H_1 \sim (1,2,\frac{1}{2})(1,1,0)$	$(H_1)' \sim (1,1,0)(1,2,\frac{1}{2})$
$H_2 \sim (1,2,\frac{1}{2})(1,1,0)$	$(H_2)' \sim (1,1,0)(1,2,\frac{1}{2}).$

$$L_{yukawa} = \lambda_{1ij}\bar{l}_L^i e_R^j H_1 + \lambda_{1ij}\bar{l'}_R^i e_L'^j H_1' + h_{1ij}\bar{l}_L^i N_R^j \tilde{H}_1 + h_{1ij}\bar{l'}_R^i N_L'^j \tilde{H}'_1 +$$
$$\lambda_{2ij}\bar{l}_L^i e_R^j H_2 + \lambda_{2ij}\bar{l'}_R^i e_L'^j H_2' + h_{2ij}\bar{l}_L^i N_R^j \tilde{H}_2 + h_{2ij}\bar{l'}_R^i N_L'^j \tilde{H}'_2 +$$
$$f_{1ij}\bar{l}_L^i (N_L'^j)^c \tilde{H}_1 + f_{1ij}\bar{l'}_R^i (N_R^j)^c \tilde{H}'_1 + f_{2ij}\bar{l}_L^i (N_L'^j)^c \tilde{H}_2 + f_{2ij}\bar{l'}_R^i (N_R^j)^c \tilde{H}'_2.$$

Cross sector terms suppressed.

Mirror symmetry in Yukawa couplings between sectors. Vacuum expectation values asymmetric between sectors. Above EW symmetry breaking scale, CP violating couplings provided by both H1 and H2 in each sector.

Mirror 2HDM

$$L_{yukawa} = \lambda_{1ij}\bar{l}^i_L e^j_R H_1 + \lambda_{1ij}\bar{l'}^i_R e'^j_L H'_1 + h_{1ij}\bar{l}^i_L N^j_R \tilde{H}_1 + h_{1ij}\bar{l'}^i_R N'^j_L \tilde{H'}_1 +$$
$$\lambda_{2ij}\bar{l}^i_L e^j_R H_2 + \lambda_{2ij}\bar{l'}^i_R e'^j_L H'_2 + h_{2ij}\bar{l}^i_L N^j_R \tilde{H}_2 + h_{2ij}\bar{l'}^i_R N'^j_L \tilde{H'}_2 +$$
$$f_{1ij}\bar{l}^i_L (N'^j_L)^c \tilde{H}_1 + f_{1ij}\bar{l'}^i_R (N^j_R)^c \tilde{H'}_1 + f_{2ij}\bar{l}^i_L (N'^j_L)^c \tilde{H}_2 + f_{2ij}\bar{l'}^i_R (N^j_R)^c \tilde{H'}_2.$$

Majorana mass terms M, and cross sector Majorana mass terms P. These must be suppressed also as after integrating these out at low energy they provide mixing among light neutrino states of different sectors.

$$P_{ij}(\bar{N}^c N'^c \bar{N'}^c N'^c) + M_{ij}(\bar{N}^c N + \bar{N'}^c N')$$

$$\begin{pmatrix} v_L & (v_R)^{c'} & (N_R)^c & (N'_L)^c \end{pmatrix} \begin{pmatrix} 0 & 0 & h_1 v & f_1 v \\ 0 & 0 & f *_2 w & h *_2 w \\ h_1^T v & f_2^\dagger w & N & P \\ f_1^T v & h_2^\dagger w & P^T & N \end{pmatrix} \begin{pmatrix} (v_L)^c \\ (v_R)^{c'} \\ (N_R)^c \\ (N'_L)^c \end{pmatrix}$$

