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# Left-Right Seesaw and SUSY New Roadmap beyond MSSM

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# Left-right Seesaw and SUSY

## New roadmap beyond MSSM


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Origin of P,CP and T Violation Workshop

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# Plan of the talk:

1. **SM and MSSM:** Hopes and problems

2. **SUSY Left-right model:** how it resolves many problems of SM and MSSM:

3. **SUSYLR:** Two incarnations:

# Problems of the standard model

- **Origin of parity breaking**
- **Gauge hierarchy -**
- **Neutrino mass-**
- **Dark matter-**
- **Strong CP problem**

- **Goal of talk:** Show how Left-Right models, originally proposed to explain parity violation, in combination with susy solves these problems and also helps in understanding SUSY breaking.

# Hopes: Gauge Hierarchy and Supersymmetry

- To every SM particle - a superpartner:
- Minimal Model
  -MSSM

$$W \leftrightarrow \widetilde{W} \qquad Q \leftrightarrow \widetilde{Q}$$

$$Z \leftrightarrow \widetilde{Z} \qquad u^c \leftrightarrow \widetilde{u}^c$$

$$\gamma \leftrightarrow \widetilde{\gamma} \qquad d^c \leftrightarrow \widetilde{d}^c$$

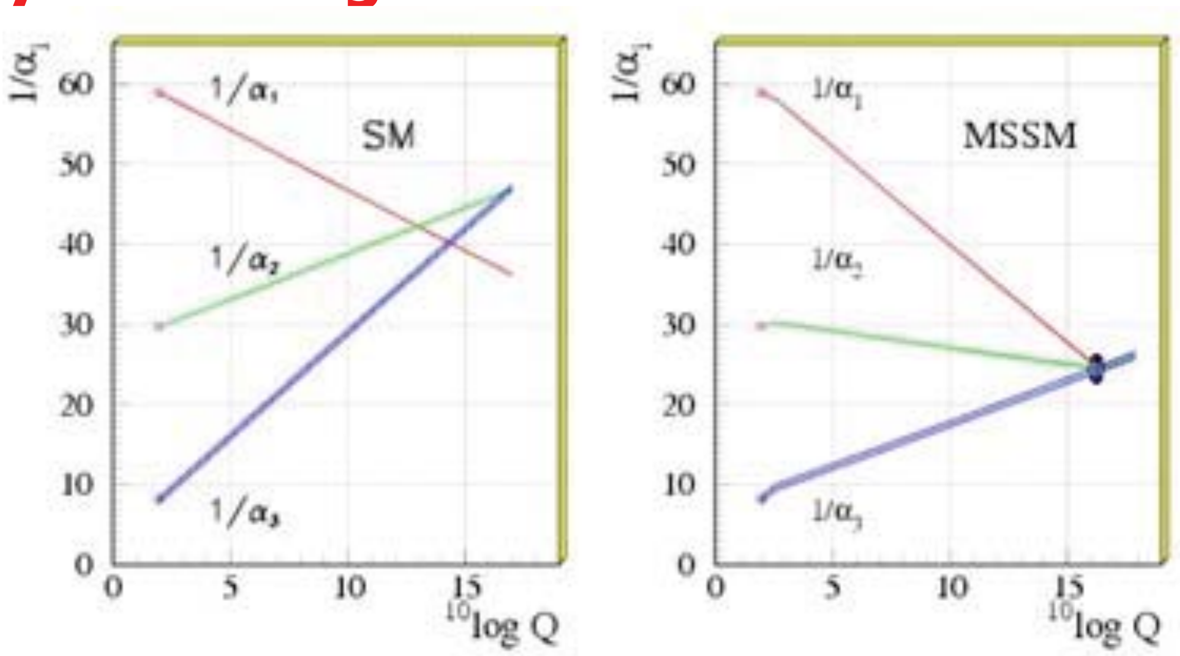
$$l \leftrightarrow \widetilde{l}$$

$$H \leftrightarrow \widetilde{H} \qquad e^c \leftrightarrow \widetilde{e}^c$$

- Cancels selfmass divergence of Higgs and solves the gauge hierarchy problem:
- Lightest sparticle stable if R-parity exact and becomes dark matter.

