# Flavorful hybrid anomaly-gravity mediation

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(based on arXiv:1101.5352, with Gudrun Hiller)

# Motivation

- weak-scale SUSY:
  - ☺ stabilize weak scale
  - ☺ dark matter candidate
  - ☺ ...
  - ↯ flavor- and CP violation
  - ↯ $\mu$-problem
  - ↯ gravitino ($\Psi_{3/2}$) problem (if baryogenesis via leptogenesis)
  - ↯ ...
- how severe above problems are depends on ~~SUSY~~ model
- e.g. anomaly mediation:
  - $\Psi_{3/2}$ so heavy that it decays before BBN ☺
  - flavor blind ☺
  - unfortunately: $m^2_{slepton} < 0$ in pure AMSB ↯

## anomaly mediation: [Randall, Sundrum; '98] [Giudice et al.; '98]

- AMSB is ~~SUSY~~ due to quantum anomaly in scaling symmetry
- soft masses (also gaugino masses, *A*-terms ...):

$$m^2|_{amsb} = \frac{1}{2}|m_{3/2}|^2 \mu \frac{d}{d\mu}\gamma \sim \underbrace{\frac{|m_{3/2}|^2}{(16\pi^2)^2}}_{\sim 10^{-4}|m_{3/2}|^2} (\mp g^4 - g^2 Y^2 + Y^4)$$

## ...compare to gravity mediation (PMSB):

$$m^2|_{pmsb} \sim \frac{|F_S|^2}{M_*^2} \underset{\substack{\uparrow \\ (F_S \simeq m_{3/2} M_{pl})}}{\simeq} |m_{3/2}|^2 \frac{M_{pl}^2}{M_*^2} \gg m^2|_{amsb}$$

$M_*$: scale of new physics

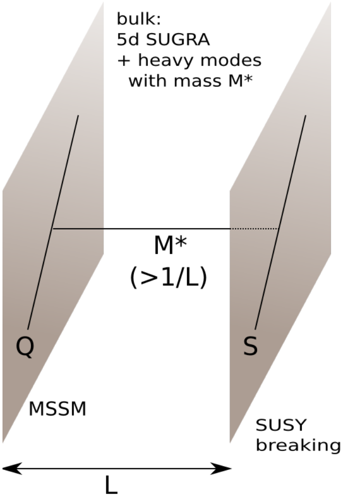
S: hidden sector superfield

$\Rightarrow$AMSB soft terms only relevant if PMSB is suppressed
(i.e. if ~~SUSY~~ sector is 'sequestered' [Randall, Sundrum; '98])

## preview: main ideas of this talk

- don't suppress PMSB completely, but only so much that $m^2_{soft}|_{pmsb} \sim m^2_{soft}|_{amsb}$
- then, $m^2_{soft}|_{pmsb}$ can cure tachyonic slepton problem
- this spoils flavor-blindness of AMSB, but keep in mind:
  - need a flavor model anyways to explain SM masses and mixings
  - the same flavor model can at the same time explain absence of excessive FV and CPV [Nir, Seiberg; '93]
- characteristic phenomenology!

# Sequestering in 5d brane worlds [Randall, Sundrum; '98]




- minimal 5d SUGRA: no ~~SUSY~~ at tree level
- effects of other (heavy) bulk modes:

X: matrix in flavor-space

$$\mathcal{L}_4 \supset e^{-M_* L} \frac{X_{ij}}{M_*^2} \, S\bar{S}Q_i\bar{Q}_j\big|_{\theta^4}$$

$\rightsquigarrow$ scalar masses:

$$m^2_{ij}\big|_{pmsb} \sim \frac{e^{-M_* L}}{M_*^2} |F_S|^2 X_{ij} \simeq \frac{|F_\Phi|^2}{(16\pi^2)^2} \, r \, X_{ij}$$

with PMSB to AMSB ratio

$$r \equiv (16\pi^2 M_{pl}/M_*)^2 e^{-M_* L}$$

usually: $r \ll 1$; here: $r \sim 1$

# Sparticle masses in hybrid AMSB-PMSB

- focus on sleptons here
- $(\tilde{\ell}_L, \tilde{\ell}^*_R)$-mass matrix is

$$\mathcal{M}^2_{\tilde{\ell}} \simeq \frac{|m_{3/2}|^2}{(16\pi^2)^2} \begin{pmatrix} -g_L \mathbf{1} + rX^L & 0 \\ 0 & -g_R \mathbf{1} + rX^R \end{pmatrix}$$

where $g_L := \frac{99}{50} g_1^4 + \frac{3}{2} g_2^4$ and $g_R := \frac{198}{25} g_1^4$