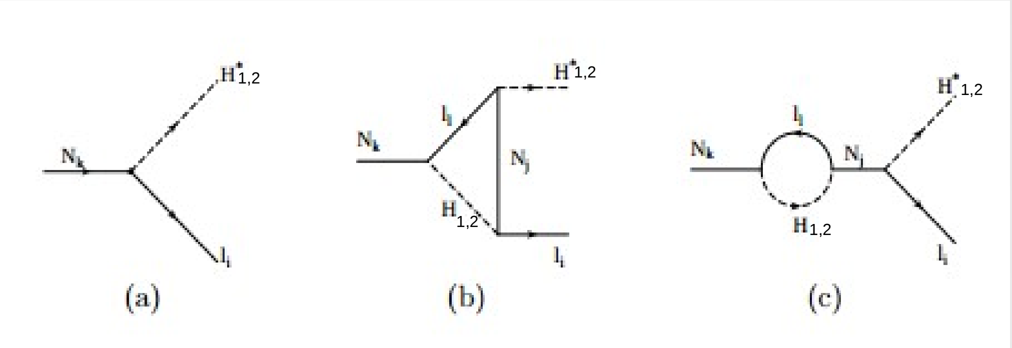
Can allow non-zero P terms. High energy mass eigenstates above mirror breaking scale are parity eigenstates. In each case, lepton asymmetry produced will be mirror symmetric.

In the case where cross sector terms are zero, model reduces to two independent see saw mechanisms. Light states in the mirror sector heavier by w/v.

Leptogenesis in two sectors

CP asymmetry from interference of tree level and one loop decays.
Key differences from vanilla leptogenesis are:

- Decays generating leptognesis in two sectors
- In each sector decays involve both types of Higgs, H_1, H_2



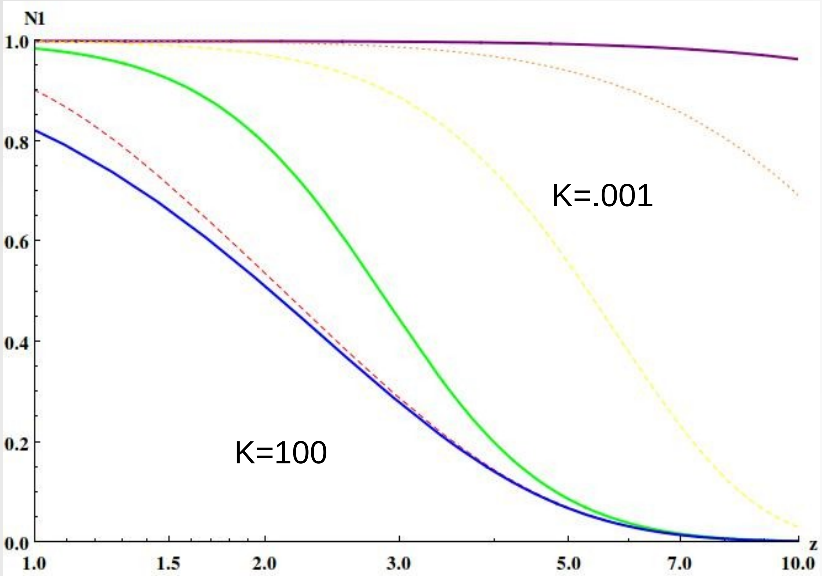
Scatterings and washout terms, inverse decay also modified by two Higgs types.

- CP asymmetry in each sector is the same by mirror symmetry, most of the CP asymmetry comes from the coupling to the second Higgs: H_2', H_2

$$\epsilon = \Sigma_{k\neq 1} \frac{16}{\pi}\frac{M_1}{M_k}\frac{(Im[3[(h_1^\dagger h_1)_{k1}]^2] + 2[(h_1^\dagger h_1)_{k1}(h_2^\dagger h_2)_{k1}] + Im[3[(h_2^\dagger h_2)_{k1}]^2] + 2[(h_2^\dagger h_2)_{k1}(h_1^\dagger h_1)_{k1}])}{(h_1^\dagger h_1)_{k1} + (h_2^\dagger h_2)_{k1}}$$

Mirror symmetry enforces that: $$\epsilon' = \epsilon$$

Leptogenesis in two sectors



Asymmetry washout rate can be parameterised by factor K.

$$K = \frac{\Gamma_D(z=\infty)}{H(z=1)}$$

Where K >>1 implies strong washout, K<<1 the weak regime.

Necessary amount of lepton asymmetry generated now sets constraints on M1, heavy state and light states of the dark sector.

$$\delta m_H^2 \sim \frac{h_1^2 M_N^2}{4\pi^2}$$

Natural Higgs mass correction for large Majorana Mass, small yukawa coupling.
Mass correction to H2 is large, but so is the mass of H2- satisfies PNP (Physical naturalness principle).

