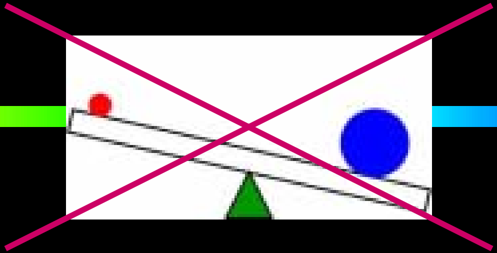
Alternatives to Seesaw



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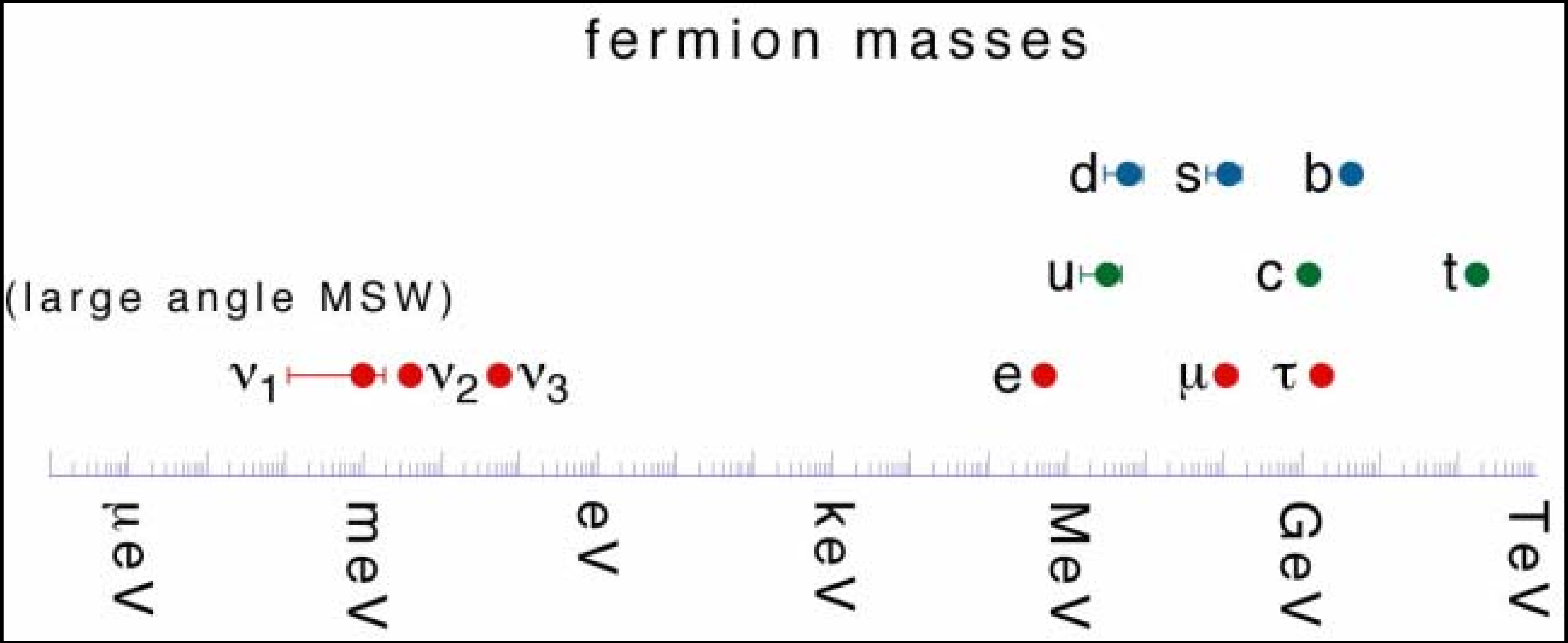
Seesaw04 @ KEK, Feb 25, 2004



fermion masses
d
s
b
u
c
t
(large angle MSW)
ν1
ν2
ν3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

What We Celebrate

- SUSY-GUT (*e.g.*, SO(10))
  - $M_R \sim M_{GUT}$
  - $m_\nu \sim v^2/M_{GUT} \sim 0.001$eV (Yanagida, Gell-Mann, Ramond, Slansky)
- Leptogenesis by ν_R decay (Fukugita, Yanagida)
  - One of $M_R \sim 10^{10}$ GeV
  - Very weakly coupled, decays late
- Further goodies
  - Natural Dark Matter candidate (neutralino) (Goldberg)
  - Radiative electroweak symmetry breaking (Inoue et al, Alvarez-Gaumé et al, Ibañez-Ross)

Problems

- SUSY-GUT
  - Flavor problem, CP problem
  - New energy scale for GUT
  - No proton decay
- Leptogenesis
  - Gravitino problem for $m_{3/2}$~100–1000 GeV
  - BBN: $T_{RH}<10^6$-10^9 GeV ($<10^4$ GeV? Kohri et al)
  - $M_R>10^{10}$ GeV
- Hard to verify experimentally
  - $m_{1,2,3}<0.1$ eV (Buchmüller, Plümacher)
  - May never see $0\nu\beta\beta$

Conclusions

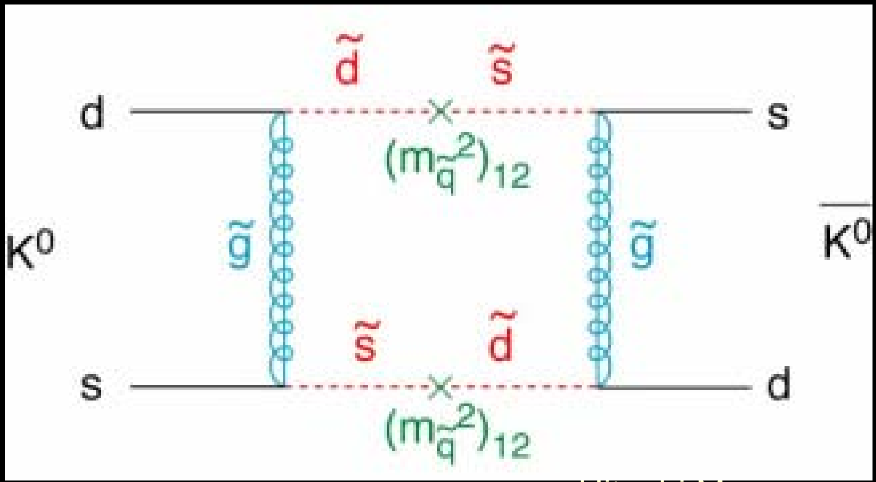
- Standard seesaw mechanism has many problems
- Consistent Anomaly Mediation
  - No supersymmetric flavor & CP problems
  - Gravitino problem solved
  - *B*–*L* conserved, yet small neutrino mass, leptogenesis
- sMajorana
  - Small neutrino mass from hidden sector
  - Weak-scale right-handed sneutrino observable at colliders
  - Reconciles DAMA vs CDMS/Edelweiss
- Flavor Anomalous U(1) For Everything
  - No need for GUT-scale to do seesaw
  - Explains fermion masses, mixings, including neutrinos
  - Interesting rates for Planck-scale proton decay

