Unified Dark Matter

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Unified Dark Matter

- Motivation: Asymmetric dark matter models
- Asymmetric symmetry breaking
- Non-supersymmetric SU(5)
- Supersymmetric ADM
- Conclusions

Asymmetric Dark Matter

- Experimental evidence suggests that dark matter makes up ~27% of the energy of the universe, much more than the matter that we know of. What is it?

- ADM models are motivated by the remarkable similarity of the mass densities of visible and dark matter.

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

- How can we explain this relation?
- The similarity suggests a connection between the origins of VM and DM.

Asymmetric Dark Matter

- The visible sector baryon number density is largely determined by the baryon asymmetry.
- Asymmetric dark matter models relate the production mechanism of visible and dark matter by the conservation of a global quantum number.
- Consider a hidden sector with only limited interaction with SM fields and which can then produce a dark analogue of the baryon in a manner similar to the baryogenesis of our own sector.
- Baryons and anti-baryons in a dark gauge group G_d obtain an asymmetry which is related to the visible sector number densities.

Asymmetric Dark Matter

- Vast majority of work on ADM models seek to explain the mechanism by which the *number density of DM particles is related to the number density of visible sector baryons*.
- But what about mass?
- If baryons of a dark sector are the dominant form of DM, then we also need to explain the similarity of their mass to that of the proton in order to explain the DM coincidence.
- **Goal of this work is to create a framework for generating such models which can explain both of these features by using GUT groups**.

Asymmetric Dark Matter

- In order to relate the two masses we must relate the confinement scales.
- Assume the couplings unify at high energy and at the GUT scale the couplings of both sectors are the same with a Z2 symmetry, then the confinement scales at low energy are related.

$$G_V \times G_D$$

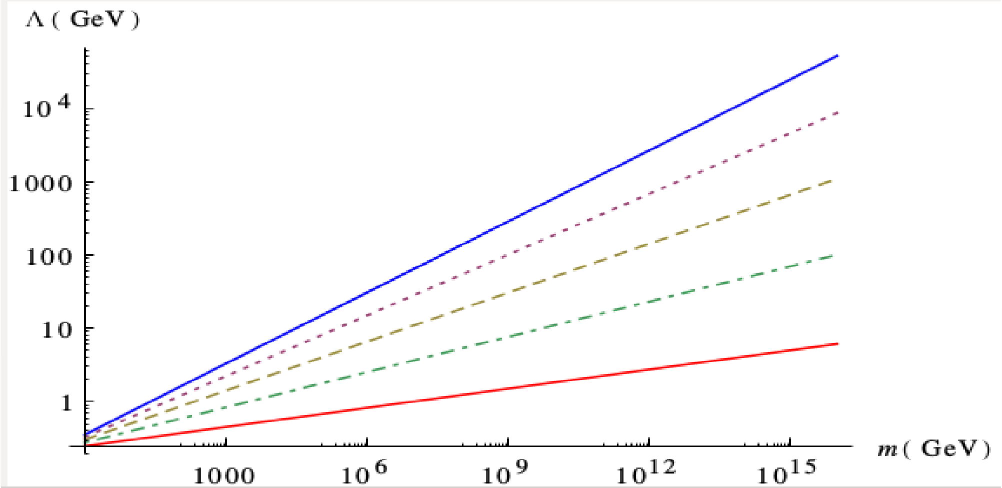
- The QCD confinement scale can be expressed (at one loop) as a function of GUT scale and the mass of quarks between the two scales,

$$\Lambda = 2^{2/9} e^{-2\pi/9\alpha_s(U)} U^{\frac{7}{9}} m_c^{\frac{2}{27}} m_b^{\frac{2}{27}} m_t^{\frac{2}{27}} .$$

- But dark confinement scale can end up far away even if dark SU(3) coupling is the same at such high energy.
- However if total number of quarks in each sector are the same, as in the case of a Z2 symmetry, then each SU(3) coupling constant will evolve the same until the first mass threshold.

Asymmetric Dark Matter

- Result is that we can express dark confinement scale as a function of the mass of the dark quarks.



- We take the assumption that all massive dark quarks share a common mass scale and observe how the confinement scale depends on both this scale and the number of quarks that gain a mass above the confinement scale.

