# Matter Parity and Scalar Dark Matter Direct Discovery at LHC

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# Cold Dark Matter does exist!

- $\Omega_{DM}/\Omega_b \approx 5$, DM should be non-relativistic
- The existence of DM is a clear signal of new physics beyond the SM

## We do not know what DM consists of, what is its mass and interactions

- Neutralino, gravitino, axion, axino, KK state, scalar singlet?
- Masses vary tens of orders of magnitude!

## We do not know why it is stable

- R-parity, T-parity, any other $Z_n$ discrete symmetry?
- Why to impose any parity at all?

## We do not know how the DM abundance is generated

- Thermal relic?
- DM due to asymmetry similarly to baryonic matter?

# Popular example – scalar Dark Matter

- Motivated by the Higgs portal paradigm – the Higgs boson is the only SM particle that couples to hidden sector
- An interesting proposal by itself, very topical and can be tested at the LHC

## Scalar Singlet DM Model

- Why scalar?
- Why singlet?
- Why to impose a discrete $Z_2$ by hand?

## Inert Doublet Model

Originally proposed to

- generate small neutrino masses via alternative seesaw
- allow large Higgs boson mass
- Why ...?

What is the origin of scalar DM?

# The aim and central claims of this talk

## Non-SUSY DM exists due to discrete gauge symmetries $Z_n$

- The UV completion of scalar DM models is non-SUSY $SO(10)$ GUT and the discrete gauge symmetry is the MATTER PARITY $P_M$
- Neutrino masses, leptogenesis and Dark Matter all come from the same source – $SO(10)$ breaking

## All matter, including DM, is odd under matter parity $P_M$

- $P_M$-odd scalar's spectrum consists of full scalar **16** of $SO(10)$ but no fermions
- All familiar squarks and sleptons are present – opposite to the split SUSY particle spectrum but without SUSY
- Scalar singlet DM – sneutrino, Inert doublet – slepton doublet

## Distinctive LHC phenomenology

- Radiative EWSB due to DM couplings to the Higgs boson
- Coloured scalars are long lived, decay due to GUT d=5 operators – R-hadrons at LHC
- Next-to-lightest DM particle decays suppressed by $SO(10)$ boundary conditions – displaced vertices at LHC

# The origin of Dark Matter

## The origin of discrete gauge symmetry – $SO(10)$ GUT symmetry breaking

- To generate discrete gauge symmetry one needs a higher rank group than $SU(5)$ (remember also $m_\nu$)
- $SO(10)$ contains two U(1) subgroups $U(1)_Y \times U(1)_X \in SO(10)$
- If $U(1)_X$ is broken by an order parameter carrying 2 charges of $X$, the center $Z_2$ of $U(1)_X$ is unbroken,

$$U(1)_X \to Z_2$$

- This discrete gauge symmetry is nothing but MATTER PARITY

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

- In SUSY models the matter parity is equivalent to the R-parity

## Classification of matter field representations

- Under $SO(10) \to SU(5) \times U(1)_X$
  - $\mathbf{10} = \mathbf{5}^{10}(2) + \bar{\mathbf{5}}^{10}(-2)$ is EVEN under $P_X$
  - $\mathbf{16} = \mathbf{1}^{16}(-5) + \bar{\mathbf{5}}^{16}(3) + \mathbf{10}^{16}(-1)$ is ODD under $P_X$
  - **45**, **54**, **120**, **126** and **210** are all EVEN under $P_X$
- Only **16** is odd. Is this an accident?

# The definition of matter

- The full SM gauge symmetry is

$$SO(10) \to SU(3) \times SU(2)_L \times U(1)_Y \times P_M$$

- WHAT WE CALL MATTER IS ODD UNDER MATTER PARITY
  - Baryonic matter – SM fermions + $N_R$ in a full fermion **16** of $SO(10)$
  - Dark Matter – scalar **16** of $SO(10)$

$$\mathbf{16} = \tilde{Q} + \tilde{u}^c + \tilde{d}^c + \tilde{L} + \tilde{e}^c + \tilde{N}^c$$

- DM spectrum is opposite to split SUSY spectrum, the scalars are light while the fermions decouple. If observed: no SUSY!
- DM candidates: singlet sneutrino $S = \mathbf{1}^{16} \equiv \tilde{N}^c$ and slepton doublet $H_2 \in \bar{\mathbf{5}}^{16} \equiv \tilde{L}$
- DM is not "dark" or "hidden", it is just the scalar component of matter

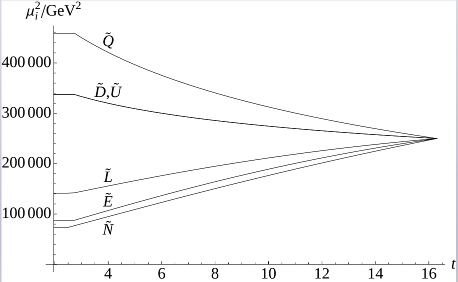
THIS IS THE UV COMPLETION OF SCALAR DM MODELS

