Unified TeV Scale Picture of Dark Matter and Baryogenesis

K.S. Babu

Oklahoma State Univeristy

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K.S. Babu, S. Nasri, R.N. Mohapatra, Phys. Rev. Lett. 98, 161301 (2007)

Current Thinking

- Dark matter is either the lightest SUSY particle, or the axion, or the lightest Kaluza-Klein mode of large extra dimensional models
- Matter-antimatter asymmetry has a different source -- from right handed neutrino decay in seesaw models for neutrinos utilizing sphalerons
- Unrelated physics

Dark matter issues in MSSM

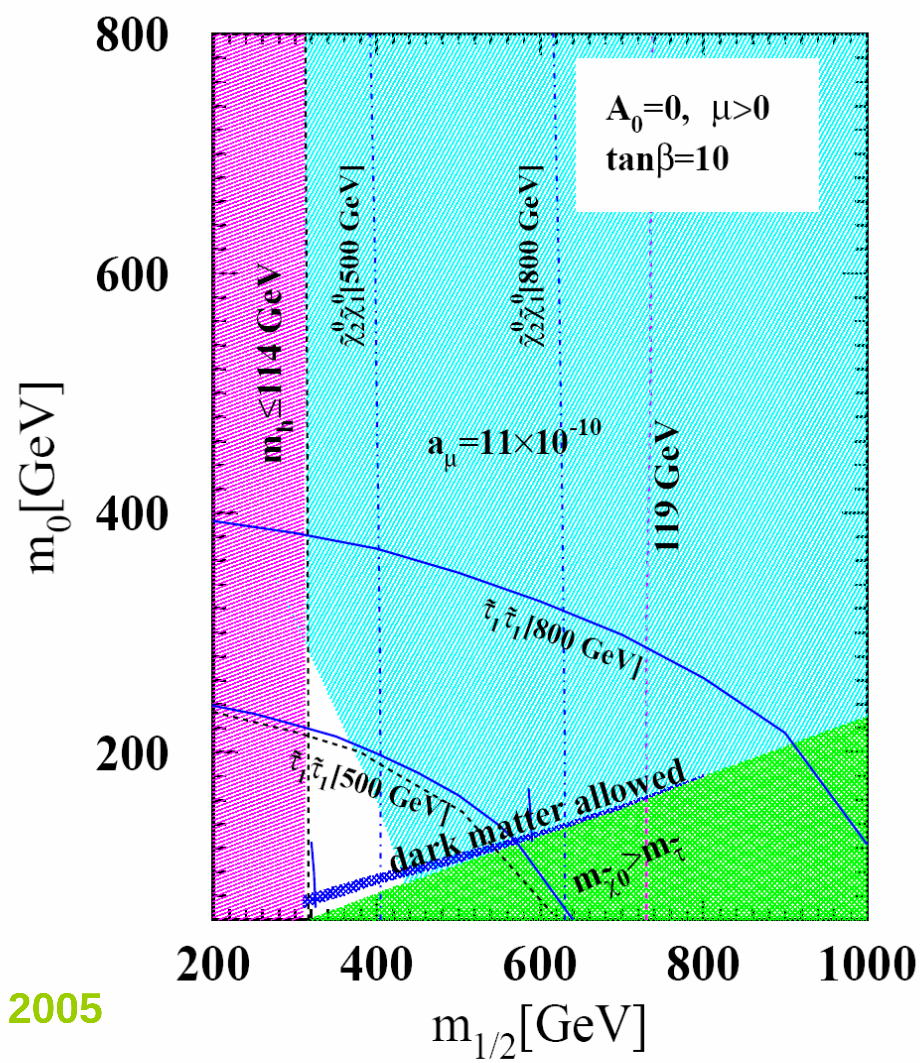
- **Getting dark matter to fit into MSSM requires some fine tuning:**

  (i) Either Bino-Higgsino mixing must be fine-tuned to get the right relic density

  or

  (ii) Co-annihilation needed where stau and neutralino LSP are nearly degenerate (within ~ 20 GeV): requires adjustment of m_0^2

Dark Matter Constraints on MSSM



Arnowitt, Dutta, 2005

Yet SUSY has its own appeal

- It stabilizes the weak scale against radiative corrections
- It leads to unification of gauge couplings
- Is there an extension of MSSM that preserves these good features, broadens the parameter space of MSSM and gives a unified picture of dark matter, origin of matter and neutrino masses?

