Less dimensions and the origin of DM

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Dark Matter is the signal of NP beyond the SM

The existence of dark component of matter is now established beyond any reasonable doubt

So far all the signals of Dark Matter are astrophysical, direct evidence is gravitational

We do not know what DM is and how is it generated

Modern particle physics concepts do provide many NP candidates for DM (SUSY, Little Higgs with T-parity, Kaluza-Klein DM, Inert Doublet Model etc)

Formulating the problem

Marco Cirelli: Why there are so many DM papers posted to arXive?

An answer: Because there is no known concept behind DM! There is no theory of DM! Models are built case-by-case.

Aims:

- Propose a general underlying concept for DM
- Show that the theory of DM becomes very predictive
- Work out its phenomenology (partially)

But first:

- Although my central claim is general, I start with motivating it within an interesting NP scenario, the less dimensions

Which Universe we live in?

- Although we live in 4-dimensional flat and homogeneous Universe, the topology of our Universe is actually not known
- Suppose at very high energies the space-time has a topology $M^3 \times S^1$, i.e., 3-dimensional Minkowski space with one space dimension compactified to a circle
- Today, after inflation, $R_S \gg L_{obs}$ and the universe looks flat and homogeneous.

- Fundamental physics must "remember" the initial conditions and the consistency of QFT in effectively lower-dimensional space-time constrains particle physics models in 4 dimensions

Less dimensions

Two opposite approaches to NP

1. Extra dimensions
   - Add N new space dimensions (small, large, warped etc) and predict signatures of NP from new effects in 4+N dimensions
2. Less dimensions
   - Assume that the initial space-time topology is effectively lower dimensional, *e.g.*, $M^3 \times S^1$ with very small compact space dimension.
   - Formulate physics theories consistently in 3-dimensions and lift the result to 4 dimensions.
   - Take care of CPT and Lorentz invariance violating effects (photon mass, S^1 must be big)
   - Use new constraints in 4-dimensional model building

Constraints on particle physics from 3-dimensional field theory

- In 3 dimensions non-Abelian gauge and gravity actions have topological Chern-Simons terms which charges are quantized
- The presence on N_F chiral fermions and N_G gauge bosons induce loop corrections to the actions and the quantization conditions require

$$\frac{1}{16}N_F - \frac{1}{8}N_G = 0$$

- For $M^3 \times S^1$ topology, to lift the 3 dimensional result to 4 dimensions there must be odd number of chiral fermion multiplets

Implications for particle physics

- Chiral fermions must come in multiples of 16 and there must be odd number of generations
- Experiment: 15 SM fermions + N fit **16** of SO(10), there are 3 generations
- Number of gauge bosons is $N_G = N_F/2 = 24$
- 24 is an adjoint of SU(5), thus less-dimensions suggest SU(5) GUT and

$$SO(10) \to SU(5) \times U(1)_X$$

Implications:

- If all matter fields come in some representation of SO(10), the U(1) quantum numbers of all of them are well defined
- The $U(1)_X$ is the origin of a discrete Z_n symmetry needed for DM.

General argument

$$SO(10) \to SU(5) \times U(1)_X,$$

- SO(10) is the symmetry group describing matter
- SU(5) is the gauge group
- $U(1)_X$ is broken by some order parameter carrying, *e.g.*, n=2 charges of X leaving Z_2 unbroken
- X is some sort of matter charge and Z_2 is its matter parity P_X under which DM must be Z_2-odd

What is the DM?

A matter field to be Z_2-odd, its X quantum number must be odd too.

Under $SO(10) \to SU(5) \times U(1)_X$

- $\mathbf{10} = \mathbf{5}^{10}(2) + \overline{\mathbf{5}}^{10}(-2)$ is even under P_X
- $\mathbf{16} = \mathbf{1}^{16}(-5) + \overline{\mathbf{5}}^{16}(3) + \mathbf{10}^{16}(-1)$ is odd under P_X
- **45**, **54**, **120**, **126** and **210** are all even under P_X

The SM:

- All SM fermions and right-handed neutrino in $\mathbf{16_i}$ are Z_2-odd
- The SM Higgs boson in $\overline{\mathbf{5}}^{10}$ is Z_2-even, thus Yukawa terms $Y^{ij} L_i e_j H_1$ are OK

The only possible source of DM is a new scalar representation **16**

The only DM candidates are $S = \mathbf{1}^{16}$ and $H_2 \in \overline{\mathbf{5}}^{16}$

What is the Z_2 discrete symmetry?