Consistent Anomaly Mediation

SUSY Flavor & CP Problems

- Squark mass^2 matrix and quark mass matrix may not be simultaneously diagonalizable

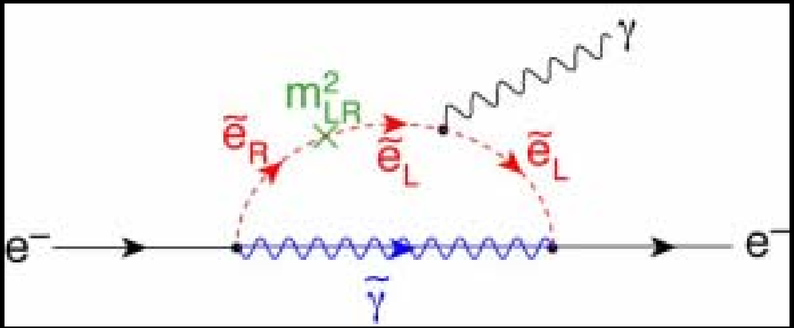
$$\left(m^2_{\tilde{q}}\right)_{12} < 10^{-3}\left(m^2_{\tilde{q}}\right)_{11}$$



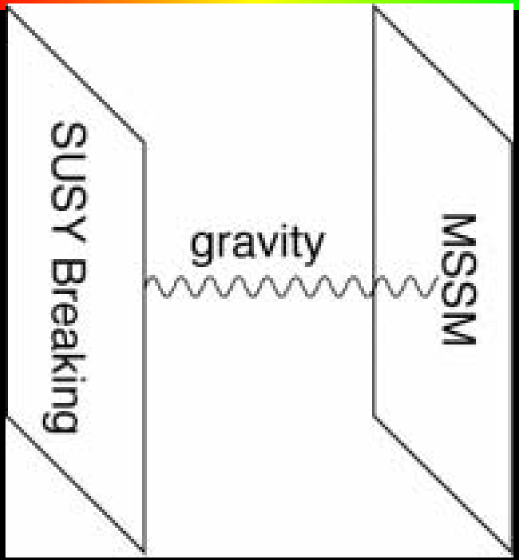
- Some terms may be complex

⇒ Electric Dipole Moment

$$\arg\left(m^2_{\tilde{e}}\right)_{LR} < 10^{-4}$$



Anomaly Mediation



Zen of SUSY breaking

Try not to mediate

You will mediate

(Randall, Sundrum)

(Giudice, Luty, HM, Rattazzi)

- Gravity couples to the energy scale
- Without dimensionful parameters, there is *no supersymmetry breaking at tree-level*
- But secretly a dimensionful paramter: renormalization scale
- Renormalization scale induces supersymmetry breaking

Anomaly Mediation

$$M_i = -\frac{\beta_i(g^2)}{2g_i^2}\frac{F}{M_{Pl}},$$

$$m_i^2 = -\frac{\dot{\gamma}_i}{4}\left|\frac{F}{M_{Pl}}\right|^2,$$

$$A_{ijk} = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k)\frac{F}{M_{Pl}}$$

- Anomaly mediation predicts SUSY breaking with theory *given at the scale of interest*

UV insensitivity

- Can be checked explicitly by integrating out heavy fields that the threshold corrections precisely match the differences in β & γ (Giudice, Luty, HM, Rattazzi)

(Boyda, HM, Pierce)

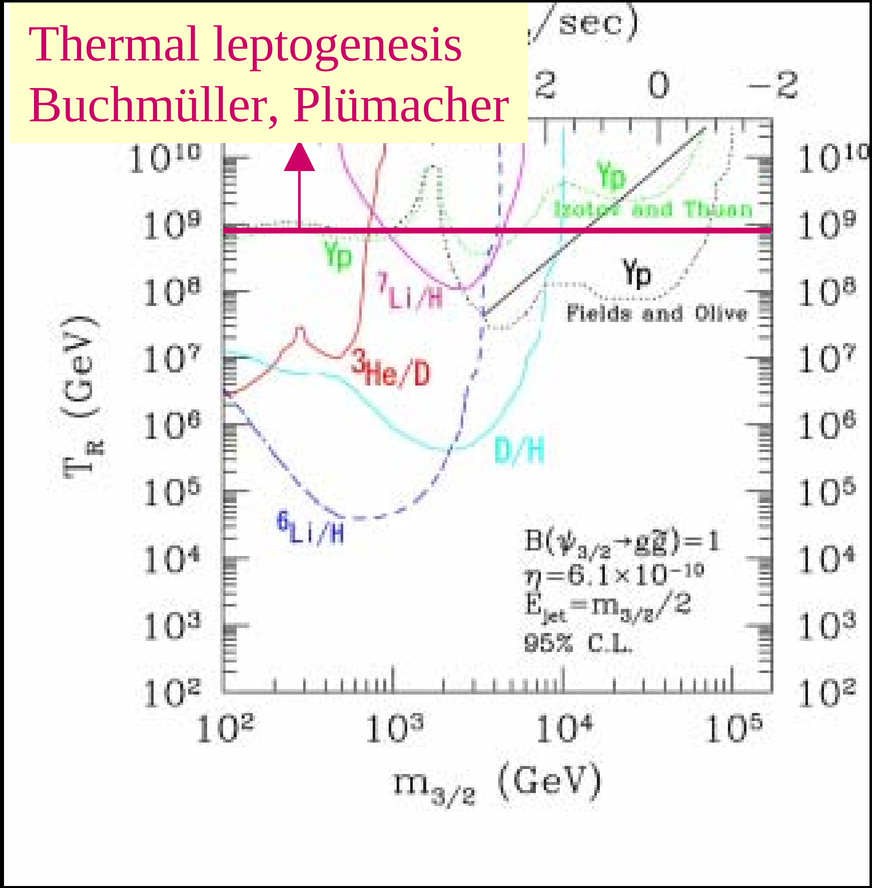
- SUSY breakings always stay on the RGE trajectory
- No SUSY flavor&CP prolems

Gravitino Problem

- Gravitinos produced in early universe

$$\frac{n_{3/2}}{s} = 1.5\times10^{-12}\,\frac{T_{RH}}{10^{10}\,\mathrm{GeV}}$$

- If decays after the BBN, destroys synthesized light elements
- Hadronic decays particularly bad (Kawasaki, Kohri, Moroi)



Heavy Gravitino

- $m^2 \sim m_{3/2}^2/(4\pi)^2$, $M_i \sim m_{3/2}/(4\pi)$
- $m_{3/2} \sim (4\pi)^2\, m_{\mathrm{SUSY}} \sim 100$ TeV
- Decays before the BBN
- *Gravitino problem solved*

$$M_i = -\frac{\beta_i(g^2)}{2g_i^2}\frac{F}{M_{Pl}},$$
$$m_i^2 = -\frac{\dot{\gamma}_i}{4}\left|\frac{F}{M_{Pl}}\right|^2,$$
$$A_{ijk} = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k)\frac{F}{M_{Pl}}$$

- Remaining constraint that the decay product (LSP) does not overclose the universe (Kawasaki, Moroi)

$$T_{RH} < 3\times10^{10}\ \mathrm{GeV} \times (100\mathrm{GeV}/m_{LSP})$$

- Good news for thermal leptogenesis

Too predictive!