# Coupling Unification and GUTs

- **MSSM does not predict coupling unification; Need to assume no new physics till high scale:**




- **Proton decay key test !**

- **For colliders, gaugino unif. important test:**

$$M_1 : M_2 : M_3 = 1 : 2 : 7$$

# Problems: MSSM needs fixing-I

- SM has stable proton- but MSSM takes a step backward !! protons decay in an instant in MSSM.
- Culprit: R-parity breaking terms

$$W' = LLe^c + QLd^c + u^c d^c d^c$$

- Also no stable dark matter-one of the much touted virtues of susy !!

# How to naturally get an R-P conserving MSSM ?

- **Recall** $$R = (-1)^{3(B-L)+2S}$$
- **A natural way to have automatic RP conservaing MSSM is to have a higher scale theory with built in local B-L symmetry and break B-L by 2 units.**
- (RNM,86; Font,Ibanez,Quevedo,89; Martin,92)
- **( R-parity is often assumed as an adhoc symmetry just to guarantee dark matter and stop proton decay- but we may be missing some important clues to new physics that way !!)**

# MSSM needs fixing-Part II

- **MSSM has other problems too !**
- **Too many parameters (~105 or so);**
- **Large flavor changing neutral current effects-**
- **Too large edm problem (SUSY CP problem), no solution to strong CP problem:**

# SUSY breaking- hope for some type II problems:

- SUSY breaking mechanism may cure the FCNC and too many parameter problem:

☎ **Gauge Mediated SUSY Breaking:**

gravitino LSP KeV- not a good dark matter !

**(ii) Anomaly Med. SUSY Breaking:**

requires new physics beyond MSSM otherwise breaks electric charge !

**Going beyond MSSM may solve others !**

# New beyond MSSM roadmap inspired by nu- mass

- **MSSM $\subset$ SUSY LEFT RIGHT**
- **Gauge group:**

$$SU(2)_L \times U(1)_Y \subset SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

- **Solves many problems of MSSM in addition to explaining small neutrinos masses:**
- **(i) No SUSY CP and strong CP problems;**
  **(ii) Automatic R-parity- stable DM;**
  **(iii) Solves the negative slepton mass square problem of AMSB.**

# Neutrino mass and $\nu$ -MSSM

- **Starting point: add RH neutrino to SM for nu mass:**

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = ( u_1^c \quad u_2^c \quad u_3^c ) \sim (\bar{3}, 1, \frac{-2}{3})$$

$$d^c = ( d_1^c \quad d_2^c \quad d_3^c ) \sim (\bar{3}, 1, \frac{1}{3})$$

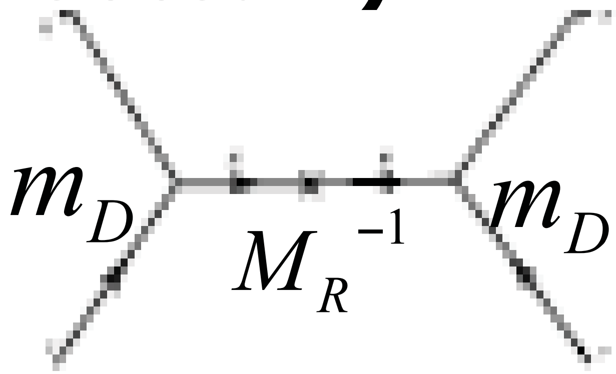
$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

# Seesaw and Small neutrino mass

- **Give large Majorana mass to the RH neutrinos: (Type I seesaw)**




$$m_\nu \cong -m_D^T M_R^{-1} m_D << m_{u,d,e}$$

Note just like R-parity, Seesaw also requires B-L=2

Minkowski,Gell-Mann,Ramond, Slansky; Yanagida; RNM,Senjanovic; Glashow

# LR Model-A natural framework for seesaw

- **Gauge group**: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

- **Fermion assignment**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- **Higgs fields** $\phi(2,2,0); \Delta_R(1,3,+2) \oplus \Delta_L(3,1,+2)$

$\uparrow$

- **Nu-R and new scale automatic !**

**(RNM, Senjanovic,79)**

# Detailed Higgs content and Sym Breaking

$$\phi = \begin{pmatrix} \phi_1^{\ 0} & \phi_2^{\ +} \\ \phi_1^{\ -} & \phi_2^{\ 0} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$$

$$\phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \qquad <\Delta>= \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