Motivated by the Pati-Salam gauge group $SU(2)_L \times SU(2)_R \times SU(4)$ the two $U(1)$ charges of SO(10) can be chosen to be $B-L$ and T_{3R}

$$X = 3(B-L) + 4T_{3R},$$

Because $T_{3R} = 1/2,\ 1, ..., 4T_{3R}$ is an even integer and the DM-parity P_X is determined by

$$3(B-L) \bmod 2$$

which is nothing but matter parity

$$P_X \equiv P_M = (-1)^{3(B-L)}, \tag{1}$$

- Our scenario generalizes matter parity to non-SUSY models
- Matter parity P_M is an intrinsic property of all matter

The low energy theory of DM

The most general 1 TeV model of DM contains Z_2-odd complex scalars S and H_2,

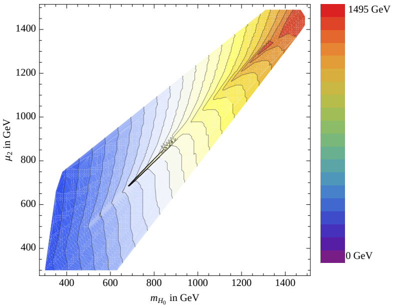
$$\begin{aligned} V &= -\mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 \\ &+ \lambda_{SH_1} (S^\dagger S)(H_1^\dagger H_1) + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\ &+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right] \\ &+ \lambda_{SH_2} (S^\dagger S)(H_2^\dagger H_2) + \frac{\mu_{SH}}{2}\left[S H_1^\dagger H_2 + S^\dagger H_2^\dagger H_1\right], \end{aligned} \tag{2}$$

which respects $H_1 \to H_1$ and $S \to -S, H_2 \to -H_2$.

- Complex scalar $S = (S_H + iS_A)/\sqrt{2}$ is split by the μ_{SH} term and becomes a viable DM candidate

Thermal relict DM abundance

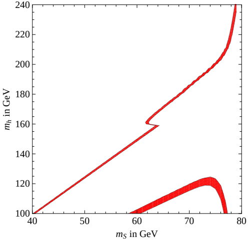
We calculated the DM abundances with MicrOMEGAs. For numerical examples we fix $m_{A_0} - m_{H_0} = 10$ GeV, $m_{H^\pm} - m_{H_0} = 50$ GeV and treat μ_2, m_{H_0} and m_S as free parameters.



Inert Doublet model prediction is the small black region in the diagonal

LHC tests of DM through Higgs portal

Discovering DM at LHC is challenging but the SM Higgs decays $H_1 \to SS$ can be addressed. If $S = DM$ and $\mu_S = 0$ we predict



- Obtain relation between the SM Higgs mass and the DM mass
- For the upper branch $H_1 \to SS$ is kinematically allowed

PAMELA, ATIC, HESS, FERMI

- 1 TeV DM annihilation $DM + DM \to H_1 H_1, \; W^+ W^-$ should give unobserved $\bar{p}/p$ excess
- PAMELA anomaly can also be explained with decaying thermal relict DM with lifetime 10^{26}s
- If Planck scale SO(10) singlet fermion N' exist, its mixing with the right-handed neutrino mNN' breaks Z_2 explicitly but is suppressed by m/M_P

Seesaw type P_M-violating operator is generated

$$\frac{\lambda_N^2}{M_N} \frac{m}{M_P} LLH_1 H_2 \to 10^{-28} LLH_2 \tag{3}$$

where we have taken $\lambda_N \sim 1$, $M_N \sim 10^{14}$ GeV and $m \sim v \sim 100$ GeV.

Conclusions

- The generalized concept of matter parity may explain the origin of DM
- The scenario assumes matter to be in multiplets of SO(10) and the breaking pattern $SO(10) \to SU(5) \times U(1)_X$
- We motivated the scenario with predictions of less-dimensional space-time but the concept itself is general
- The only possible $SU(2)_L \times U(1)_Y$ candidates of DM are complex singlet S and inert doublet H_2 of **16** of SO(10)
- The dark sector does not exist and DM is part of our world like the SM fermions
- The SM Higgs boson is the portal to new physics