Since the CP asymmetry in the VS is largely generated by the Yukawa coupling to the Higgs multiplet that does not give Dirac Masses to neutrinos, model is less constrained by current neutrino bounds.
DS neutrinos can be completely decoupled.

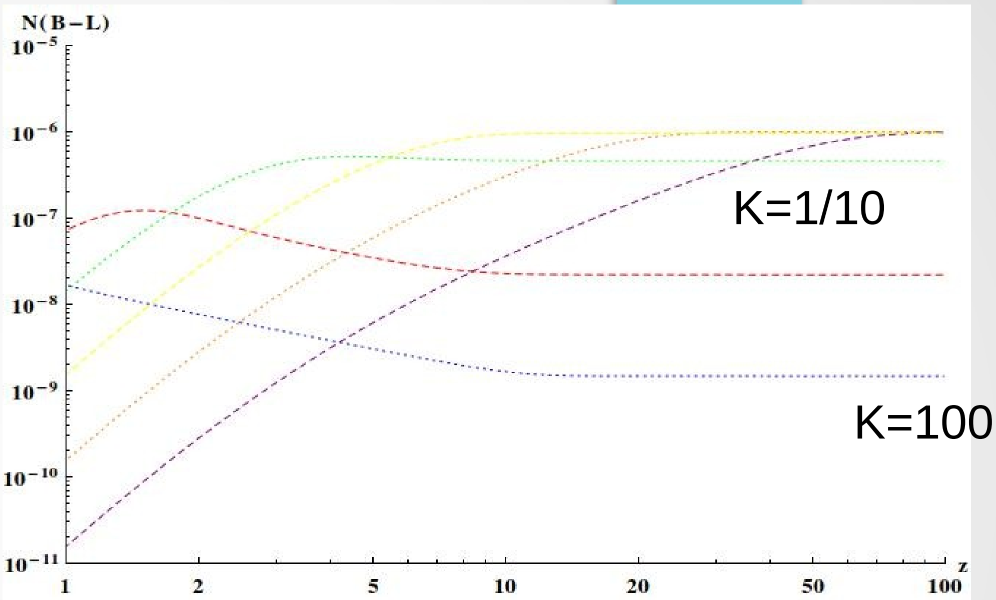
Leptogenesis in two sectors

Baryon asymmetry from sphaleron conversion of lepton asymmetry at EW scale.

$$N_B = \xi N_{B-L}$$

Fraction converted by sphaleron process

$$N'_B = \xi' N'_{B-L}$$



Mirror baryon asymmetry is the same up to a small difference ξ' from the different degrees of freedom. (B-L) Asymmetry the same.

For suitable ratio of confinement scales we have need a relation between the total visible and dark matter of the universe.

$$\frac{\lambda'_{QCD}}{\lambda_{QCD}} \sim 5$$

Larger VEV of H2 in DS sets Quark mass thresholds at higher energy, dark SU(3) confines slightly earlier.

Compare to experimental baryon asymmetry.

$$\eta_B = 6.11 \times 10^{-10}$$

Temperature of the Universe

- Bounds on the light degrees of freedom at the scale of BBN (effective number of neutrino flavours) are strong.
- Can either remove sufficient particle species by this temperature or meet these bounds by having T' < T at the scale of BBN.

$$\frac{T_V^3}{T_D^3} = (\frac{g_V}{g_D})_{Dec}\frac{g_D}{g_V}$$

- If the two sectors were to decouple and cool at different rates, then the dark sector can be sufficiently cool by time of BBN. This leads to an effectively small number of additional neutrino flavours.

$$\Delta N_{eff} \simeq \frac{2}{0.45}(\frac{T'}{T})^4 \simeq .17$$

Compatible with present constraints.

Temperature of the Universe

- Need to decouple the two sectors when the degrees of freedom of the dark sector is much less. (i.e Have entropy density transferred to the visible sector.)
- Our model already contains exactly such a period! - The time between confinement of dark and visible QCD's...
- Need a sufficiently rapid interaction to switch off between the temperature of the two confinement scales.
- Many interactions possible but few suitable - Need cross sector higgs portal small to maintain difference in EW scales. Photon kinetic mixing maintains thermal contact too late, neutrino portals induce washout...