- note: elements of $X^{L/R}$ specified by FN model (see next slides...)
  $\rightarrow$ O(1) uncertainty
  $\rightarrow$ can neglect:
  - $F$- and $D$-terms
  - $L - R$ mixing
  - RG effects, in particular those from RH neutrinos

# Alignment

- need to explain both SM and MSSM flavor puzzles
- here: employ a Froggatt-Nielsen model
- FCNCs constrain mass insertion parameters $\delta_{ij}^M \simeq \frac{m^2_{\tilde{\ell}^M_j} - m^2_{\tilde{\ell}^M_i}}{m^2_{\tilde{\ell}}} K_{ij}^M$
  - $m^2_{\tilde{\ell}}$: average slepton mass
    $K_{ij}^M$: coupling of $\tilde{B}^0/\tilde{W}^0$ to $M$-chiral leptons $\ell_i$ and sleptons $\tilde{\ell}_j$
  - in FN models, $(m^2_{\tilde{\ell}^M_j} - m^2_{\tilde{\ell}^M_i})/m^2_{\tilde{\ell}}$ is O(1)
    $\Rightarrow$ offdiag. entries of $K_{ij}^M$ must be supressed! ('alignment')
  - useful relation: $K_{ij}^M \sim \max\{|X_{ij}^M|, |V_{ij}^M|\}$
    ↖ ($V^{R\dagger} Y^T V^L$ is diagonal)

# How much alignment is needed?

- strongest constraint on $|\delta|$'s comes from $\ell_i \to \ell_j \gamma$:

$$\begin{aligned} BR(\mu \to e\gamma) &\leq 1.2 \times 10^{-11} \\ BR(\tau \to e\gamma) &\leq 3.3 \times 10^{-8} \\ BR(\tau \to \mu\gamma) &\leq 4.4 \times 10^{-8} \end{aligned}$$

- theory: [Masina, Savoy; '03]

$$\frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{48\pi^3\alpha}{G_F^2}(|A_L^{ij}|^2 + |A_R^{ij}|^2) \sim 10^{-4}(\tan\beta\,\frac{m_W^2}{\tilde{m}^2})^2\,|\delta_{ij}^L|^2$$

$\Rightarrow$roughly need:

| $i$-$j$ mixing | 1-2 | 1-3 | 2-3 |
|---|---|---|---|
| $\delta_{ij}^L \lesssim$ | $6 \times 10^{-4}$ | 0.08 | 0.10 |

(bounds on $|\delta_{ij}^R|$'s weaker due to possible cancellation in $A_R^{ij}$)

# A $U(1)_p \times U(1)_q$ example cf. [Feng et al.; '08]

flavor charge assignment:

| | $L_1$ | $L_2$ | $L_3$ | $\bar{E}_1$ | $\bar{E}_2$ | $\bar{E}_3$ |
|---|---|---|---|---|---|---|
| $U(1)_p$ | 3 | 1 | 0 | 3 | 2 | 2 |
| $U(1)_q$ | 0 | 2 | 3 | 1 | $-1$ | $-3$ |

[RH neutrinos + Higgs: neutral]

$$Y_e \sim \lambda^2 \begin{pmatrix} \lambda^5 & 0 & 0 \\ \lambda^5 & \lambda^2 & 0 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix}$$

[assume $\lambda_p \sim \lambda_q$ with $\lambda_p \equiv \lambda \sim 0.2$]

$$X^L \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^6 \\ \lambda^4 & 1 & \lambda^2 \\ \lambda^6 & \lambda^2 & 1 \end{pmatrix}, \quad X^R \sim \begin{pmatrix} 1 & \lambda^3 & \lambda^5 \\ \lambda^3 & 1 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix}$$

$$(m_\nu)_{ij} \sim \frac{\langle H_u^0 \rangle^2}{\hat{M}_R} \lambda^6 \quad \forall i,j \qquad \leftarrow \text{through seesaw}$$

comments:

- $m_\nu$ anarchical $\rightarrow$ $\sin\theta_{13}$ accidentally small
- RH neutrino mass scale $\hat{M}_R$ should be $\sim 10^{10}$ GeV for $m_\nu \sim 0.1$ eV
  $\rightarrow$ OK with leptogenesis

# ... and one with stronger alignment

- above example has minimal amount of alignment (in 1-2 mixing): $\mu \to e\gamma$ could be around the corner
- is stronger alignment possible?
- there is in fact a lower bound on the $\delta^L$'s, nevertheless it is possible to have precise enough alignment that no signals would be seen even in planned future rare decay measurements:

