Dark Matter Considerations in the E_6SSM

arXiv:1201.5488

Work done with Steve King

arXiv/0905.2696, arXiv/1104.2259

and also with Marc Sher, Roman Nevzorov, and Sandip Pakvasa

arXiv/1012.5114

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Contents

- The E_6SSM
- Neutralinos and Charginos
- E_6SSM Dark Matter

- The EZSSM
- EZSSM Dark Matter

- Main Points

The E_6SSM arXiv/0904.2169, arXiv:1201.5488

- One of the main motivations for supersymmetry softly broken near the EWSB scale is as a solution to the hierarchy problem
- The MSSM suffers from the μ problem

$$\mu H_d.H_u$$

- Singlet extensions replace this term in the superpotential with

$$\lambda S H_d.H_u$$

  and relate the VEV of S to the supersymmetry breaking scale along with the EWSB VEVs
- Axion (and domain wall) problems can be avoided if the resulting $U(1)'$ symmetry is gauged
- If the enlarged gauge group $G_{\text{SM}} \otimes U(1)'$ is a subgroup of E_6 and the matter content comprises complete representations of the E_6 then the theory is anomaly free

The E_6SSM arXiv/0904.2169, arXiv:1201.5488

- In the E_6SSM the unified gauge group

$$\begin{aligned} E_6 &\supset SO(10) \otimes U(1)_\psi \\ &\supset SU(5) \otimes U(1)_\chi \otimes U(1)_\psi \end{aligned}$$

is assumed broken to

$$G_{\rm SM} \otimes U(1)_N$$

below the unification scale, where

$$G_{\rm SM} \subset SU(5) \quad \text{and} \quad U(1)_N = \cos(\vartheta)U(1)_\chi + \sin(\vartheta)U(1)_\psi,$$

with $\tan(\vartheta) = \sqrt{15}$

The E_6SSM arXiv/0904.2169, arXiv:1201.5488

- The fundamental representation of E_6 decomposes under the $SU(5) \otimes U(1)_N$ subgroup as

$$27 \rightarrow \left(10, \frac{1}{\sqrt{40}}\right) \oplus \left(\overline{5}, \frac{2}{\sqrt{40}}\right) \oplus \left(\overline{5}, -\frac{3}{\sqrt{40}}\right) \oplus \left(5, -\frac{2}{\sqrt{40}}\right) \oplus \left(1, \frac{5}{\sqrt{40}}\right) \oplus \left(1, 0\right)$$

- This contains three generations of Higgs down- and up-type doublets and SM-singlets
- There are also three generations of exotic $\bar{D}$ and D fields from the same $\overline{5}$ and 5 as the Higgs doublets as well as three right-handed neutrinos

The E_6SSM arXiv/0904.2169, arXiv:1201.5488

- The low energy gauge invariant and renormalizable superpotential is

$$\mathcal{W} = \mathcal{W}_0 + \mathcal{W}_1 + \mathcal{W}_2,$$

where

$$\begin{aligned}\mathcal{W}_0 &= \lambda_{ijk} S_i H_{dj}.H_{uk} + \kappa_{ijk} S_i \bar{D}_j D_k + h^N_{ijk} \tilde{\mathfrak{N}}^c_i H_{uj}.\tilde{L}_k \\ &\quad + h^U_{ijk} \tilde{u}^c_{Ri} H_{uj}.\tilde{Q}_{Lk} + h^D_{ijk} \tilde{d}^c_{Ri} H_{dj}.\tilde{Q}_{Lk} + h^E_{ijk} \tilde{e}^c_{Ri} H_{dj}.\tilde{L}_{Lk},\end{aligned}$$

$$\mathcal{W}_1 = g^Q_{ijk} D_i \tilde{Q}_{Lj}.\tilde{Q}_{Lk} + g^q_{ijk} \bar{D}_i \tilde{d}^c_{Rj} \tilde{u}^c_{Rk},$$

$$\mathcal{W}_2 = g^N_{ijk} \tilde{\mathfrak{N}}^c_i D_j \tilde{d}^c_{Rk} + g^E_{ijk} \tilde{e}^c_{Ri} D_j \tilde{u}^c_{Rk} + g^D_{ijk} \tilde{Q}_{Li}.\tilde{L}_{Lj} \bar{D}_k$$

- The terms that R-parity is invoked to remove in the MSSM are already not present since they are forbidden by the gauge symmetry
- Some discrete symmetry can be imposed to forbid either $\mathcal{W}_2$ or $\mathcal{W}_1$
- Both $U(1)_B$ and $U(1)_L$ are then symmetries of this superpotential if the coloured exotics are either diquarks or leptoquarks respectively

The E_6SSM arXiv/0904.2169, arXiv:1201.5488

- It is assumed that the third (by definition) generation of Higgs doublets and SM-singlets are distinguished from the others by some flavour symmetry
- The first and second, called inert, generations would have small couplings to matter and therefore would not radiatively acquire VEVs
- FCNCs would be suppressed