- Anomaly mediation highly predictive with only one parameter: overall scale
- Slepton mass-squareds come out *negative*
- Phenomenologically dead on start
- Remedies:
  - Add uinversal scalar mass
  - Cause symmetry breaking via SUSY breaking
- Destroy UV insensitivity

Viable UV-insensitive Anomaly Mediation

- Add $U(1)_{B\text{-}L}$ and $U(1)_Y$ D-terms (Jack, Jones)
- Three SUSY-breaking parameters now

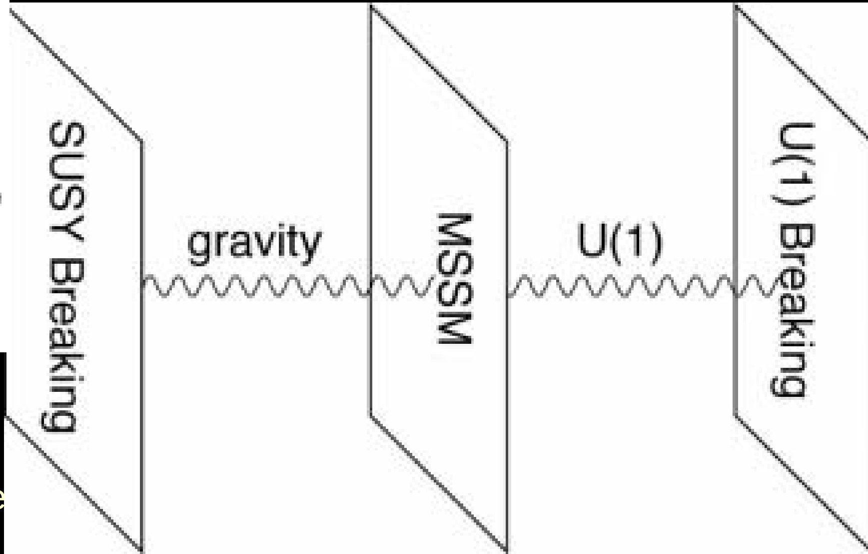
$$M_i = -\frac{\beta_i(g^2)}{2g_i^2} m_{3/2},$$

$$m_i^2 = -\frac{\dot{\gamma}_i}{4} m_{3/2}^2 + Y D_Y + (B-L) D_{B-L},$$

$$A_{ijk} = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k) m_{3/2}$$

- *UV*-insensitive thanks to $U(1)_{B\text{-}L}$ and $U(1)_Y$ symmetries

(Arkani-Hamed, D.E. Kaplan, HM, Nomura)



Conformal sequestering

- Inspiration from AdS/CFT correspondence
- Make hidden sector nearly superconformal
- Dangerous coupling between hidden and observable fields suppressed because Kähler potential of hidden fields flow to IR fixed point (Luty, Sundrum)
- Can be extended to include dynamical $U(1)$ breaking sector to make the scenario phenomenologically viable (Harnik, HM, Pierce)
- A viable 4D theory with no SUSY flavor&CP problems

$U(1)_{B-L}$

- Strict UV insensitivity requires (global) $U(1)_{B-L}$
- *What about neutrino mass?*
- No superpotential $\int d^2\theta\, L\, H_u\, N$ with symmetry (*i.e.*, $U(1)_R$)
- Term in the Kähler potential ($\Phi=\theta^2 F$)

  $\int d^4\theta\, \Phi^*\Phi\, L\, H_u\, N / M_{\text{Planck}}$
- Induces Yukawa coupling from SUSY breaking

  $\int d^2\theta\, m_{3/2}\, L\, H_u\, N / M_{\text{Planck}}$
- $m_\nu \sim m_{3/2}\langle H_u\rangle/M_{\text{Planck}} \sim 0.01\text{eV}$
- Neutrino mass from Planck scale
- No new mass scales, *i.e.*, M_{GUT}, M_R
- (Possible to introduce M_R; reintroduce LFV)

$$Q, L(2/3) \quad U, D, E(1/3) \quad H_u, H_d(1) \quad N(-5/3)$$

Electroweak Symmetry Breaking

- Works well with the following Higgs sector

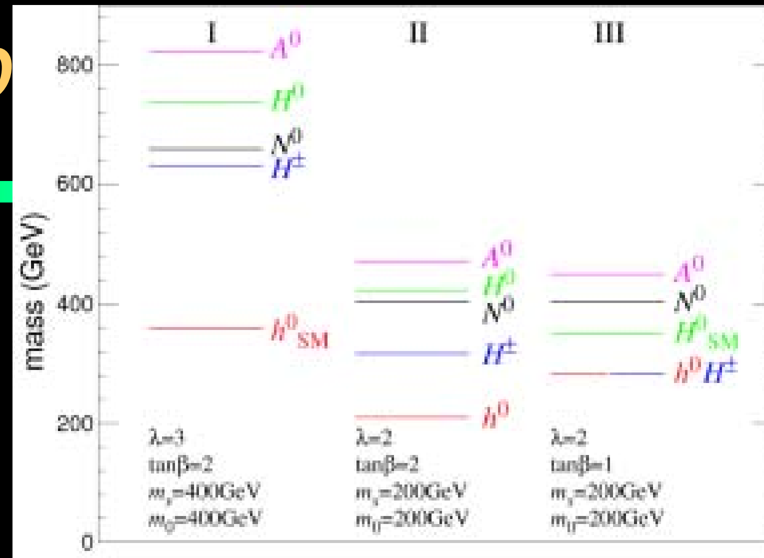
  $$W=\lambda S (H_u H_d - v_0^2)$$

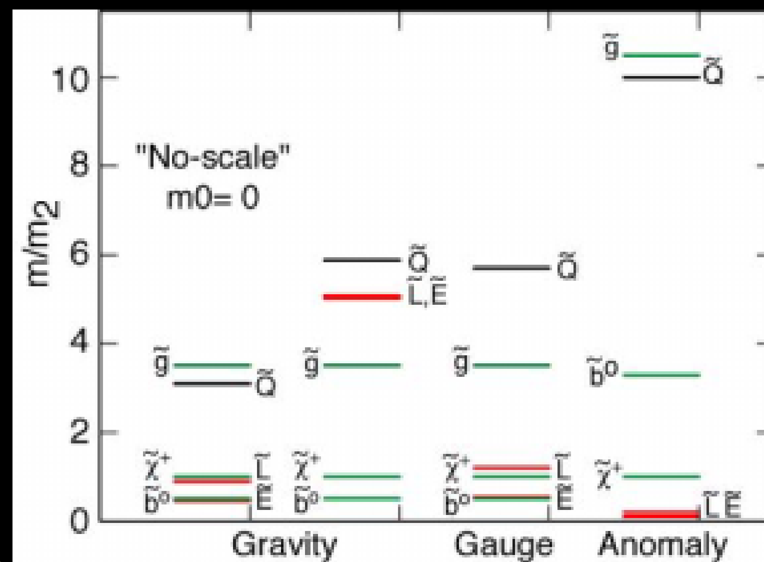
  S is an electroweak singlet (Kitano, Kribs, HM)
- A predictive model with five parameters

  $$(m_{3/2}, D_Y, D_{B-L}, \lambda, v_0^2)$$
- #parameters the same as the CMSSM
- No SUSY flavor and CP problems
- No gravitino problem