# Constrained Scalar DM Model (CSDMM)

## The minimal $M_G$ model for one scalar 16

$$
\begin{aligned}
V \;=\;& \mu_1^2\, \mathbf{10}\,\mathbf{10} + \lambda_1 (\mathbf{10}\,\mathbf{10})^2 + \mu_2^2\, \overline{\mathbf{16}}\,\mathbf{16} + \lambda_2 (\overline{\mathbf{16}}\,\mathbf{16})^2 \\
+\;& \lambda_3 (\mathbf{10}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{16}) + \lambda_4 (\mathbf{16}\,\mathbf{10})(\overline{\mathbf{16}}\,\mathbf{10}) \\
+\;& \lambda'_S \left[\mathbf{16}^4 + \text{h.c.}\right] + \frac{\mu'_{SH}}{2} \left[\mathbf{16}\,\mathbf{10}\,\mathbf{16} + \text{h.c.}\right],
\end{aligned}
$$

CONSTRAINED: SMALL NUMBER OF PARAMETERS AT $M_G$




## Below $M_G$ many more parameters allowed

$$
\begin{aligned}
V =\;& \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\
&+ \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}\left[S^2 + (S^\dagger)^2\right] + \lambda_S (S^\dagger S)^2 + \frac{\lambda'_S}{2}\left[S^4 + (S^\dagger)^4\right] \\
&+ \frac{\lambda''_S}{2}(S^\dagger S)\left[S^2 + (S^\dagger)^2\right] + \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) \\
&+ \frac{\lambda'_{S1}}{2}(H_1^\dagger H_1)\left[S^2 + (S^\dagger)^2\right] + \frac{\lambda'_{S2}}{2}(H_2^\dagger H_2)\left[S^2 + (S^\dagger)^2\right] \\
&+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H
\end{aligned}
$$

## $M_G$ scale boundary conditions

$$
\begin{gathered}
\mu_1^2(M_G) > 0,\; \mu_2^2(M_G) = \mu_S^2(M_G) > 0, \\
\lambda_2(M_G) = \lambda_S(M_G) = \lambda_{S2}(M_G),\; \lambda_3(M_G) = \lambda_{S1}(M_G), \\
\mu_S'^2,\; \mu_{SH}^2 \lesssim \mathcal{O}\left(\frac{M_G}{M_P}\right)^n \mu_{1,2}^2, \\
\lambda_5,\; \lambda'_{S1},\; \lambda'_{S2},\; \lambda''_S \lesssim \mathcal{O}\left(\frac{M_G}{M_P}\right)^n \lambda_{1,2,3,4}.
\end{gathered}
$$

PREDICTS MASS DEGENERACY BETWEEN DM AND NL SCALAR

DM IS PREDOMINANTLY SINGLET

May have importance for LHC phenomenology, DAMA

# Direct detection of scalar DM

- DM IS PREDICTED TO BE PREDOMINANTLY SINGLET BY RG RUNNING OF SCALAR MASS PARAMETERS
- DM direct detection cross-section per nucleon is mediated by the SM Higgs boson exchange
- The spin-independent direct detection cross section is approximately

$$\sigma_{\rm SI} \approx \frac{1}{\pi} f_N^2 \left( \frac{\lambda_{\rm eff} v}{v M_{\rm DM}} \right)^2 \left( \frac{M_N}{M_h} \right)^4 ,$$

where the effective coupling is

$$\lambda_{\rm eff}\, v = \frac{1}{2} ( \sqrt{2} s\, c\, \mu'_{SH} - 2 s^2 (\lambda_3 - \lambda_4) v + 2 c^2 \lambda_{S1} v ),$$

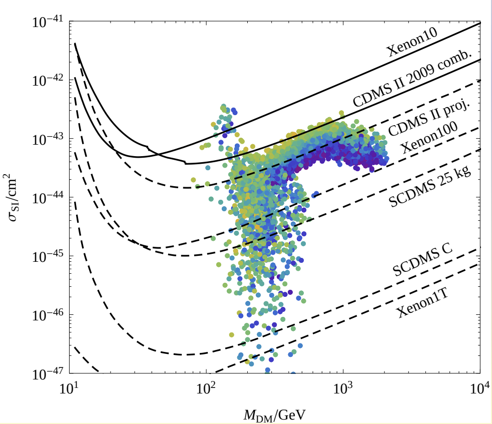
where $s$ is the sine of (small) singlet-doublet mixing angle

- Experiments (CDMS, XENON, DAMA etc.) search for DM recoils on nuclei

# Spin-independent direct detection cross section

## We require

- The observed DM thermal relic abundance $\Omega_{DM}$ (calculated with MicroMEGAS)
- Successful dynamical EWSB due to RGE effects (DM couplings run the SM Higgs boson mass parameter negative)