**Break symmetry- and in particular B-L by 2 units as required to guarantee R-parity**

# Quark and lepton masses:

- **SM:** $$L_Y = h_u \overline{Q} H u_R + h_d \overline{Q} \widetilde{H} d_R + h_e \overline{L} \widetilde{H} e_R$$
- **13 parameters;**
- **LR:** $$L_Y = h_{u,d} \overline{Q}_L \phi_{u,d} Q_R + h_{e,\nu} \overline{L} \phi_{d,u} R + f L L \Delta_L + L \leftrightarrow R$$
- **For u,d,e sector same 13 parameters except now Yukawa coupling matrices are hermitean due to LR symmetry.**

# Symmetry breaking and seesaw for neutrinos

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\begin{pmatrix} 0 & 0 \\ 0 & fv_R \end{pmatrix} \qquad \downarrow \quad <\Delta_R>\neq 0$$

$$SU(2)_L \otimes U(1)_Y$$

$$\begin{pmatrix} fv_L & h\kappa \\ h\kappa & fv_R \end{pmatrix} \qquad \downarrow \quad <\phi>=\begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

$$U(1)_{em} \qquad M_{W_L}, M_Z \neq 0; m_{q,l} \neq 0$$

**I+II seesaw :** $$m_\nu \cong fv_L - M^T{}_D M_R^{-1} M_D$$

# Summary of bounds on LR Scale: Non-SUSY case

- **Collider limits on $W_R$ and Z′:** around 780 GeV- 800 GeV.
- **Low energy limits:** K-K-bar, CPV, edm etc:  WR mass > 2.5 TeV.(See talk by X. Ji.)
- **Limits from Neutrinoless double beta decay+ vacuum stability:**

  WR mass > 1.5 TeV.

# What is the Seesaw (LR) scale ? GUT vs sub-GUT

- **Type I term** $\sim Y_\nu^2$ **; so** $Y_\nu \sim Y_e$ **can allow WR anywhere from TeVs up for right nu masses.**
- **Type II term** $v_L \cong \frac{v_{wk}^2}{v_R}$ **; sub-eV neutrino mass would then imply** $v_R \geq 10^{14}\,GeV$ or the standard GUT scenario e.g. SO(10) with 126 Higgs . **(Talks by Aulakh and Parida)**
- **Two questions arise:**

  **(i) Why contemplate lower scale seesaw ?**

  **-unlike GUT seesaw, TeV and other sub-GUT scale seesaw testable in colliders;**

  **(ii) Doesn't the type II term need extreme fine tuning ? -With SUSYLR, they do not.**

# SUSY ESSENTIAL FOR LOW SCALE LR SEESAW

- $v_L \cong \frac{v_{wk}^2}{v_R}$ naturally arises in Non-susy left-right model due to the term $Tr(\phi^+ \Delta_L^+ \phi \Delta_R)$
- SUSY LR does not allow such terms and hence implies $v_L = 0$ and thus no restriction on the seesaw scale.
- We will contemplate seesaw (left-right) scales anywhere from TeV up.

# SUSYLR and Strong CP:

- **Under Parity:** $\phi_i \rightarrow \phi^{+}_i$

- **This implies that the Yukawa coupling matrices defined by:**

$$L_Y = h^{i}_{ab} \overline{Q}_{La} \phi_i Q_{Rb} + h.c.$$

**h are hermitean to be parity invariant.**

- **This implies that the quark mass matrices are hermitean provided the vacuum expectation values are real.**
- **This has several consequences:**

# Consequences of Hermitean M

- Left and Right CKM angles are equal. (less parameters in weak currents)
- Solves Strong CP problem – no axion

$$\theta = \theta_g + \theta_Q$$

- $\theta_g = 0$ by parity symmetry
- $\theta_Q \equiv Arg.Det.M_u M_d = 0$ by hermiticity (Babu's Talk)

( **Non-SUSY LR:** Beg, Tsao; Senjanovic, RNM,78; Babu,RNM, 90;

**Susy:** RNM, Rasin; Kuchimanchi (1995); Babu, Dutta, RNM (2000))

# Again SUSY essential for strong CP

- **Mass matrices:** $M = h < \phi >$
- **h hermitean due to parity but M is hermitean only if <*phi*> is real.**
- **In non-susy <*phi*> is not real due to the presence of arbitrary phases in pot.**

$$V' = \lambda e^{i\alpha} Tr(\phi^+ \tilde{\phi}) \Delta_L{}^+ \Delta_L + (\phi \leftrightarrow \phi^+, L \leftrightarrow R)$$