Asymmetric Dark Matter

- So we can create dark baryons of mass scale just above the proton provided that

  a) You can generate dark sectors containing SU(3) from unified origins and

  b) the dark sector can generate quarks with masses different to those of the SM.

- We will see that both of these can be done in a natural way with a mechanism known as *asymmetric symmetry breaking*.

Asymmetric symmetry breaking

Consider the simple case of four scalar fields $\phi_1, \phi_2, \chi_1, \chi_2$ transforming under the Z2 symmetry :

$$\phi_1 \leftrightarrow \phi_2, \qquad \chi_1 \leftrightarrow \chi_2.$$

We can examine the minima of such a toy model with general potential given by

$$\begin{aligned} V = \lambda_\phi(\phi_1^2 + \phi_2^2 - v_\phi^2)^2 + \lambda_\chi(\chi_1^2 + \chi_2^2 - v_\chi^2)^2 + \\ \kappa_\phi(\phi_1^2\phi_2^2) + \kappa_\chi(\chi_1^2\chi_2^2) + \\ \sigma(\phi_1^2\chi_1^2 + \phi_2^2\chi_2^2) + \rho(\phi_1^2 + \chi_1^2 + \phi_2^2 + \chi_2^2 - v_\phi^2 - v_\chi^2)^2. \end{aligned}$$

If each of the parameters in this potential are positive then each term is positive definite and the absolute minima then has an *asymmetric* configuration:

$$\begin{aligned} \phi_1 &= v_\phi, & \chi_1 &= 0, \\ \phi_2 &= 0, & \chi_2 &= v_\chi. \end{aligned}$$

Asymmetric symmetry breaking

- Result is that though the Lagrangian is completely symmetric under the Z2 symmetry, the different sectors gain nonzero VEVs from different varieties of fields.
- We will extend this idea to Higgs multiplets in different representations of GUT groups.
- We can also add more such fields and link together sets of fields with nonzero VEVs in each sector, useful for fermion mass generation. Simple to build a model of eight fields that has minima of the form

$$
\begin{aligned}
\phi_1 &= v_\phi \ , & \chi_1 &= 0 \ , \\
\phi_2 &= 0 \ , & \chi_2 &= v_\chi \ , \\
\Omega_1 &= v_\Omega \ , & \eta_1 &= 0 \ , \\
\Omega_2 &= 0 \ , & \eta_2 &= v_\eta \ .
\end{aligned}
$$

SU(5)

- Look at an SU(5) x SU(5) as an example.
- Replace ϕ_1, ϕ_2 with adjoints of SU(5) and χ_1, χ_2 with two 10 dimensional representations. Build a potential along the same rules as the toy model and the minimum breaks the symmetry such that

$$SU(5)_d \to SU(3) \times SU(2),$$

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

SU(5)