- An approximate $\mathbb{Z}_2$ symmetry, called $\mathbb{Z}_2^H$, would have this effect
- One possible theory of flavour for the E_6SSM exhibits this approximate symmetry [arXiv/0908.2067]

- In the E_6SSM chargino interaction basis $\tilde{C}_{\text{int}} =$

$$\begin{pmatrix} \tilde{W}^+ & \tilde{H}^+_{u3} & \tilde{H}^+_{u2} & \tilde{H}^+_{u1} & | & \tilde{W}^- & \tilde{H}^-_{d3} & \tilde{H}^-_{d2} & \tilde{H}^-_{d1} \end{pmatrix}^{\mathrm{T}}$$

the E_6SSM chargino mass matrix is $M^C =$

$$\begin{pmatrix} & P^{\mathrm{T}} \\ P & \end{pmatrix},$$

where

$$P = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin(\beta) & 0 & 0 \\ \sqrt{2} m_W \cos(\beta) & \mu & \frac{1}{\sqrt{2}}\lambda_{332} s & \frac{1}{\sqrt{2}}\lambda_{331} s \\ 0 & \frac{1}{\sqrt{2}}\lambda_{323} s & \frac{1}{\sqrt{2}}\lambda_{322} s & \frac{1}{\sqrt{2}}\lambda_{321} s \\ 0 & \frac{1}{\sqrt{2}}\lambda_{313} s & \frac{1}{\sqrt{2}}\lambda_{312} s & \frac{1}{\sqrt{2}}\lambda_{311} s \end{pmatrix},$$

with

$$\begin{aligned} \mu &= \lambda_{333} s/\sqrt{2}, \\ \langle S_3 \rangle &= s/\sqrt{2} \end{aligned}$$

- In the USSM neutralino interaction basis $\tilde{N}_{\text{int}} =$

$$\left(\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_{d3} \quad \tilde{H}^0_{u3} \;\middle|\; \tilde{S}_3 \quad \tilde{B}' \right)^{\text{T}}$$

the USSM neutralino mass matrix $M^N_{\text{USSM}} =$

$$\left(\begin{array}{cccc|cc} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 & 0 \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 & 0 \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu & -\mu_s s_\beta & g_1' v c_\beta Q_d^N \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 & -\mu_s c_\beta & g_1' v s_\beta Q_u^N \\ \hline 0 & 0 & -\mu_s s_\beta & -\mu_s c_\beta & 0 & g_1' s Q_s^N \\ 0 & 0 & g_1' v c_\beta Q_d^N & g_1' v s_\beta Q_u^N & g_1' s Q_s^N & M_1' \end{array} \right),$$

where

$$\begin{aligned} \mu_s &= \lambda_{333} v/\sqrt{2}, \\ \langle H^0_{d3} \rangle &= v\cos(\beta)/\sqrt{2}, \\ \langle H^0_{u3} \rangle &= v\sin(\beta)/\sqrt{2} \end{aligned}$$

- In the full E_6SSM neutralino interaction basis $\tilde{N}_{\text{int}} =$

$$\left(\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_{d3} \quad \tilde{H}^0_{u3} \;\middle|\; \tilde{S} \quad \tilde{B}' \;\middle|\; \tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2 \;\middle|\; \tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1 \right)^{\mathrm{T}}$$

the E_6SSM neutralino mass matrix $M^N =$

$$\begin{pmatrix} M^{\text{n}}_{\text{USSM}} & B_2 & B_1 \\ B_2^{\mathrm{T}} & A_{22} & A_{21} \\ B_1^{\mathrm{T}} & A_{21}^{\mathrm{T}} & A_{11} \end{pmatrix},$$

where

$$A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda_{3\alpha\beta} s & \lambda_{\beta\alpha 3} v \sin(\beta) \\ \lambda_{3\beta\alpha} s & 0 & \lambda_{\beta 3\alpha} v \cos(\beta) \\ \lambda_{\alpha\beta 3} v \sin(\beta) & \lambda_{\alpha 3\beta} v \cos(\beta) & 0 \end{pmatrix}$$

with

$$\alpha, \beta \in \{1, 2\} \quad \text{and} \quad s \gtrsim 3700\text{GeV}$$

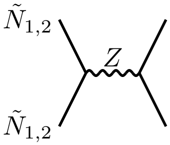
E_6SSM Dark Matter arXiv/1012.5114, arXiv:1201.5488

- If the LSP mass is much smaller than $m_Z/2$ or it is singlino dominated it will not annihilate efficiently in the early universe

- Since $\lambda_{3\alpha\beta}$ control the inert chargino masses they cannot be made too small
- Some of $\lambda_{\alpha 3\beta}$ & $\lambda_{\alpha\beta 3}$ must be large if the LSP is not to be light and singlino dominated

- Requiring perturbativity of the Yukawa couplings up to the unification scale when some of $\lambda_{\alpha 3\beta}$ & $\lambda_{\alpha\beta 3}$ are increased implies that the lightest two inert neutralino states cannot have masses greater than about 60 GeV
- Therefore two inert neutralinos must have masses of order $m_Z/2$