Mass Sp

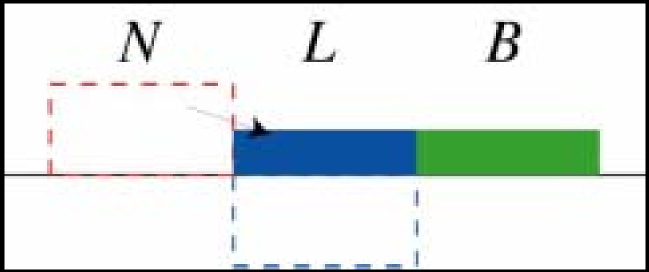
- Higgs and SUSY mass spectrum can be unusual, quite different from the CMSSM
- Combine LHC+LC
- May also need VLHC+CLIC





Dirac Leptogenesis

- B–L conserved
- How do we do baryogenesis?
- Heavy doublets decay to
  $X \rightarrow L_i N_j$, $X^* \rightarrow L_k E_l$
- Decay produces asymmetry (≥2 X's)
  - $L_\nu + L_N = 0$, but $L_\nu = -L_N \neq 0$
  - $L_N \neq 0$ protected because of small Yukawa
  - L_ν partially converted to B
  - Practically only now ($T \sim m_\nu \sim 10^3$ K), L_ν & L_N equilibrate, but do not cancel B any more



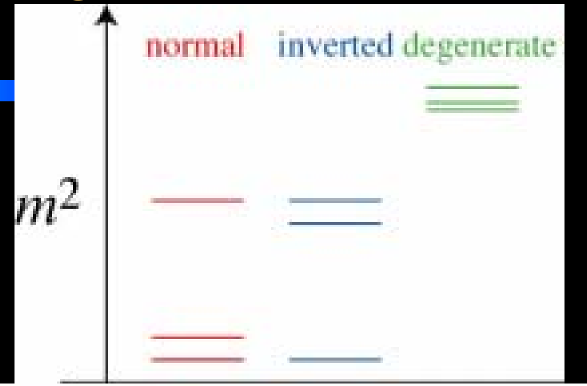
(Dick, Lindner, Ratz, Wright)

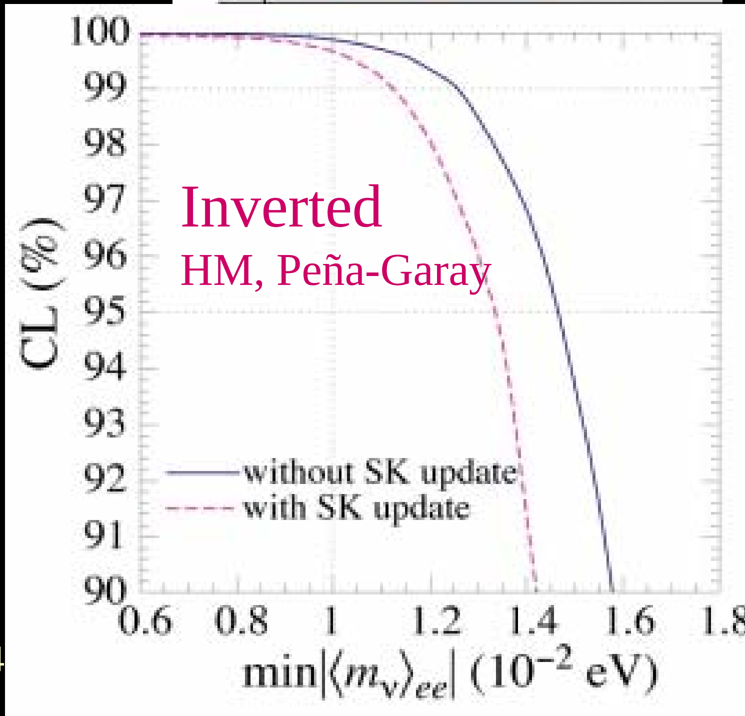
(HM, Pierce) (to be written)

(Nearly) Verifiable

Suppose the following possible outcome

- Find SUSY at LHC&LC
  - Verify spectrum of anomaly mediation with *D*-terms
- LBL ν oscillation
  - Establish inverted hierarchy
  - Implies $<m_{ee}> > 0.01$eV (HM, Peña-Garay)
- No $0\nu\beta\beta$
  - Establishes Dirac neutrinos
- *Pretty much conclusive*





sMajorana

Why are neutrinos light?

(Arkani-Hamed, Hall, HM, Smith, Weiner)

(Borzumati, Nomura)

- Standard seesaw mechanism:

$$\mathcal{L} = \frac{1}{M}(LH_u)(LH_u) \to \frac{v_2^2}{M}\nu\nu$$

- Another way to get small neutrino mass from hidden sector SUSY breaking: "sMajorana"

$$\langle X \rangle = m_I + \theta^2 m_I^2, \qquad m_I = \sqrt{m_{3/2} M_P}$$

$$\mathcal{L} = \int d^2\theta \, \frac{X}{M_P} L H_u N + \int d^4\theta \frac{X^*}{M_P} N N$$

$$= \int d^2\theta \, (\sqrt{\frac{m_{3/2}}{M_P}} L H_u N + m_{3/2} N N) + m_{3/2} \tilde{L} H_u \tilde{N}$$