$$
\begin{aligned}
V &= \lambda_{a1}(\phi_{v_j}^{\ i}\phi_{v_i}^{\ j} + \phi_{d_j}^{\ i}\phi_{d_i}^{\ j} - \mu_a^2)^2 + \kappa_a(\phi_{v_j}^{\ i}\phi_{v_i}^{\ j}\phi_{d_k}^{\ h}\phi_{d_h}^{\ k}) + \lambda_{a2}(\phi_{v_j}^{\ i}\phi_{v_k}^{\ j}\phi_{v_h}^{\ k}\phi_{v_i}^{\ h} + \phi_{d_j}^{\ i}\phi_{d_k}^{\ j}\phi_{d_h}^{\ k}\phi_{d_i}^{\ h}) \\
&+ \lambda_{t2}(\chi_{v_{ij}}\chi_v{}^{ji} + \chi_{d_{ij}}\chi_d{}^{ji} - \mu_t^2)^2 + \kappa_t(\chi_{v_{ij}}\chi_v{}^{ji}\chi_{d_{ij}}\chi_d{}^{ji}) \\
&+ \lambda_{t2}(\chi_{v_{ij}}\chi_v{}^{ij}\chi_{v_{ij}}\chi_v{}^{ij} + \chi_{d_{ij}}\chi_d{}^{ij}\chi_{d_{ij}}\chi_d{}^{ij}) + C_0(\chi_{v_{ij}}\chi_v{}^{ij}\phi_{v_j}^{\ i}\phi_{v_i}^{\ j} + \chi_{d_{ij}}\chi_d{}^{ji}\phi_{d_j}^{\ i}\phi_{d_i}^{\ j}) \\
&+ C_1(\chi_{v_{ij}}\chi_v{}^{jk}\phi_{v_k}^{\ l}\phi_{v_l}^{\ i} + \chi_{d_{ij}}\chi_d{}^{jk}\phi_{d_k}^{\ l}\phi_{d_l}^{\ i}) + C_2(\chi_{v_{lq}}\chi_v{}^{ij}\phi_{v_j}^{\ l}\phi_{v_i}^{\ q} + \chi_{d_{lq}}\chi_d{}^{ij}\phi_{d_j}^{\ l}\phi_{d_i}^{\ q}) \\
&+ C_3(\chi_{v_{su}}\chi_v{}^{pq}\phi_{v_m}^{\ n}\phi_{v_j}^{\ i}\epsilon^{smujt}\epsilon_{pnqit} + \chi_{d_{su}}\chi_d{}^{pq}\phi_{d_m}^{\ n}\phi_{d_j}^{\ i}\epsilon^{smujt}\epsilon_{pnqit}) \\
&+ C_4(\phi_{v_j}^{\ i}\phi_{v_i}^{\ j}\chi_{d_{lk}}\chi_d{}^{kl} + \phi_{d_j}^{\ i}\phi_{d_i}^{\ j}\chi_{v_{kl}}\chi_v{}^{lk}).
\end{aligned}
$$

- **Extending the same principles of a toy model to an SU(5)XSU(5) potential, VEVs of different representations now break the symmetry of the visible and hidden sector differently**.

SU(5)

- Fermion masses- adapt additional Higgs $\Omega_{1,2}, \eta_{1,2}$ to copies of the 45 and 5 representations as a simple example.
- Allows one to build models where the visible sector breaks to the SM with the 5 gaining a VEV for fermion mass generation in that sector, while in the dark gauge group the 45 takes on the role.
- This has the interesting effect of giving mass to five of the six dark quarks. If these gain a mass around the EW scale, then the dark baryons gain a mass ~ 10 times higher than the proton.
- A fully realistic model would need more Higgs multiplets to prevent lepton-quark mass relations in the visible sector. Other problems such as proton decay, hierarchy problem still persist as in generic SU(5) models.
- In addition we have assumed unified coupling constants, but minimal SU(5) does not unify the gauge couplings . **Move on to supersymmetric asymmetry models**.

SUSY ADM

- So the question is: can we build asymmetric potentials in SUSY?
- Answer is yes but a larger number of fields is needed.

$$\Phi_v \sim (24, 1), \qquad X_v \sim (10, 1), \qquad Y_v \sim (\overline{10}, 1),$$
$$\Phi_d \sim (1, 24), \qquad X_d \sim (1, 10), \qquad Y_d \sim (1, \overline{10}),$$
$$S \sim (1, 1).$$

- Need terms in the potential that are positive definite and link visible and dark sector fields.
- In the case of minimally adapting the SU(5)xSU(5) model we need the additional fields shown above, different choice of symmetry breaking chains can require different fields.

SUSY ADM

- For the SUSY SU(5) case the general superpotential is given by

$$
\begin{aligned}
W &= s_1(X_vY_v + X_dY_d) + s_2(\Phi_v\Phi_v + \Phi_d\Phi_d) + s_3(\Phi_v\Phi_v\Phi_v + \Phi_d\Phi_d\Phi_d) + s_4(X_d\Phi_dY_d + X_v\Phi_vY_v) \\
&+ s_5(\Phi_v\Phi_vS + \Phi_d\Phi_dS) + s_6(X_vY_vS + X_dY_dS) + s_7S + s_8SS + s_9SSS.
\end{aligned}
$$

- With D-terms and soft terms can generate appropriate scalar potential interactions such as