Temperature of the Universe

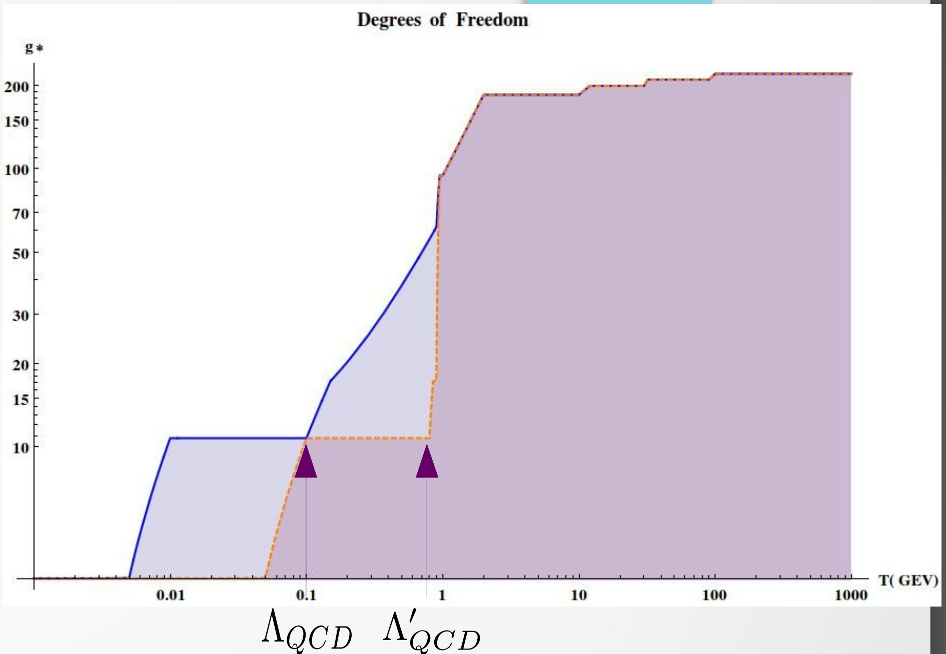
Degrees of freedom shared between two sectors until the region between confinement scales.
Consider two ways of decoupling the sectors.
Lepton dim-9 operator:

$$\frac{1}{M^5}\overline{l}\overline{l}\overline{e}^c l' l' e'^c + h.c$$

Could decouple the sectors if suppressed by a scale of aprrox 10-100 TeV

$$\frac{T_D^{11}}{M^{10}} \sim H(T_D)$$

Or have the interaction drop off from the boltzmann suppression of muons/dark muons
In the case of a muon only dim 9 operator.



Alternatively, may be possible that confinement 'switches-off' interactions. In a dim-9 neutron portal operator, neutrons of dark sector become boltzmann suppressed, decay into visible sector quarks...

Constraints

- FCNC (Flavour changing neutral currents) must be highly suppressed. Mdel resembles a type III 2HDM. By large mass decoupling limit of H2 and the small yukawa couplings of H2 to visible sector fermions these VS interactions are small.
- Dark matter self-interaction bounds from Bullet Cluster. With free yukawa couplings of H2, we can set the mass difference between dark up and down quarks small to make neutron lightest stable baryon in the dark sector. Neutron-neutron scattering passes current DM self interaction bounds.
- Switching on more cross sector terms we quickly run into sterile neutrino constraints. Minimal interactions between the sectors such as photon-mirror photon kinetic mixing. Natural explanation in GUT models.

Summary

- Asymmetric model of dark matter that explains both the similarity of the mass of dark matter particles and their number density to explain 1-5 ratio of visible and dark matter.
- Utilise asymmetric symmetry breaking to take models that are mirror symmetric at high energy, and develops into a low energy theory with different masses, gauge groups, astrophysical properties...
- Generate models that decouple the temperature of the two sectors allowing for different epoch such as BBN to occur at different points in time.
- Provides a mechanism for neutrino mass, baryon/lepton asymmetry and dark matter.
- Possible extensions into Inflation, GUT baryogenesis, Affleck-dine mechanism.

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Thank You