$$m_\nu = \frac{m_{3/2}^2}{M_P}$$ ~0.001eV

Sneutrinos Mix

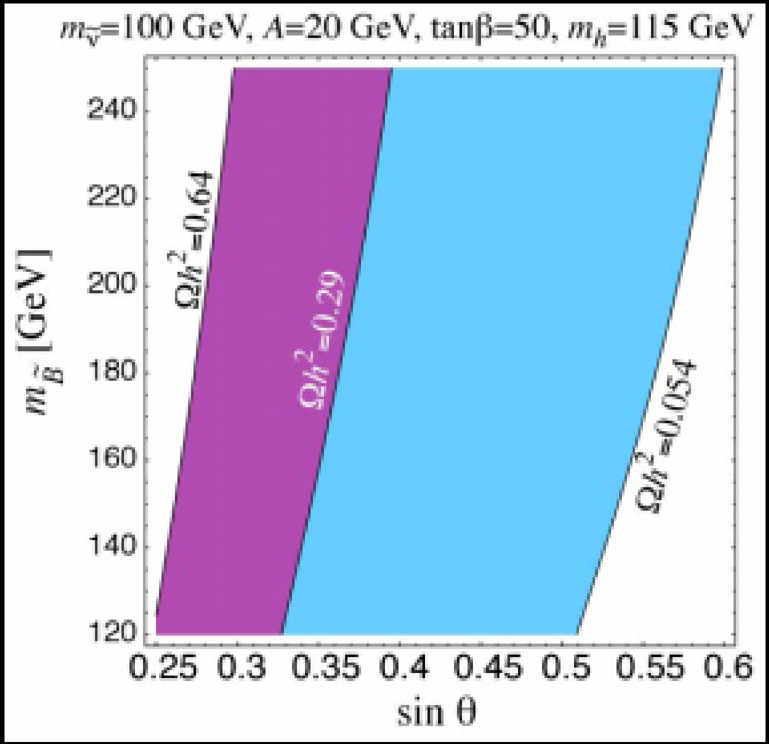
$$\mathcal{L} = \int d^2\theta \, \frac{X}{M_P} L H_u N + \int d^4\theta \frac{X^*}{M_P} N N$$
$$= \int d^2\theta \, (\sqrt{\frac{m_{3/2}}{M_P}} L H_u N + m_{3/2} N N) + m_{3/2} \tilde{L} H_u \tilde{N}$$

- Large LR mixing ~$m_{3/2}$ $\langle H_u \rangle$ despite small Yukawa ~ $\sqrt{(m_{3/2}/M_P)}$
- Mass eigenstates: mixtures of left-handed and right-handed sneutrinos
- Natural with *R*-charge $N(2/3)$, $X(4/3)$, $L(0)$, $H_u(0)$

Bosonic LSP Dark Matter

- Normal sneutrinos annihilate too much
- Annihilation of mixed sneutrino is suppressed by the mixing angle

  $\propto \sin^4 \theta_{LR}$
- Can suppress the annihilation cross section $\Rightarrow$ viable dark matter candidate



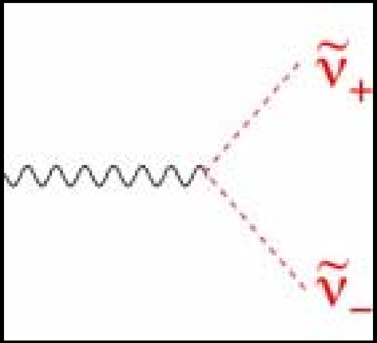
Lepton-Number Violation

$$\int d^4\theta \frac{X^*}{M_P}\left(1+\frac{XX^*}{M_P^2}\right)NN = \int d^2\theta m_{3/2} NN + \frac{m_{3/2}^{5/2}}{M_P^{1/2}}\tilde{N}\tilde{N}$$

- *B*-term mixes right-handed sneutrino and anti-sneutrino *à la* neutral kaon
- CP-even $\tilde{\nu}_+$ and CP-odd $\tilde{\nu}_-$ states with $\Delta m \sim m_{3/2}^{3/2}/M_P^{1/2} \sim 100\text{keV}$

Inelastic Dark Matter
(Hall, Moroi, HM)

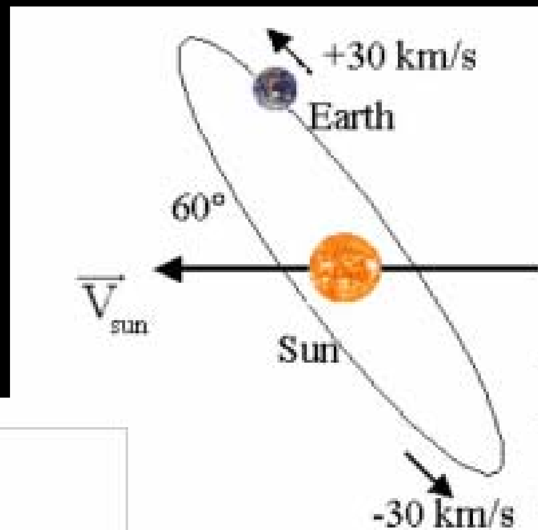
- The coupling to Z-boson off-diagonal because of the Bose symmetry



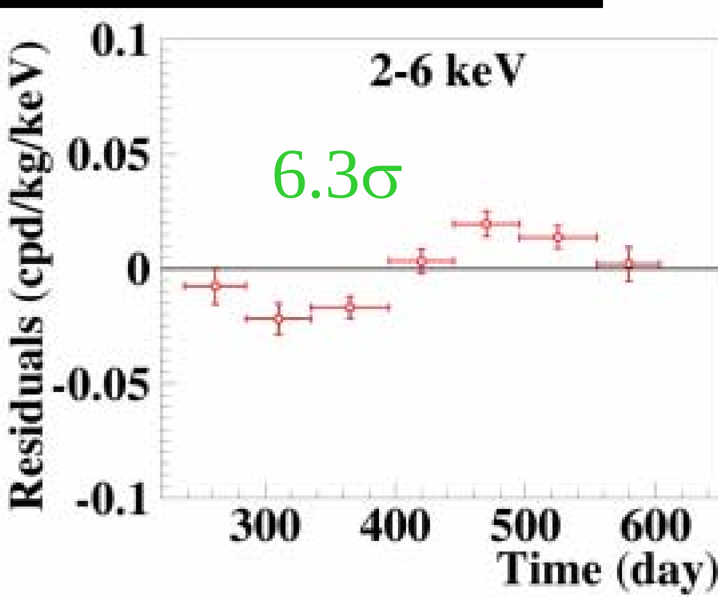
- Scatters *inelastically* on nuclei
- Kinetic energy $mv^2/2 \sim 10^{-6}\, m$ vs $\Delta m \sim 100$keV
- Only a part of the phase space has enough energy

$$v^2 \geq 2\Delta m \frac{m + m_N}{m m_N}$$

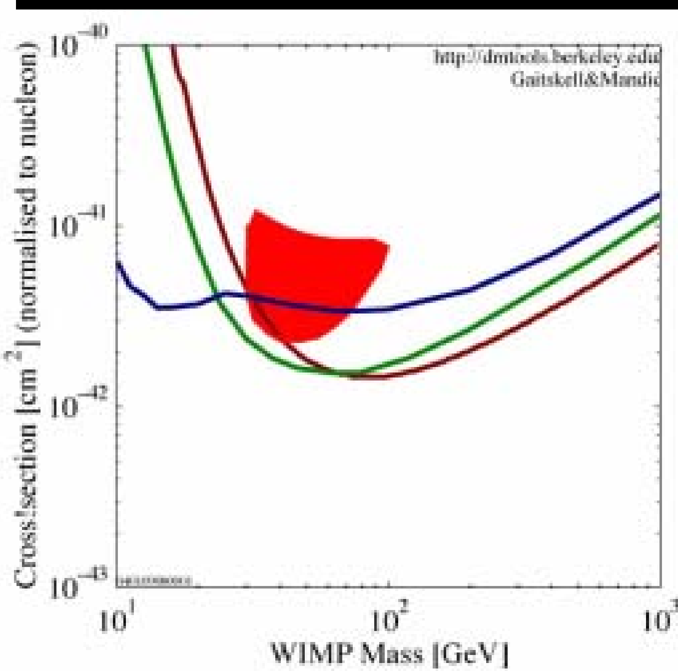
DAMA



+30 km/s
Earth
60°
$\overline{V}_{sun}$
Sun
-30 km/s



2-6 keV
6.3σ
Residuals (cpd/kg/keV)
0.1
0.05
0
-0.05
-0.1
300
400
500
600
Time (day)