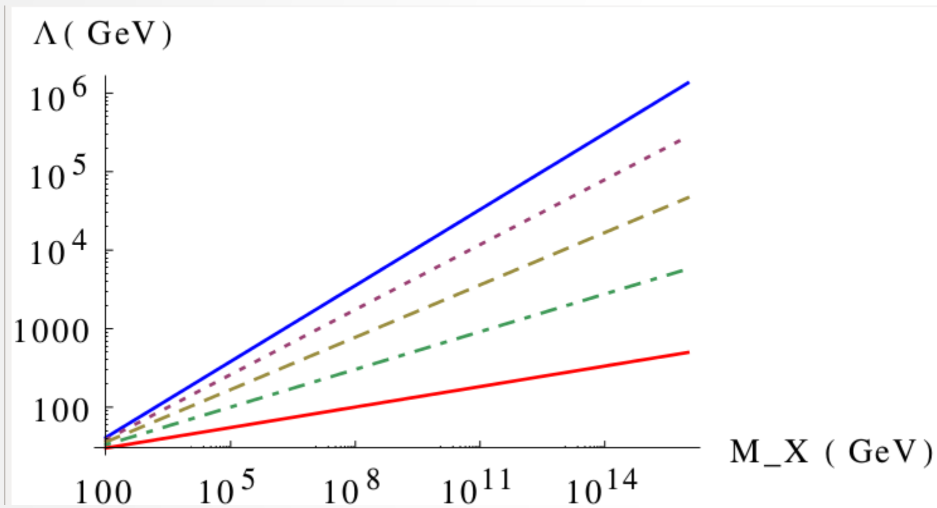
$$\Phi_v\Phi_v\Phi_d\Phi_d,$$

$$(\Phi_v\Phi_vX_vX_v + \Phi_v\Phi_vY_vY_v + \Phi_d\Phi_dX_dX_d + \Phi_d\Phi_dY_dY_d).$$

- Give positive definite terms that ensure the VEVs are opposing in the visible and dark sectors.
- And again generates different symmetry breaking in visible and dark sectors with the visible sector breaking to the standard model and the dark sector breaking to alternate gauge groups.
- Asymmetric symmetry breaking can be generalised to your favourite GUT model in such a way.

SUSY ADM

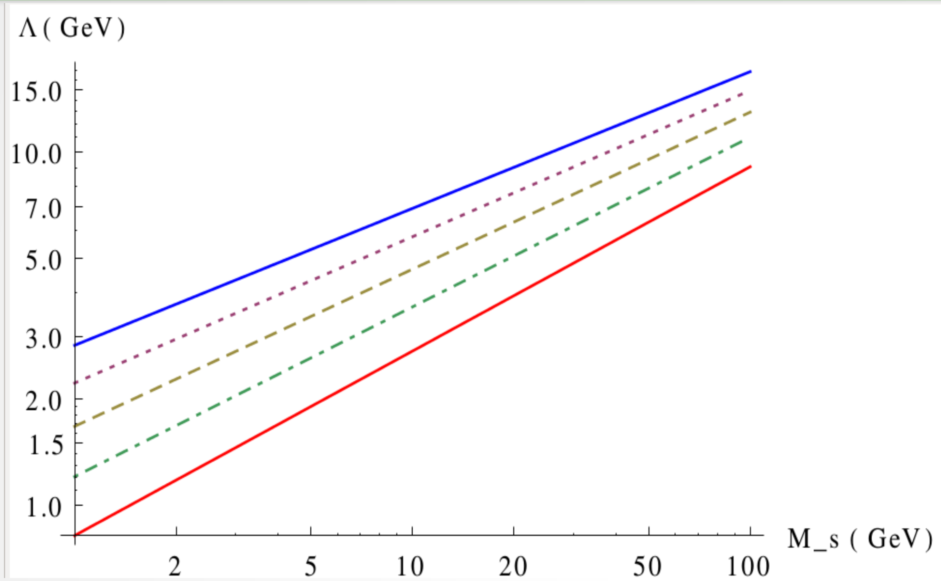
- In the case of dark SUSY, SU(3) models follow similar relations of the confinement scale, accounting for sparticles.