Neutrino mass extension of MSSM

- Add three right handed neutrinos with heavy Majorana masses
- New superpotential:

$$W_\nu = W_{MSSM} + h_\nu L H_u N + \frac{1}{2} M_R N N$$

- Leads to seesaw formula for neutrino masses:

$$M_\nu = -\frac{m_D^2}{M_R}$$

- N decay via leptogenesis leads to baryon asymmetry

Two points about this model:

- Neutrino observations do not require three RH neutrinos -- two are enough. (the so-called 3 x 2 seesaw)

- SUSY seesaw models for leptogenesis have some problems!

Issues with leptogenesis models

- In typical scenarios, often the lightest RH neutrino masses are higher than the reheat temperature after inflation coming from gravitino abundance- posing a problem.

Davidson, Ibarra have a lower bound on $M_R \geq 10^9$ GeV; also true in many interesting SO(10) models

The upper bound on T-reheat for generic TeV scale gravitinos is $T_R \leq 10^7$ GeV (Kohri, Mori,Yotsuyanagi)

New Model

- Could it be that only two of the RH neutrinos are heavy and the third one is very light (i.e. TeV scale)
- We show that
- (i) such a model can naturally arise from a simple symmetry
- (ii) In this case, one can have a unified TeV scale model for baryogenesis, neutrino masses and dark matter

New proposal: νXMSSM

- **3 x 2 seesaw model with the third RH neutrino in the TeV scale and decoupled from the neutrino sector**
- **Plus a pair of color triplets: $X, \overline{X}$ with couplings:**

$$W_{new} = \lambda_i N u_i^c X + \lambda'_{ij} d_i^c d_j^c \overline{X} + \frac{M_N}{2} N N + M_X X \overline{X}$$

Impose R-parity symmetry as in MSSM.

This simple extension provides a remarkably natural model for dark matter, neutrinos and baryogenesis and has testable predictions !!

Grand unification of this model

- If $X, \overline{X}$ belong to full SU(5) multiplets 10 and 10-bar, coupling unification unaffected
- Only the unified value of the GUT coupling changes

  - Couplings motivated by SO(10) GUT:

  part of 120 Higgs and 16 .16. 120 coupling leads to our interactions

  - Discrete symmetry guarantees the third RH N decoupling naturally (see later)

Baryogenesis and Dark Matter

- **Mass ordering among particles**:

$$M_{X,\overline{X}} \sim \text{TeV}, \quad M_{\text{squarks, sleptons}} > M_{N,\tilde{N}} \sim 100 \text{ GeV}$$

mSUGRA boundary conditions imply that

$$M_{\tilde{N}_1} \leq M_N, \; M_{\tilde{N}_2}$$

Where $\tilde{N}_{1,2}$ are the real and imaginary parts of $\tilde{N}$

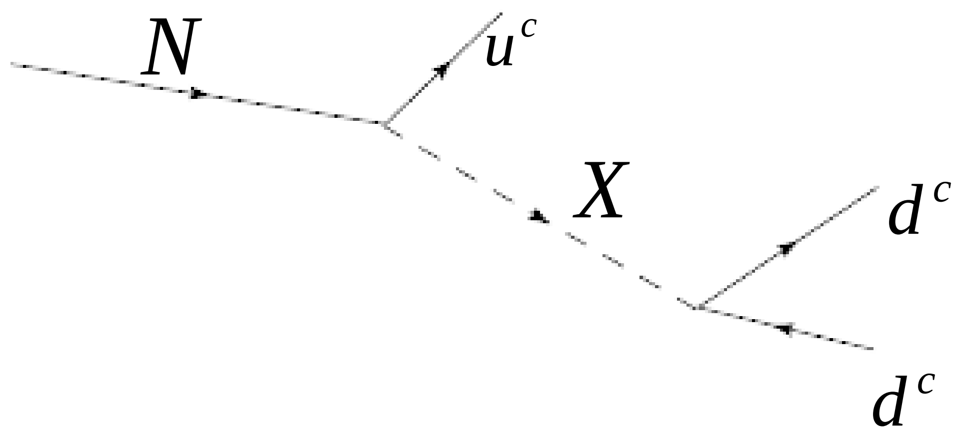
$\tilde{N}_1$ is stable and is the dark matter candidate. N unstable and gives

$$\frac{n_B}{n_\gamma}$$

Decay mode of N-fermion

- X-exchange gives a decay

$$N \to u^c d^c d^c$$ + anti-quark mode



$$G_{Njkl} = \frac{\lambda_j \lambda'_{kl}}{M_X^2}$$

Post Sphaleron Baryogenesis

- **Babu, Mohapatra, Nasri, Phys Rev. Lett. 97, 131301 (2006)**

- **Out of equilibrium condition (one of three Sakharov conditions) satisfied at:**