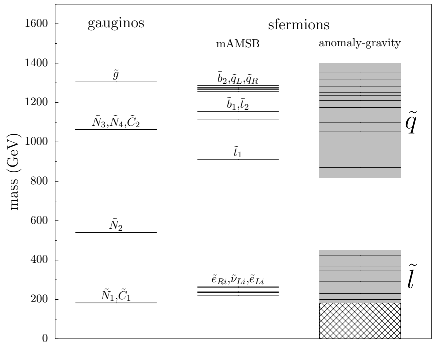
| | $L_1$ | $L_2$ | $L_3$ | $\bar{E}_1$ | $\bar{E}_2$ | $\bar{E}_3$ |
|---|---|---|---|---|---|---|
| $U(1)_p$ | 5 | 2 | 0 | 1 | 1 | 1 |
| $U(1)_q$ | 0 | 3 | 5 | 1 | $-2$ | $-4$ |

$$Y_e \sim \lambda^2 \begin{pmatrix} \lambda^5 & 0 & 0 \\ 0 & \lambda^2 & 0 \\ \lambda^5 & 0 & 1 \end{pmatrix}$$

$$X^L \sim \begin{pmatrix} 1 & \lambda^{10} & \lambda^6 \\ \lambda^{10} & 1 & \lambda^4 \\ \lambda^6 & \lambda^4 & 1 \end{pmatrix}, \quad X^R \sim \begin{pmatrix} 1 & \lambda^{11} & \lambda^5 \\ \lambda^{11} & 1 & \lambda^6 \\ \lambda^5 & \lambda^6 & 1 \end{pmatrix}$$

$$(m_\nu)_{ij} \sim \frac{\langle H_u^0 \rangle^2}{\hat{M}_R} \lambda^{10} \quad \forall i, j$$

# Sample spectrum ...




$\tan\beta = 5$, $m_{3/2} = 60$ TeV, $\mu > 0$

2nd column: mAMSB sfermion spectrum with universal scalar mass uplift $m_0 = 350$ GeV

features:

1) gaugino spectrum as in pure AMSB
(at least assuming that ~~SUSY~~ field $S$ is not gauge singlet)
2) O(1) slepton mass splitting
3) O(10 %) squark mass splitting (assuming squark flavor is also due to FN)

# ... and its signatures:

1) soft pion in $\tilde{C}_1^\pm \to \tilde{N}_1 \pi^\pm$ decays cf. [Gherghetta, Giudice, Wells; '99]

2) same-flavor dilepton edge measurements with missing energy in $\tilde{N}_2 \to \ell_i \tilde{\ell}_i^*, \bar{\ell}_i \tilde{\ell}_i \to \bar{\ell}_i \ell_i \tilde{N}_1$ cascades:

$$m^2_{\bar{\ell}_i \ell_i, max} = \frac{(m^2_{\tilde{N}_2} - m^2_{\tilde{\ell}_i})(m^2_{\tilde{\ell}_i} - m^2_{\tilde{N}_1})}{m^2_{\tilde{\ell}}}$$

$\Rightarrow$ expect multi edge structure from $\tilde{\ell}_i^R$ and $\tilde{\ell}_i^L$ exchanges, both for dielectron and dimuon final states
($\tilde{e}$-$\tilde{\mu}$ mass splitting from comparing $m^2_{\bar{e}e}$ and $m^2_{\bar{\mu}\mu}$ edges cf. the mSUGRA study [Allanach, Conlon, Lester; '08])

3) $D$-$\bar{D}$ mixing close to exp. limit cf. [Feng et al.; '08]
reason: SU(2) symmetry implies

$$|\delta^u_{L12} - \underset{\substack{\uparrow \\ \lesssim 10^{-3} \text{ from } K\text{-}\bar{K}}}{\delta^d_{L12}}| \gtrsim \sin\theta_c \, (m^2_{\tilde{q}^L_2} - m^2_{\tilde{q}^L_1})/m^2_{\tilde{q}}$$

# Conclusions

- ★ a simple way to avoid the tachyonic slepton problem of AMSB is to suppress gravity mediation not completely, but only so much that it still gives a comparable contribution
- ★ the heavy gravitino is beneficial for cosmology
- ★ the SM and SUSY flavor puzzles are solved by a FN symmetry
- ★ characteristic signatures, due to
  - AMSB pattern of gaugino masses
  - $\mathcal{O}(1)$ slepton mass splitting
  - $\mathcal{O}(10\%)$ squark mass squared splittings

outlook:

- model-building: $\mu$-term? Stabilization of brane distance ...
- phenomenology: prospects of measuring large slepton mass splittings at the LHC?