- **Again SUSY does not allow such terms-parity makes all couplings in super-pot real and all vevs real real.**

# SUSYLR: Two incarnations

- **(i) Purely renormalizable**

$$W = W(\phi_{1,2}) + W(\Delta, \Delta^c, \overline{\Delta}, \overline{\Delta}^c)$$

***phi and Delta sectors decoupled:***

- **(ii) Add non-renormalizable terms:**

$$W = W(\phi_{1,2}) + W(\Delta, \Delta^c, \overline{\Delta}, \overline{\Delta}^c) + \frac{\overline{\Delta}^c \Delta^c}{M_X}(\overline{\Delta}^c \Delta^c, \phi^2, \Delta\overline{\Delta})$$

- **NR terms connect the two sectors:**

# Renormalizable version (i)

- In order parity to break, **R-parity must break;** otherwise electric charge is not conserved i,.e. vevs must be

$$\langle \widetilde{L}_i^c \rangle = \begin{pmatrix} \langle \widetilde{\nu_i^c} \rangle \\ 0 \end{pmatrix}, \ \langle \Delta^c \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \ \langle \bar{\Delta}^c \rangle = \begin{pmatrix} 0 & \bar{v}_R \\ 0 & 0 \end{pmatrix}$$

- There is an upper limit on the WR scale in the TeV range.

(kuchimanchi, RNM, 93,95)

**Have we lost the dark matter ?**

# Unstable gravitino dark matter and SUSY LR

- Getting neutrino masses from TeV scale seesaw implies that R-P breaking couplings are of the form:

$$\lambda, \lambda' \leq 10^{-6}; \lambda'' = 0$$

- If gravitino is the LSP with m <10 GeV, its lifetime is > $10^{27}$ sec. naturally and hence it can be a dark matter.

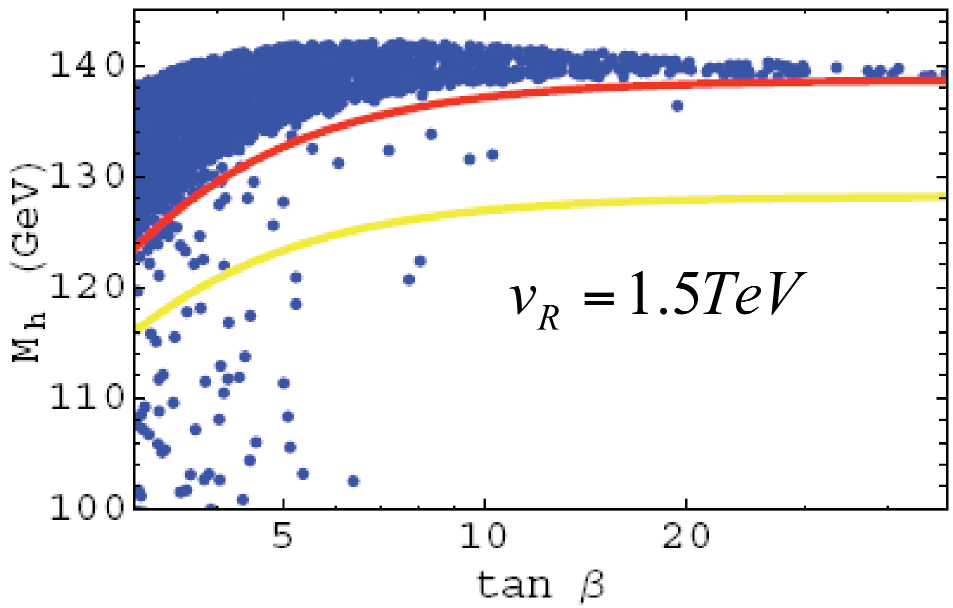
(Ji,RNM, Nussinov, Zhang, to appear)

- Idea of unstable gravitino dark matter: Ibarra et al; Takayama, Yamaguchi;…)
- It also leads to displaced vertices at LHC from NLSP decays.