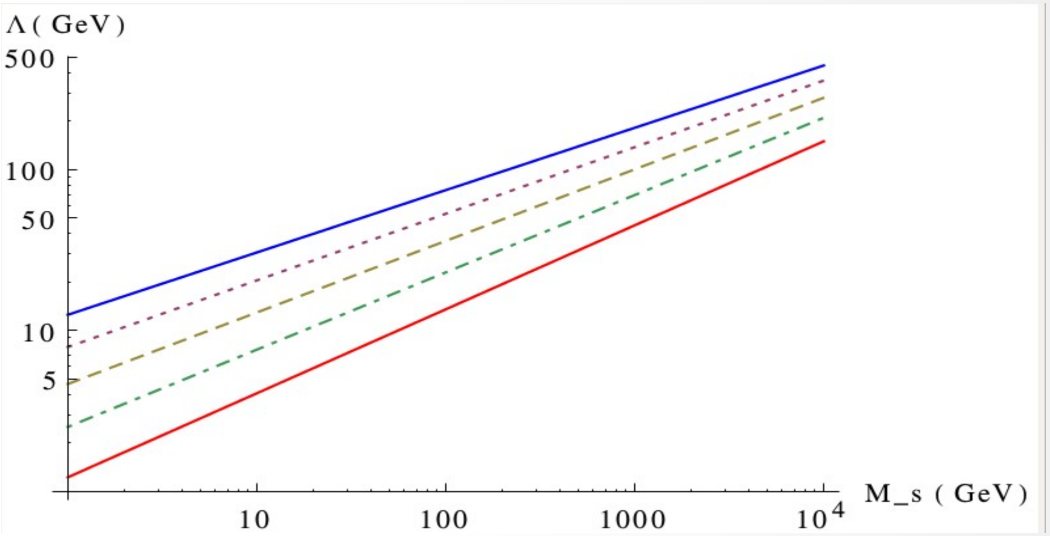


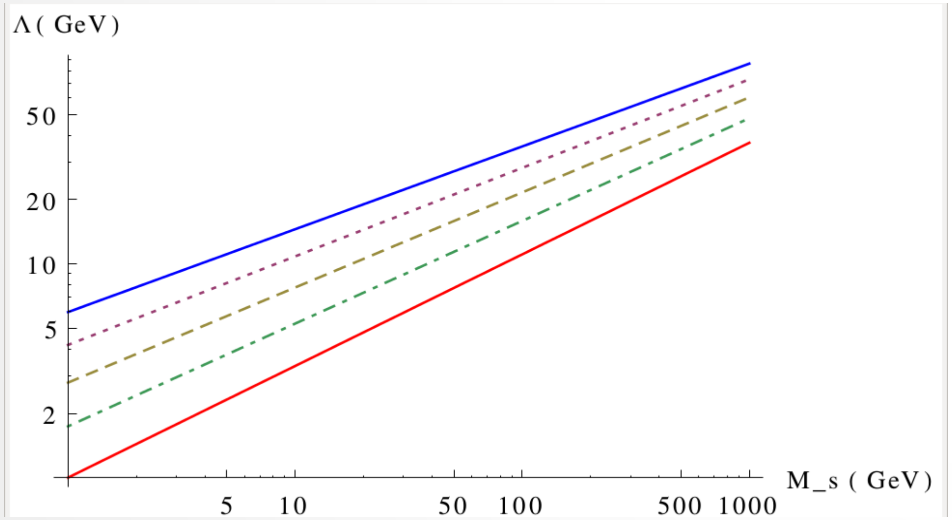
Similar dependence on the mass scale for confinement scale in a supersymmetric dark SU(3) theory, approximately a factor of 10 higher compared to the non-susy case.

- Can also consider how the soft SUSY scale affects the confinement scale in an SU(3) theory the same way we examined how the mass of quarks heavier than the confinement scale affected its value.

SUSY ADM







Scale of sfermions and gauginos will also affect the running of dark SU(3).
Assume MSSM running of SU(3) coupling in the VS, and observe the dark confinement scale as a function of soft SUSY scale for a set of fixed dark quark masses.

Conclusions

- ASB models of asymmetric dark matter can explain the relative abundance of VM and DM with mass relations from linked couplings.
- Would be Interesting to see a full theory with fields that communicate between the two sectors, complete description of baryogenesis in such a model including a way to annihilate away dark baryon/anti-baryon symmetric component.
- Further work on supersymmetric models and how SUSY breaking is communicated to the visible and hidden sectors.
- Asymmetric symmetry breaking allows us to generate hidden sectors with completely unique masses and symmetries from unified origins. One can also think how to generalise to SO(10) and higher rank GUT groups.

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THANK YOU