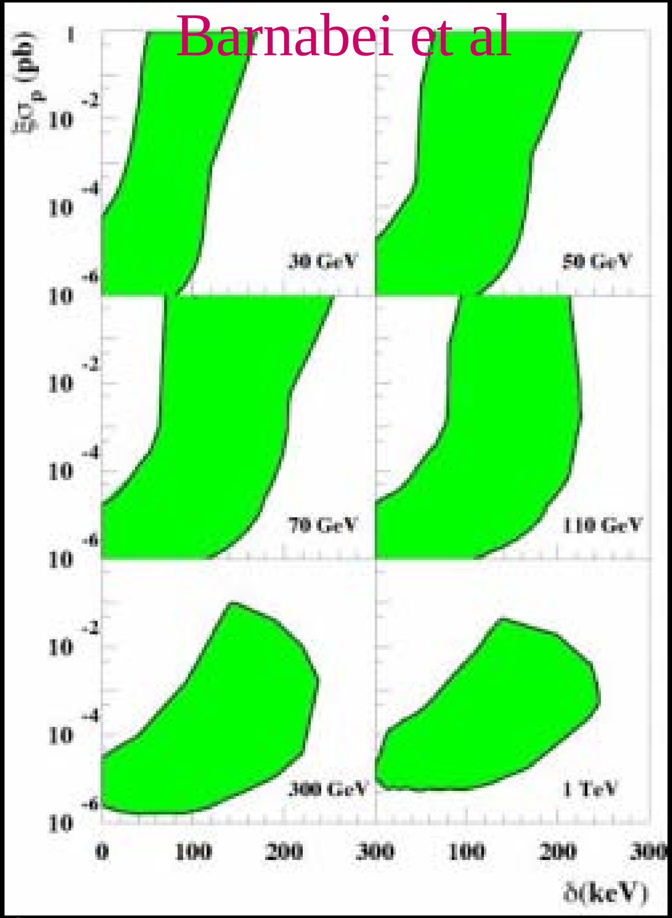
http://dmtools.berkeley.edu
Gaitskell&Mandic
Cross-section [cm^2] (normalised to nucleon)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^1
10^2
10^3
WIMP Mass [GeV]

Reconciling DAMA
(Smith, Weiner)

- Larger phase space to satisfy the kinematic threshold for heavier nucleus

$$v^2 \geq 2\Delta m \frac{m + m_N}{m m_N}$$

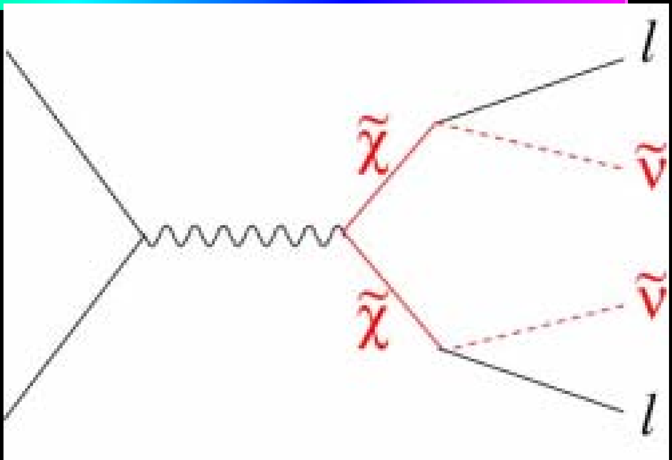
- More phase space for I than Ge
- Inelastic dark matter can reconcile DAMA with CDMS/Edelweiss
- Annual modulation enhanced
- Consistent (HM, Peña-Garay)



Confusing Collider Signature
(de Gouvêa, Friedland, HM)

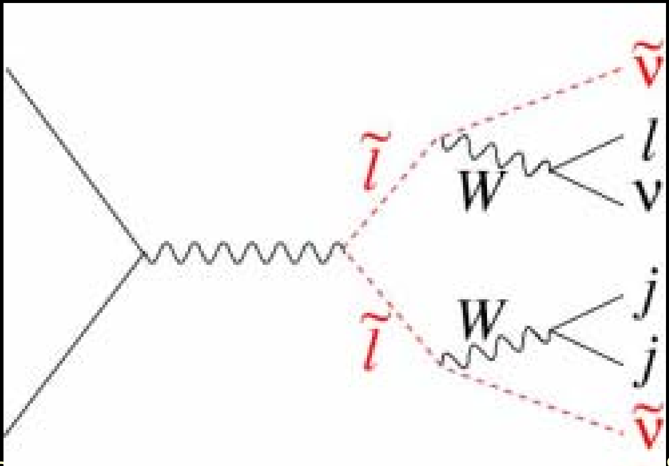
- Acoplanar leptons

Sleptons? No, charginos



- Lepton+jets+missing

Charginos? No, sleptons



Spin Determination

- Threshold behavior

  $\sigma \propto \beta$ (spin 1/2),

  $\sigma \propto \beta^3$ (spin 0)

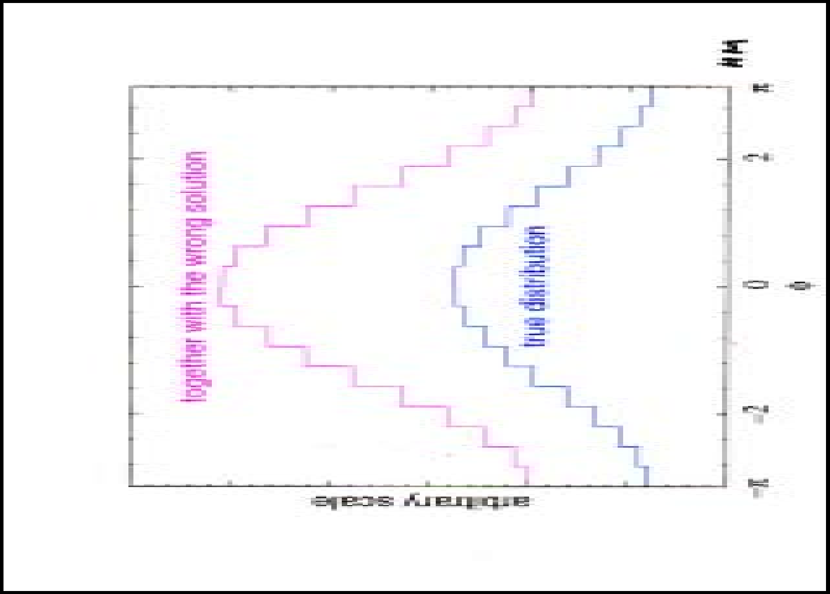
- Polar angle distribution

$d\sigma/d\cos\theta \propto 1+\cos^2\theta$ (spin 1/2)