# New upper bound on light Higgs mass:

- **MSSM:** $M_h \leq 135 GeV$
- **SUSYLR with TeV scale WR**

$$\frac{\delta m^2}{m_h^2} \sim \frac{m^2}{v_R^2}$$




(Zhang,Ji,An,RNM,2008)

# Nonrenormalizable version:

- **Key operators: allow all possible terms:**
- $$W_{nr} = +\frac{\bar{\Delta}^c \Delta^c}{M_X}(\bar{\Delta}^c \Delta^c, \phi^2, \Delta\bar{\Delta})$$
- **Two questions:**

  **(i) what is $M_X$ ?**

  **(ii) how high the seesaw scale can be ?**

# Non-ren. version

- **(i) WR scale can be higher but must satisfy the condition:** $$\frac{v_R^2}{M_X} \geq 100 GeV$$
- Otherwise light doubly charged particles < 100 GeV.
- **(ii) Low energy th. conserves R-parity without breaking electric charge. Conventional Neutralino DM** (Aulakh, Melfo, Senjanovic,98)
- **(iii) Strong CP constraint .** $$\frac{v_R^2}{M_X} \leq 10^{-7}$$ GeV $\otimes$

  (See however Babu's talk)
- **(iv) Type II seesaw constraint:** $$\frac{v_{wk}^2}{M_X} \leq 10^{-9} GeV$$ **OK**

# Light $\Delta^{+,++}$ Higgs despite High seesaw scale-Role of SUSY

- Naïve logic: Higgs mass is of the order of symmetry breaking scale; Not always true !
- Most general SUSYLR superpotential:

$$W(\Delta\bar{\Delta} + \Delta^c\bar{\Delta}^c, ...)$$

- Has U(6,c) global symmetry which breaks down to U(5,c) (in the absence of higher dim term.)
- eleven massless complex Higgs bosons: 3 absorbed in gauge sym. breaking from $SU(2)_R x U(1)_{B-L}$ to $U(1)_Y$.
- **Remaining Eight are two doubly charged Higgs bosons and two SU(2) left triplets;**
- **(Aulakh,Melfo,Senjanovic; Chacko, RNM)**

# Theory with TeV scale Delta's but higher scale LR

- Consider the theory with $v_R$ and $M_X$ such that the Delta fields are at TeV scale and no type II seesaw issue.
- This modifies the low energy theory to MSSM+left triplets+right doubly charged Higgs field coupled to leptons.

$$W_{new} = W^{RP}{}_{MSSM} + fll\Delta + fe^c e^c \Delta^c$$

This also helps solving electric charge breaking problem of AMSB, which has other nice features.

# What is AMSB and why it is problematic ?

- **Superconformal anomaly to generate SUSY breaking effects:**
- Like Einstein action from Weyl Inv:

$$S=\int d^4x\sqrt{-g}\,\eta(x)R$$

Technique: Matter fields Weyl weight w=0; Superpotential must have weight w=3 ; D-terms must have w=0;conformal compensator field Φ w=1. conformal inv. Action:

$$S=\int d^4\theta\phi^+\phi Q^+Q+\int d^2\theta\phi^3Q^3$$

# Anomaly and Soft SUSY breaking terms

- **SUSY breaking** vev for compensator field from hidden sector:

$$\phi = 1 + F_\phi \theta^2$$

- **Renormalization introduces mass**

$$Z(\mu) \rightarrow Z\left(\frac{\mu}{\Lambda(\phi^+\phi)^{1/2}}\right)$$

- **Leads to soft susy breaking terms:**
- **Only one parameter describes all susy breaking terms.**
- **(Randall,Sundrum;Giudice,Luty,Murayama,Rattazzi,98)**

# SUSY Breaking in AMSB

$$m_0^{\;2} = m_{3/2}^{\;2} c\beta(g) + m_{3/2}^{\;2} c_1 \beta(Y)$$

$$YA_Y = -\beta(Y) m_{3/2}$$

$$gM_\lambda = \beta(g) m_{3/2}$$

$$c = \frac{d\gamma}{dg}, c_1 = \frac{d\gamma}{dY}$$

$$\frac{dY}{dt} = -\beta(Y, g)$$

$$\frac{dg}{dt} = -\beta(g)$$

# AMSB in MSSM

- **In MSSM, all Yukawas but $h_t$ are negligible;**
- $\beta_3(g_3) = \frac{3g_3{}^3}{16\pi^2}; \; \beta_2(g_2) = -\frac{g_2 3}{16\pi^2}; \quad \beta_1(g_1) = -\frac{33g_1{}^3}{16\pi^2}$
- **Thus all squarks have +ve mass square; but all sleptons have –ve mass square.**
- **Also $B\mu$ problem** :generic prediction: $B\mu \approx m_{3/2}\mu$