- The observed or less than the observed relic density of DM can arise with inert neutralinos self- or co-annihilating via an s-channel Z boson in the early universe



- In these cases the LSP necessarily contains large inert Higgsino components and has a large coupling to the SM-like Higgs
- With the above Yukawa coupling constraints scenarios in which E_6SSM inert neutralinos make up all cosmological dark matter are now in severe disagreement with XENON100 constraints on the spin-independent DM-nucleon cross-section

- If the two light inert neutralinos are made to be exactly massless then these two massless inert singlinos do not contribute to CDM

- They do contribute to the expansion rate of the universe prior to ^{4}He synthesis, increasing the effective number of neutrinos contributing to the expansion rate by 0.2.
- They decouple from equilibrium with the photon earlier than neutrinos with a decoupling temperature above the strange quark mass
- This is because they only interact via the Z'

EZSSM Dark Matter arXiv/1104.2259, arXiv:1201.5488

- The massless inert singlinos are decoupled and the next lightest supersymmetric particle is stable

- A stable bino can provide the observed amount of dark matter in this model
- A pair of pseudo-Dirac inert neutral Higgsinos, approximately degenerate with the corresponding chargino, may be close by in mass to the bino
- Such Higgsinos co-annihilate efficiently
- Frequent inelastic scattering off of SM particles allows the ratios of the number densities of binos and the inert Higgsinos to maintain their equilibrium values during the time of thermal freeze-out

EZSSM Dark Matter arXiv/1104.2259, arXiv:1201.5488

- In order to use the thermal freeze-out equation

$$\dot{n} = -3Hn - \langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right), \qquad \text{where}$$
$$\langle\sigma v\rangle = \sum_i \sum_j \langle\sigma_{ij} v_{ij}\rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

  for n the number of non-inert-singlino supersymmetric particles, we need to make sure that interactions in which n changes by 1 involving inert singlet bosons can be neglected

- This equation also assumes that inelastic scattering of non-inert-singlino supersymmetric particles off of SM matter happens with a much greater frequency than self-annihilation or co-annihilation of the non-relativistic supersymmetric particles

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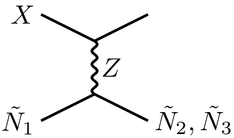

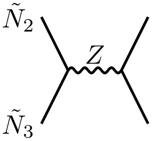

- $\tilde{N}_1$ is the bino, $\tilde{N}_2$ and $\tilde{N}_3$ are the lightest pseudo-Dirac pair of inert Higgsinos, and X is some SM particle
- The ratio of an inelastic scattering rate to the inert Higgsino coännihilation rate

$$\begin{aligned} \Upsilon &= \frac{\langle \sigma'_{X12} v_{1X} \rangle n_1^{\text{eq}} n_X^{\text{eq}}}{\langle \sigma_{23} v_{23} \rangle n_2^{\text{eq}} n_3^{\text{eq}}} \\ &\sim R_{Z12}^2 \left(\frac{T}{m} \right)^{3/2} \exp\left(\frac{T}{m} \right), \end{aligned}$$

  where R_{Z12} is the Z-$\tilde{N}_1$-$\tilde{N}_2$ coupling relative to the Z-ν-ν coupling.
- $\mathbb{Z}_2^H$ breaking Yukawas of order 10^{-2} give $\Upsilon \sim 10^8$

Main Points

- The inert neutralino E_6SSM inert dark matter scenario is very constrained and is now severely challenged by direct detection observations
- The model can still be consistent with all observation if the LSP relic density is lower than the observed dark matter density
- The presence of the light inert neutralinos lead to new phenomena such as longer gluino decay chains and invisible Higgs decays(!)

- The EZSSM dark matter scenario presented is not currently constrained by direct detection experiments
- The typical dark candidate is the bino and the observed dark matter relic density can be accounted for in the model when a pair of pseudo-Dirac inert Higgsinos is close by in mass
- In this case the DM would show up phenomenologically as a pure bino, but other aspects of the model would still look very different to the MSSM

E_6SSM Dark Matter Direct Detection arXiv:1201.5488

- In arXiv/1012.5114 we predicted that this inert neutralino dark matter should be detected by the XENON100 experiment
- The XENON100 Collaboration now claims a 90% confidence level limit on the spin independent WIMP-nucleon cross-section of 7.0×10^{-45} cm^2 for a 50 GeV WIMP [arXiv/1104.2549]
- In the considered model this cross-section would be dominated by t-channel Higgs exchange
- Even allowing for the theoretical uncertainties in its calculation [arXiv/0801.3656] the cross-section in the E_6SSM for regions where the correct DM relic density is predicted cannot be less than about 17×10^{-45} cm^2, and this is for a Higgs mass of 133 GeV
- This model of dark matter therefore looks to be ruled out now by direct detection observations