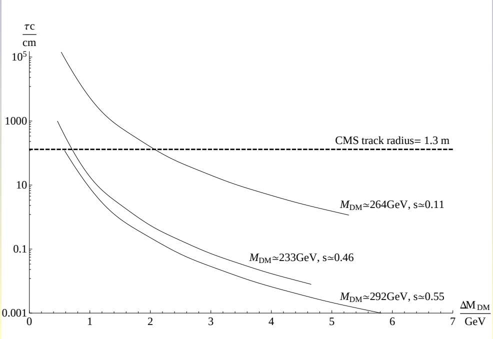
# Model predicts long lifetime of NLP

## Displaced vertices at LHC

- The experimental signature of $\ell\ell$ or $jj$ plus missing $E_T$ signal the decays

$$S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-,\ S_{\rm DM}q\bar{q}$$

- This decay rate is predicted to be suppressed by two factors
  - Small DM and NL mass difference due to the GUT boundary conditions
  - By the singlet-doublet mixing angle
- DISPLACED VERTEX IN THE DECAYS OF NEXT-TO-LIGHTEST SCALAR (NL) IS THE SIGNATURE OF THIS MODEL



# DM and NL pair production cross-sections at LHC

## LHC discovery potential

- The pair production cross sections are large, thousands of events a year expected
- Displaced vertex of a lepton pair $\ell\ell$ plus missing $E_T$ is a SM background-free signal

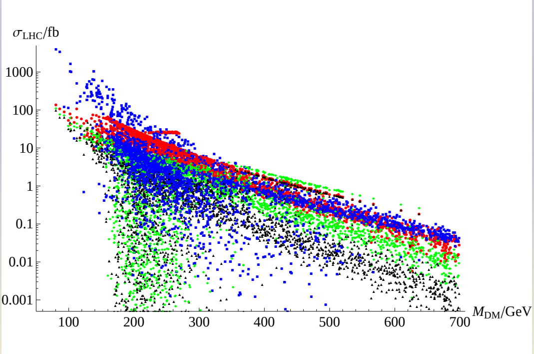



**Figure:** Direct production cross-section of $pp \to H^+H^-$ (red), $pp \to S_{\rm DM,NL}S_{\rm DM,NL}$ (blue), $pp \to S_{\rm DM,NL}H^\pm$ (green) and $pp \to S_{\rm DM}S_{\rm NL}$ (black) at the LHC for $\sqrt{s} = 14\ TeV$.

# R-hadrons at LHC – the low luminosity discovery ?

## Matter-parity-odd scalar DM – opposite to the split SUSY spectrum

- CSDMM predicts new coloured scalars $\tilde{Q}, \tilde{u}^c, \tilde{d}^c$ with mass spectrum

$$M_{\tilde{Q}} > M_{\tilde{L}} > M_{DM}$$

due to strong interaction in RGE effects of the mass parameters

## At the scalar potential level the lightest coloured scalar is stable

- It decays due to GUT scale heavy scalar exchange via d=5 operators

$$d = 5 \qquad \frac{\lambda}{M_P}\tilde{Q}\tilde{L}QL, \qquad \tau \sim 10^{2-3} s$$

- May solve the lithium problem of nuchleosynthesis

## Ideal discovery channel for the low energy/luminosity LHC

- $\sqrt{s} = 7$ TeV LHC with 1 $\mathrm{fb}^{-1}$ can produce many $\sim$ 500 GeV couloured particles (squarks, gluinos)
- The long-lived lightest coloured scalars form colour-neutral R-HADRONS
- Unique signal at LHC! May be trapped in detector, decays after 100 s
- Coloured scalar of CSDMM vs gluino? Different distributions in $pp \to \tilde{u}\tilde{u}, \tilde{g}\tilde{g}$

# Conclusions

- UV completion of scalar DM models is non-SUSY $SO(10)$ GUT with scalar representation **16**
- Generally: matter, baryonic or "dark", is odd under MATTER PARITY
- In this scenario $\Omega_{DM}$, $\Omega_b$ and $m_\nu > 0$ all come from the same source
- CSDMM predicts new coloured, charged and neutral scalars with squark and slepton quantum numbers, $\mathbf{16} = \tilde{Q} + \tilde{u}^c + \tilde{d}^c + \tilde{L} + \tilde{e}^c + \tilde{N}^c$,
- The mass hierarchy $M_{\tilde{Q}} > M_{\tilde{L}} > M_{DM}$ and the predominantly singlet DM is predicted in most of the parameter space by RGE arguments
- Regarding scalars vs. fermions – scalar DM model has an opposite mass spectrum to the split SUSY
- DM direct detection of CSDMM DM is just around the corner, XENON100 will probe significant fraction of the parameter space
- Displaced vertices of $\ell\ell$ plus missing $E_T$ in $S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-,\ S_{\rm DM}q\bar{q}$
- The lightest coloured scalars have lifetime $\tau \sim 10^{2-3}s$ and form R-hadrons – ideal for the early discovery at the LHC