**AMSB NEEDS NEW PHYSICS !!**

# Slepton masses in SUSYLR + AMSB

**New contributions from light Delta couplings to leptons affects lepton masses in AMSB.**

$$m_{\tilde{l}}^{\ 2} = \left(\frac{m_{3/2}}{16\pi^2}\right)^2 [-g^4 - (-f)(f^3 - fg^2)]$$

$$\gamma(f,g) = \frac{1}{16\pi^2}(g^2 - f^2) \qquad \beta(f,g) = \frac{f}{16\pi^2}(g^2 - f^2)$$

$With....SUSYLR, f \geq 0.5$ sleptons no more tachyonic

(N. Setzer, S. Spinner, RNM, Phys. Rev. D77:053013,2008; JHEP 04 (2008) 091)

# Double charged and triplet Higgs key predictions:

- **Upper limit for AMSB to work:**

$$M_{\Delta^{++}} \leq 10 TeV$$

- **Lower limit : muonium-anti-muonium oscillation has an expt upper limit:**

$$A_{\mu^+e^- \to \mu^-e^+} \leq 3G_F \times 10^{-3} \approx \frac{f_{ee} f_{\mu\mu}}{8M_\Delta{}^2}$$

$$\Rightarrow M_\Delta \geq 1 TeV$$

- **Model predicts:** $A_{\mu^+e^- \to \mu^-e^+} \geq 6G_F \times 10^{-5}$
- **PRISM reach:** $G_F \times 10^{-4}$

# Different gaugino mass ratios as another test.

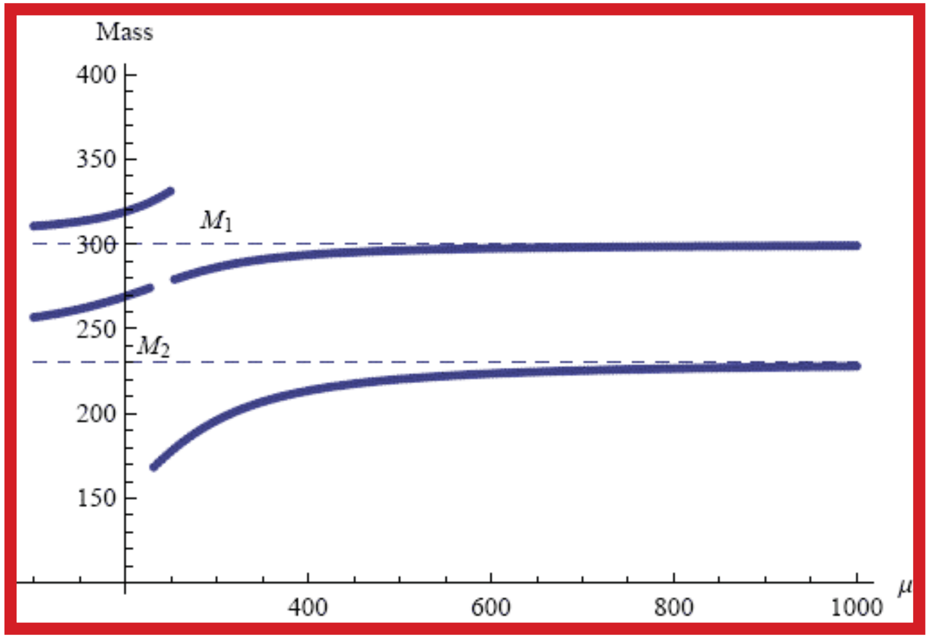
- Different prediction for gaugino mass ratios:
- GUTs: $$M_1 : M_2 : M_3 = 1 : 2 : 7$$
- Gluinos as the most massive spartner !
- For our AMSB: ratio is