$d\sigma/d\cos\theta \propto \sin^2\theta$ (spin 0)

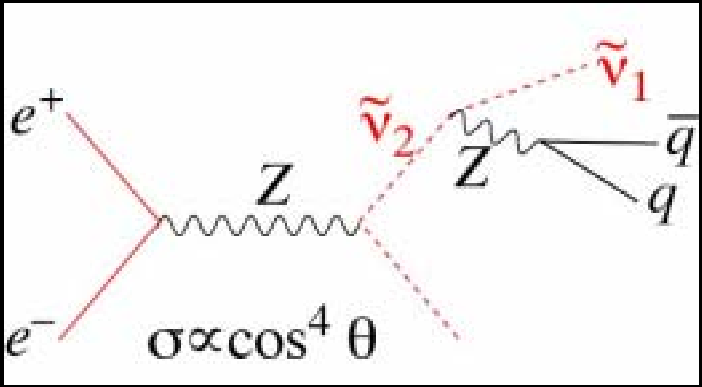
- Azimuthal correlation in decay planes for charginos

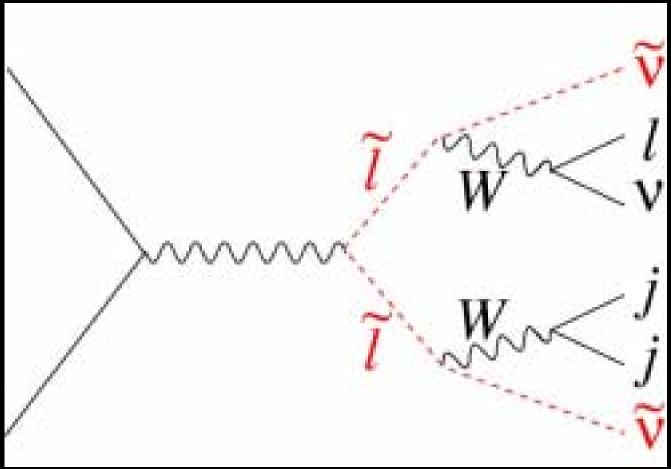
  (HM, LCWS2000)



Parameter Measurements

- Measure mixing angle
- Both sneutrino masses
- Slepton mass
- Use *D*-term relation to cross check
- Measure bino mass from selectron production
- Calculate Ωh^2





Excluding Seesaw

- Once right-handed sneutrinos found at colliders

$\Rightarrow$Unambiguous exclusion of the seesaw mechanism

Flavor Anomalous U(1)
For Everything

Question of Flavor

- What distinguishes different generations?
  - Same gauge quantum numbers, yet different
- Hierarchy with small mixings:

  $\Rightarrow$ Need some ordered structure
- Probably a hidden *flavor quantum number*

  $\Rightarrow$ Need flavor symmetry
  - Flavor symmetry must allow top Yukawa
  - Other Yukawas forbidden
  - Small symmetry breaking generates small Yukawas

Broken Flavor Symmetry

- Flavor symmetry broken by a VEV $\langle \varepsilon \rangle \sim 0.02$
- SU(5)-like (anarchy):
  - 10(Q, u_R, e_R) (+2, +1, 0)
  - 5*(L, d_R) (+1, +1, +1)

$$M_u \sim \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}, M_d \sim \begin{pmatrix} \varepsilon^3 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon & \varepsilon \end{pmatrix}, M_l \sim \begin{pmatrix} \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \end{pmatrix}$$

  - $m_u : m_c : m_t \sim m_d^2 : m_s^2 : m_b^2 \sim m_e^2 : m_\mu^2 : m_\tau^2 \sim \varepsilon^4 : \varepsilon^2 : 1$

Dirty Little Secret about Supersymmetry

- *Even without GUT, proton decays too fast*
- Once supersymmetry is there, *Planck-scale physics can cause too-rapid proton decay*
- Dangerous operators:

$$\frac{h}{M_{Pl}} Q_1 Q_1 Q_2 L_i \qquad \frac{h}{M_{Pl}} Q_1 Q_2 Q_2 L_i$$

- Typically, $h < 4\times10^{-8}$, 10^{-7}, respectively (Kakizaki, Yamaguchi)
- Flavor symmetry can suppress these operators adequately (HM, D.B. Kaplan)

Anomalous U(1) from String Theory

- Flavor symmetries tend to be anomalous. Isn't that a problem?
- Actually, string theory tends to give you an anomalous U(1) *gauge* symmetry
- Because it is anomalous, it gets broken shortly below the string scale

$$\langle A \rangle = \frac{g}{8\pi\sqrt{3}}\sqrt{\sum_i q_i} \cdot M_{Pl} \sim 0.2 M_{Pl} \sim \lambda M_{Pl}.$$

- Dynamically generates the "seed hierarchy" for fermion masses $\lambda \sim \langle A \rangle / M_{Pl}$ (Binétruy, Ramond)

Anomalous U(1) from String Theory

- Anomalies actually cancelled by the Green–Schwarz mechanism
- Still subject to strong constraints

$$\frac{\mathcal{A}_{CCX}}{k_C} = \frac{\mathcal{A}_{WWX}}{k_W} = \frac{\mathcal{A}_{YYX}}{k_Y} = \frac{\mathcal{A}_{XXX}}{3\,k_X} = \frac{\mathcal{A}_{GGX}}{24}, \qquad \mathcal{A}_{YXX} = 0.$$

- Given phenomenological constraints on quarks & lepton masses, CKM matrix, now even neutrino masses and MNS matrix, the charge assignments quite restricted

A Very Ambitious Attempt

- Use anomalous U(1) for *everything*
  - The only symmetry beyond $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Only two right-handed neutrinos
  - No new mass scales except for M_{Pl} and m_{SUSY}
  - Get $\lambda \sim \langle A \rangle / M_P \sim 0.22$ correctly
  - Quark masses and CKM matrix
  - Lepton masses
  - Right-handed neutrino masses (no GUT-scale)
  - Left-handed neutrino masses and MNS matrix
  - *R*-parity as an unbroken subgroup of U(1)
  - Adequate suppression of proton decay

(Dreiner, HM, Thormeier)

Ansatz

- Successful masses and mixings

$$m_e : m_\mu : m_\tau \sim \lambda^5 : \lambda^2 : 1, \qquad m_\tau : m_b \sim 1$$

$$m_d : m_s : m_b \sim \lambda^4 : \lambda^2 : 1, \qquad m_u : m_c : m_t \sim \lambda^8 : \lambda^4 : 1$$