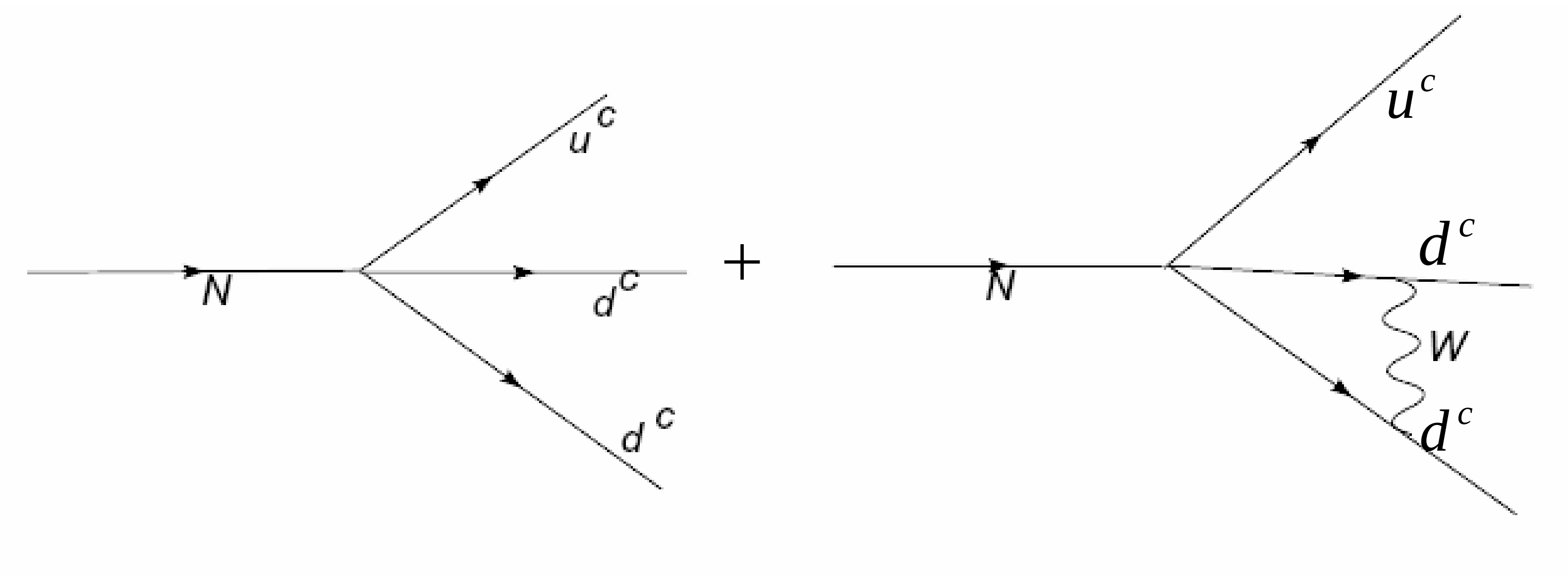
$$\Gamma_{N\to u^c d^c d^c} \leq \sqrt{g*}\frac{T^2}{M_{\rm Pl}}$$

$$\Gamma_N = \frac{C}{128}\frac{(\lambda^\dagger\lambda)\mathrm{Tr}[\lambda'^\dagger\lambda')]}{192\pi^3}\sin^2 2\theta M_N^5\left(\frac{1}{M_{X_1}^2}-\frac{1}{M_{X_2}^2}\right)^2$$

For $[\lambda^\dagger\lambda \mathrm{Tr}(\lambda'^\dagger\lambda')]^{1/2} \simeq 10^{-4}$ **, N goes out of equilibrium below its mass and is ready to generate baryons via its CP and baryon violating decay**

Baryogenesis Diagrams

- **N decay to 3 quarks and anti-quarks are different due to CKM CP violation and interference between tree and one loop diagrams: (no sphalerons needed)**



Estimate of ε_B

Dominant contribution is from W-exchange and is:

$$\varepsilon_B \cong -\frac{\alpha_2}{4}\frac{m_c m_b \lambda'_{23}\lambda'_{21}V_{ub}\sin\delta}{M_W{}^2\,|\,\lambda'_{22}{}^2\,|}$$

Gives: $$\varepsilon_B \cong 3\times 10^{-8}\frac{\lambda'_{21}\lambda'_{23}}{|\,\lambda'_{22}\,|^2}$$

Right order.