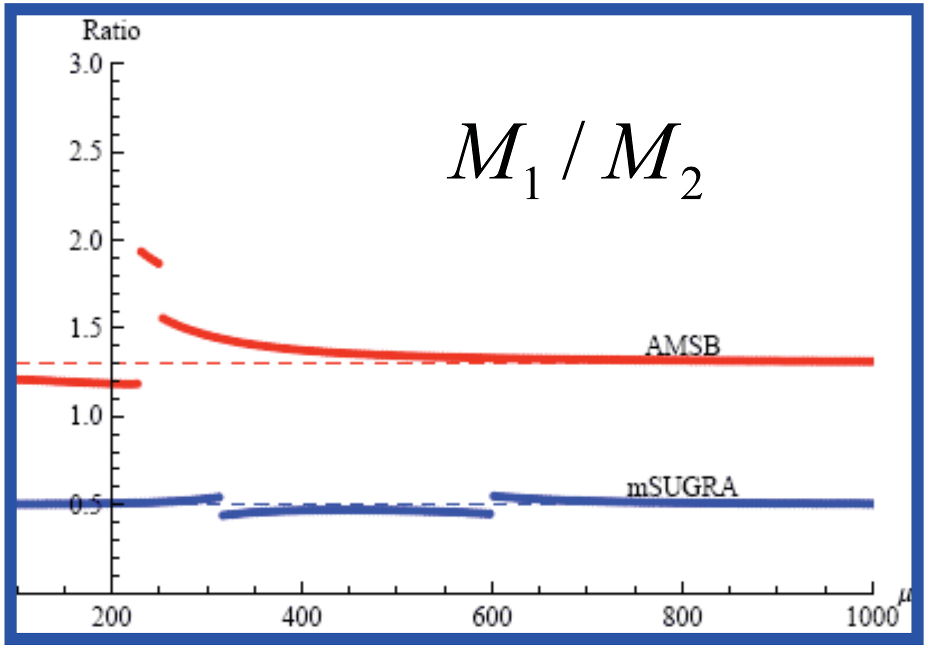
$$M_3 : M_2 : M_1 = 1.3 : 1 : 1.3$$

- This is a crucial signal to test between GUT and sub-GUT models.