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad M_\nu \sim \begin{pmatrix} \lambda^2 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

- Find U(1) charges consistent with this ansatz, anomaly cancellation, automatic *R*-parity ⇒ four solutions

Consequence on Proton Decay

- The Planck-scale operators $\frac{h}{M_{Pl}} Q_1 Q_1 Q_2 L_i$

- Suppression factors for many viable models:

  - $h \sim \lambda^{12}$ or $\lambda^{13} \sim 3.0\text{–}7.4\times10^{-9}$

$$\tau(p \to K^+ \bar{\nu}_i) \simeq 0.4\text{–}2.3 \times 10^{34} \text{years} \left(\frac{f(c,d') + f(u,\ell_i)}{\text{TeV}} \right)^2 \left(\frac{\beta}{0.01\text{GeV}^2} \right)^2$$

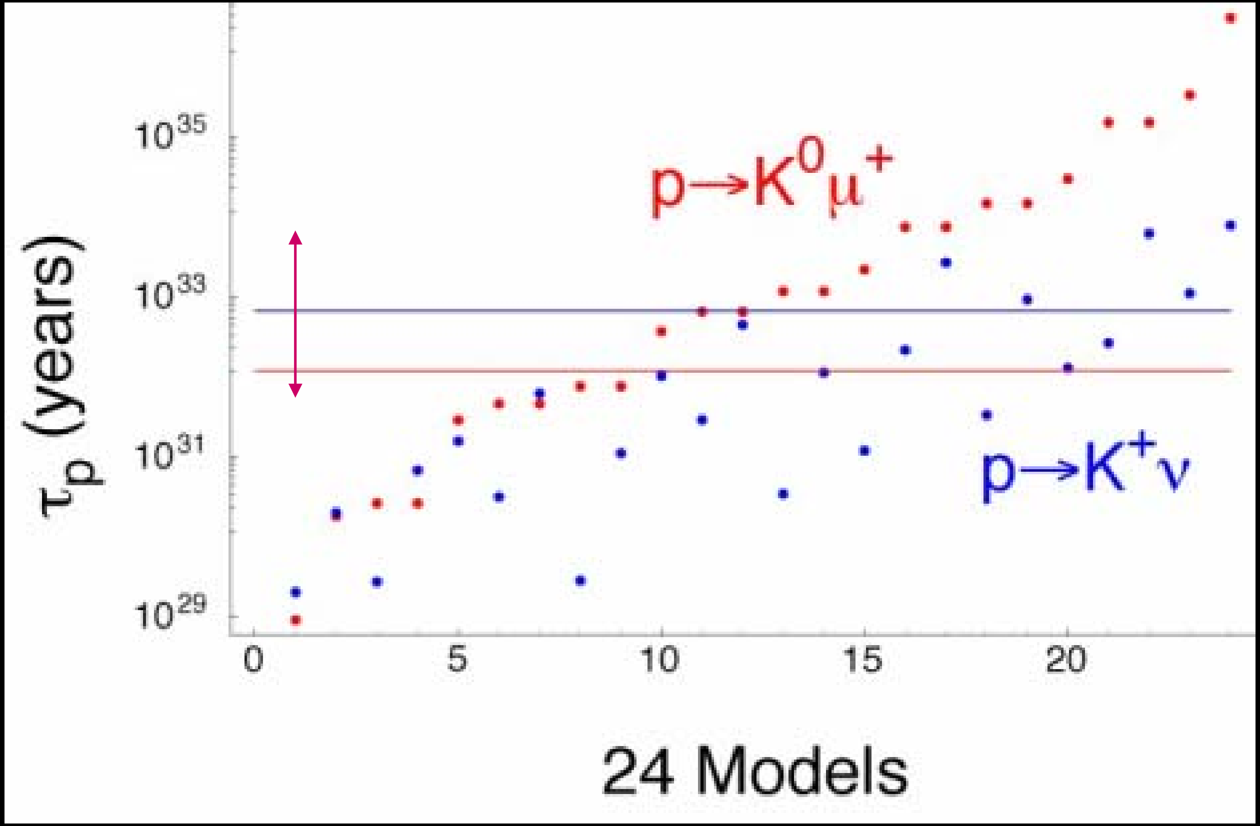
  - *cf.* $\tau(p\to K^+\nu) > 1.9\times10^{33}$ years (90% CL) (SK)

Consequence on Proton Decay

- $p \to K^+ \nu$ still dominant $\Rightarrow$ liquid Argon?
- However, $$\frac{\Gamma(p \to K^0 \mu^+)}{\Gamma(p \to K^+ \bar{\nu})} \simeq 0.1$$
- $p \to K^0 \mu^+$, $K^0 \to \pi^0 \pi^0 \to \gamma\gamma\gamma\gamma$ would be quite spectacular in water Cherenkov, presumably with a higher efficiency than ~10% for $K^+ \nu$
- But nuclear absorption?
- Important lesson:

many different modes are possible

Proton Lifetime



Harnik, Larson, HM, Thormeier, in progress

Charges aren't pretty

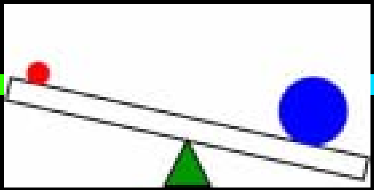
$$X_{H^{\mathcal{D}}} = \frac{11}{10}, \quad X_{H^{\mathcal{U}}} = -\frac{21}{10}$$

Generation i	X_{Q^i}	$X_{\overline{D^i}}$	$X_{\overline{U^i}}$	X_{L^i}	$X_{\overline{E^i}}$
1	$\frac{67}{15}$	$\frac{13}{30}$	$\frac{169}{30}$	$\frac{3}{5}$	$\frac{53}{10}$
2	$\frac{52}{15}$	$-\frac{17}{30}$	$\frac{79}{30}$	$-\frac{2}{5}$	$\frac{33}{10}$
3	$\frac{22}{15}$	$-\frac{17}{30}$	$\frac{19}{5}$	$-\frac{2}{5}$	$\frac{13}{10}$

Conclusions

- Standard seesaw mechanism has many problems
- Consistent Anomaly Mediation
  - No supersymmetric flavor & CP problems
  - Gravitino problem solved
  - $U(1)_{B-L}$ symmetry, yet small neutrino mass, leptogenesis
- sMajorana
  - Small neutrino mass from hidden sector
  - Weak-scale right-handed sneutrino observable at colliders
  - Reconciles DAMA vs CDMS/Edelweiss
- Flavor Anomalous U(1) For Everything
  - No need for GUT-scale to do seesaw
  - Explains fermion masses, mixings, including neutrinos
  - Interesting rates for Planck-scale proton decay

But the Spirit of Seesaw Lives!



Small neutrino mass is a window to physics beyond the Standard Model.