$\tilde{N}_1$ As Scalar dark matter

Relic density:

Annihilation channel

$$\tilde{N}_1 \tilde{N}_1 \rightarrow u^c \bar{u}^c$$

Cross section:

$$\sigma v \approx \frac{1}{8\pi} (\lambda^+ \lambda)^2 \frac{|\vec{p}|^2}{{M_X}^4}$$

For reasonable choice of parameters, cross section is of order of a 0.1 - 1 pb and gives the right relic density.

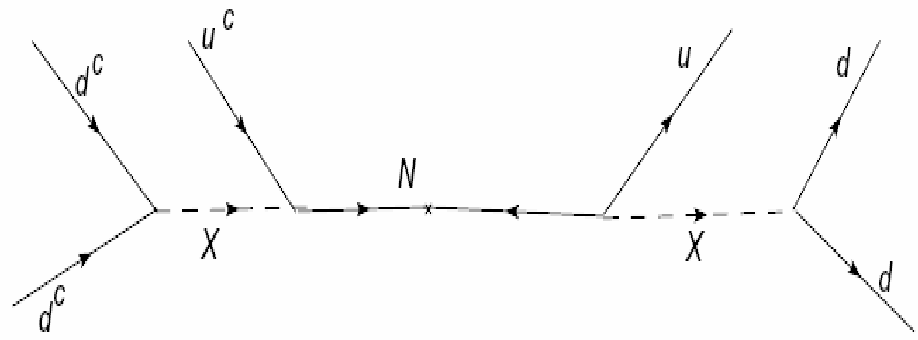
Direct detection of dark matter

$$\sigma_{\tilde{N}_1+p} \simeq \frac{|\lambda_1|^4 m_p^2}{64\pi M_X^4}\left(\frac{A+Z}{A}\right)^2$$

Cross section about 10^(- 45) cm^2-
In the observable range.

A crucial experimental test

- N-N-bar oscillation: Diagram involves Majorana N exchange



- Effective strength:

$$G_{\Delta B=2} \cong \frac{\lambda_1 \lambda'_{12}}{M^4{}_X M_N}$$

$$O = u^c d^c s^c u^c d^c s^c$$

- Will lead to N-N-bar osc via the s-content in neutron.
- Transition time expected to be around 10^8 sec.

Present expt situation in N-N-bar Osc.

Range accessible to current reactor fluxes:

$$\tau_{n-\bar{n}} \sim 10^{8} - 10^{11}\,\text{sec.}$$

Present limit:ILL experiment: **Baldoceolin et al. (1994)**

$$\tau_{n-\bar{n}} \geq 10^{8}\,\text{sec.}$$

New proposal by Y. Kamyshkov et al for an expt at

$$10^{10} - 10^{11}\,\text{sec}\,.$$

Tests at LHC--New signatures

(i) Monojet + missing energy signals from X-production in pp collision.

$$\overline{q} + \overline{q} \rightarrow X \rightarrow \overline{q} + N$$

(Missing energy is N)

(ii) 4 jets + missing energy from:

$$q + \overline{q} \rightarrow \tilde{q}^c + \tilde{\overline{q}}^c$$

$$\tilde{q}^c \rightarrow q^c q^c \tilde{N} \qquad \tilde{\overline{q}}^c \rightarrow q^c q^c \tilde{N}$$

Symmetry giving this model

Consider Seesaw model for neutrinos invariant under a $Z^R{}_{2,\mu-\tau}$ that exchanges only $N_\mu - N_\tau$

RH neutrino field $N_- = \frac{1}{\sqrt{2}}(N_\mu - N_\tau)$ decouples from seesaw formula which now becomes a 3 x 2 seesaw involving N_e and $N_+ = \frac{1}{\sqrt{2}}(N_\mu + N_\tau)$.

Our singlet field then is N= $N_- = \frac{1}{\sqrt{2}}(N_\mu - N_\tau)$

N mass can be chosen in the 100 GeV range without affecting neutrino masses or other low energy observations !!

Tests in neutrino mixings

- **3 x 2 seesaw with 2 RH neutrinos:**
- **For normal hierarchy, it necessarily predicts nonzero θ_{13} and of order $\sqrt{\frac{\Delta m^2{}_{atm}}{\Delta m^2{}_{solar}}}$; hence testable.**

- Inverted hierarchy if θ_{13} is close to zero.

Conclusion

- A simple extension of MSSM that gives a unified TeV picture of dark matter and baryogenesis. Less fine tuned than MSSM. Embeddable into a seesaw model for neutrinos.
- Opens up MSSM parameter space.
- SUSY phenomenology (e.g. LHC signal) very different from MSSM.
- Crucial test is Neutron-anti-neutron osc time in the observable range.