# Gaugino mass ratios after mixing:

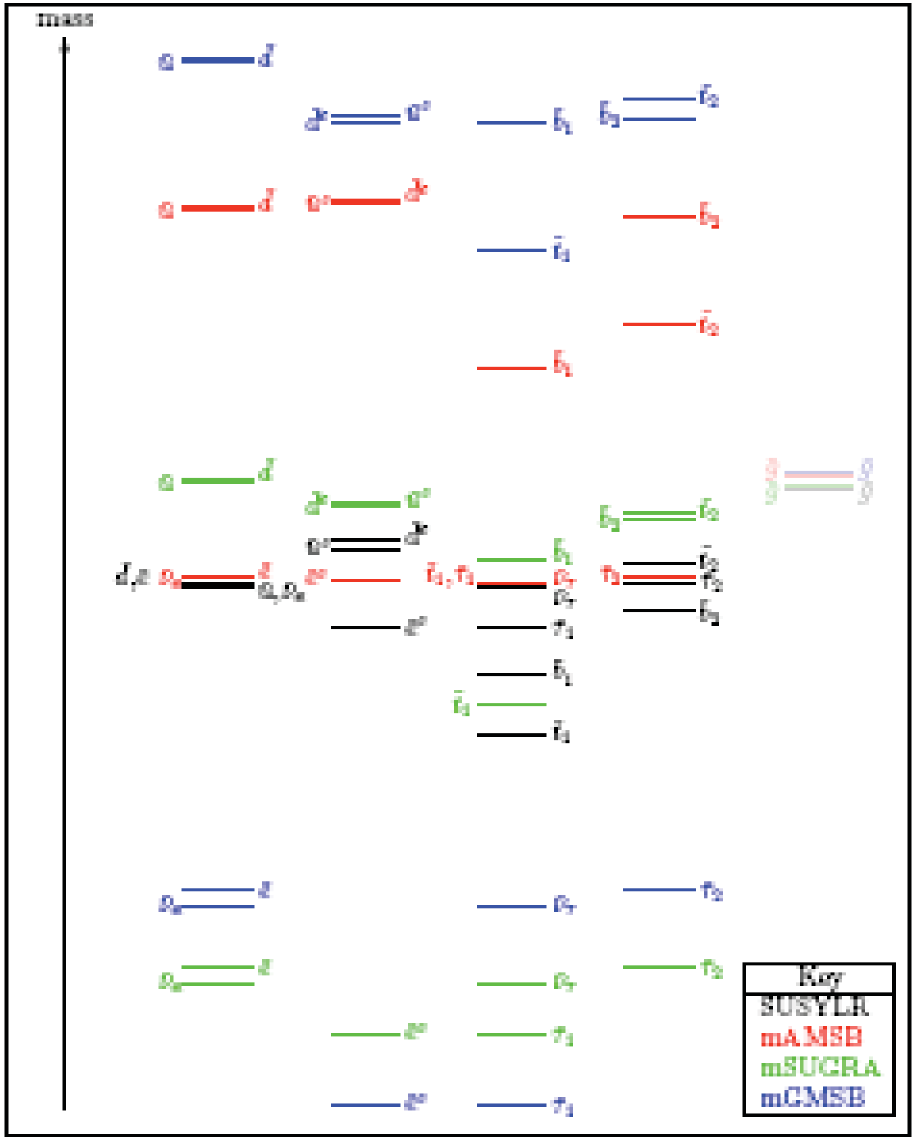
- **AMSB:** **AMSB vs MSUGRA**



# Predictions for slepton masses

- Bunched spectrum
- LSP Wino+
- Higgsino
- DM from gravitino decay



# Summary

- **A simple extension of MSSM that explains neutrino mass and stable dark matter is minimal SUSYLR with B-L=2 triplets:**
- **Two incarnations:**

**(i) TeV scale WR with Rp breaking: has gravitino dark matter. Solves strong CP.**

**(ii) Second has non-ren terms: strong CP sol. needs extension but fixes AMSB.**

- If gaugino masses indicate AMSB, will suggest minimal LR seesaw with TeV scale $\Delta^{++}{}_R, \vec{\Delta}_L$ Higgs

  Experimental tests: (muonium-anti-muonium oscillation lower bound, Bunched sparticle spectrum, new Higgs etc.)

# Bottom-line for AMSB in SUSYLR:

- Minimal SUSYLR allows extra couplings at the TeV scale which change the beta functions of low scale theory and cure the tachyonic slepton problem of AMSB;

- The model predicts a pair of doubly charged Higgs and SM triplet Higgs (and Higgsinos) with mass in the range of

$$1TeV \leq M_{\Delta^{++}} \leq 10TeV$$

- Plus many characteristic testable sparticle predictions

# AMSB upper limit on the Seesaw Scale

- Seesaw helps solve the problem of AMSB
- This requires that Delta mass be less than 10-20 TeV. If more, it will decouple and not help AMSB.
- If only new physics is at the Planck scale

$$M_\Delta \approx \frac{v_R^2}{M_{Pl}} \quad \sim\text{TeV}$$

- fixes the value of seesaw scale to be less than 10^11-10^12 GeV.

# GUTs with Non-Universal Gaugino masses vs AMSB

- **GUT scenarios can also have NUGM**
- **Different from AMSB:**

Table 1: High-scale and approximate low-scale gaugino mass ratios for SU(5).

| Representation | $M_3 : M_2 : M_1$ at $M_{GUT}$ | $M_3 : M_2 : M_1$ at $M_{EWSB}$ |
|---|---|---|
| **1** | 1:1:1 | 6:2:1 |
| **24** | 2:(-3):(-1) | 12:(-6):(-1) |
| **75** | 1:3:(-5) | 6:6:(-5) |
| **200** | 1:2:10 | 6:4:10 |

Table 2: High-scale and approximate low-scale gaugino mass ratios for SO(10).

| Representation | $M_3 : M_2 : M_1$ at $M_{GUT}$ | $M_3 : M_2 : M_1$ at $M_{EWSB}$ |
|---|---|---|
| 1 | 1:1:1 | 6:2:1 |
| **54(i)**: $H \to SU(2) \times SO(7)$ | 1:(-7/3):1 | 7:(-5):1 |
| **54(ii)**: $H \to SU(4) \times SU(2) \times SU(2)$ | 1:(-3/2):(-1) | 7:(-3):(-1) |

**(Table from Bhattacharya, Datta, Mukhopadhyaya;)**