Hidden Sectors at a GeV

arXiv:0904.2567 [hep-ph]

(with D. Morrissey and K. Zurek)

David Poland

Harvard University

SUSY Breaking '09, 4/21/09

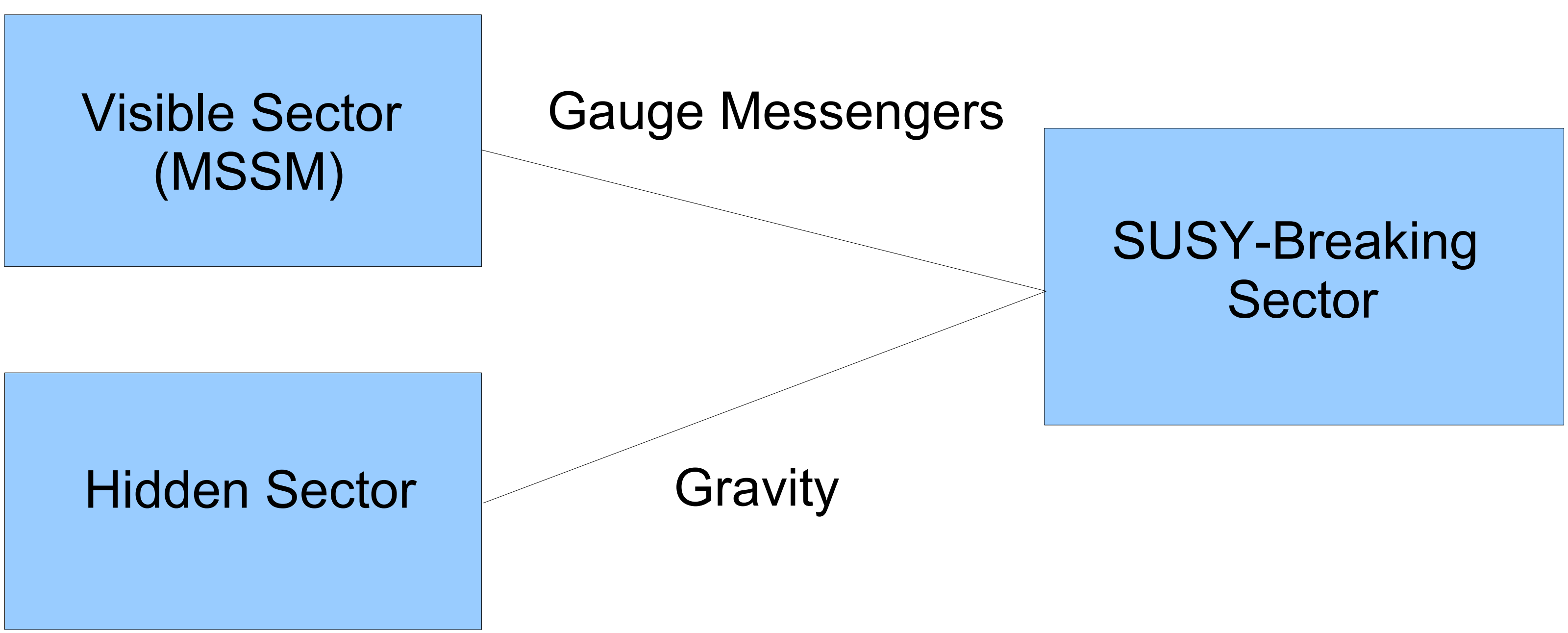
Supersymmetry and Gauge Mediation

- Weak-scale supersymmetry (with R-parity) is an elegant proposal for BSM physics
  - Stabilizes the hierarchy and makes radiative corrections to the Higgs mass calculable and small
  - Gauge coupling unification
  - Possible dark matter candidates
  - Exciting LHC phenomenology
- However, it leads to a new puzzle:
  - Why are SUSY-breaking masses flavor blind?

This motivates mediating SUSY-breaking through gauge interactions, or *gauge/gaugino mediation*

Light Hidden Sectors

- States uncharged under the “messenger” gauge group are generically *lighter* than the visible sector.
- Without additional interactions, hidden-sector mass scales will be set by the gravitino mass $m_{3/2} \sim F / M_{pl}$



GeV Hidden Sectors

- If HS contains a $U(1)_x$, there can be kinetic mixing with hypercharge:

$$\int d^2\theta \frac{\epsilon}{2} B^{\alpha} X_{\alpha}$$

- This is induced through RGE running if there are (heavy) fields charged under both $U(1)_x$ and $U(1)_Y$:

$$\Delta\epsilon(\mu) \simeq \frac{g_x(\mu)\, g_Y(\mu)}{16\pi^2} \sum_i x_i Y_i \ln\left(\frac{\Lambda^2}{\mu^2}\right) \sim \left(10^{-2} - 10^{-4}\right)$$

GeV Hidden Sectors

- If HS contains a $U(1)_x$, there can be kinetic mixing with hypercharge: $$\int d^2\theta \frac{\epsilon}{2} B^\alpha X_\alpha$$
- This is induced through RGE running if there are (heavy) fields charged under both $U(1)_x$ and $U(1)_Y$: $$\Delta\epsilon(\mu) \simeq \frac{g_x(\mu)\, g_Y(\mu)}{16\pi^2} \sum_i x_i Y_i \ln\left(\frac{\Lambda^2}{\mu^2}\right) \sim \left(10^{-2} - 10^{-4}\right)$$
- This then shifts the $U(1)_x$ D-term potential by ξ_Y, inducing hidden-sector masses and VEVs at the GeV scale:

[Baumgart, et al '09], [Cui, Morrissey, DP, Randall '09]

$$V_x = \frac{g_x^2}{2}\left(x_H |H|^2 - \frac{\epsilon}{g_x}\xi_Y\right)^2 \quad \Longrightarrow \quad \langle H \rangle \simeq \sqrt{\frac{\epsilon\, \xi_Y}{x_H\, g_x}}$$

Dark Motivations

- Hidden sectors at a GeV have independent motivation from dark matter: [Arkani-Hamed, Finkbeiner, Slatyer, Weiner + many others]
  - If weak-scale dark matter is charged under $U(1)_x$, it can annihilate to GeV-scale gauge bosons
    - Annihilation is Sommerfeld-enhanced
    - Primarily decay to leptons due to kinematics

  ⇒ Can potentially explain PAMELA and/or ATIC

  - Can give light elastic DM or induce inelastic splittings in a heavy DM multiplet of order ~100 keV

  ⇒ Can potentially explain DAMA

Our Primary Goal

What are the simplest *viable* Abelian hidden sectors in the context of gauge (and gaugino) mediation?

Little Gauge Mediation

- What does kinetic mixing do in gauge mediation?
  - Start in holomorphic basis, use analytic continuation:

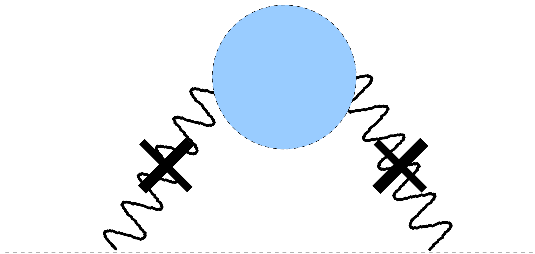
$$\int d^2\theta \left[\frac{1}{4 g_Y^2(\mu, M)} B^\alpha B_\alpha + \frac{1}{4 g_x^2(\mu)} X^\alpha X_\alpha + \frac{\epsilon_h}{2} B^\alpha X_\alpha \right] + h.c.$$

  - Running one-loop exact (and ϵ_h doesn't run without BFs)
  - Only g_Y depends on messenger threshold M, which is promoted to a chiral superfield $X = M + \theta^2 F$

$$\boxed{M_{gaugino} = \begin{pmatrix} M_1 & 0 \\ 0 & 0 \end{pmatrix}}$$

(up to terms suppressed as ~ $\epsilon_h^2/(16\pi)^3 F/M$)

Little Gauge Mediation



- What about the scalar masses?

$$\int d^4\theta \left[Z_i(\mu, M)\, \phi_i^\dagger e^{x_i V_X} \phi_i \right]$$

$$\frac{d \ln Z_i}{d t} \simeq \frac{x_i^2}{4\pi^2} \left[g_x^2(\mu) + \epsilon_h^2 g_Y^2(\mu, M)\, g_x^4(\mu) + \ldots \right]$$

$$\Rightarrow \quad \left. \frac{d^2 \ln Z_i}{d M^2} \right|_{\mu=M} \simeq \epsilon_h^2 x_i^2 g_x^4(M) \left. \frac{d^2 \ln Z_{E^c}}{d M^2} \right|_{\mu=M}$$

$$\Rightarrow \quad \boxed{m_i^2(M) \simeq \epsilon_h^2 x_i^2 g_x^4(M)\, m_{E^c}^2(M)}$$

- Scalar masses are suppressed by a factor of $\sqrt{\epsilon}$ relative to D-term contribution!

RGE Effects

- These are important because they often will give the dominant contribution to $U(1)_R$-breaking in the HS
  - B-terms and A-terms generated from visible-sector gaugino mass at order $\epsilon^2 M_1$:

$$(4\pi)^2 \frac{d}{dt} b^{ij} = -\epsilon^2 M^{ij} \left[4 (x_i^2 + x_j^2) g_x^2 M_1 \right] + \ldots$$

$$(4\pi)^2 \frac{d}{dt} a^{ijk} = -\epsilon^2 y^{ijk} \left[4 (x_i^2 + x_j^2 + x_k^2) g_x^2 M_1 \right] + \ldots$$

  - Scalar masses also get O(1) correction

- $U(1)_R$-breaking parameters suppressed by a factor of ϵ relative to scalar masses!

First Model Attempt...

- Vector-like pair of fields {H,H^c} charged under U(1)$_x$

$$W = \mu' H H^c$$

(To leading order in ϵ, we can ignore soft terms...)

$$V = |\mu'|^2 \left(|H|^2 + |H^c|^2 \right) + \frac{g_x^2}{2} \left(x_H |H|^2 - x_H |H^c|^2 - \xi \right)^2$$

$$\langle H \rangle = \sqrt{\frac{\xi}{x_H} - \frac{|\mu'|^2}{(x_H g_x)^2}}$$

$$\langle H^c \rangle = 0$$

$$\xi = -\frac{\epsilon}{2} \frac{g_Y}{g_x} c_{2\beta} v^2$$

First Model Attempt...

- The VEV breaks the gauge group and leads to the fermion masses:

$$M^f = \begin{pmatrix} 0 & 0 & m_{Z_x} \\ 0 & 0 & \mu' \\ m_{Z_x} & \mu' & 0 \end{pmatrix} \Rightarrow \boxed{\begin{aligned} M^f_{2,3} &= \sqrt{m^2_{Z_x} + |\mu'|^2} \\ M^f_1 &= 0 \end{aligned}}$$

First Model Attempt...

- The VEV breaks the gauge group and leads to the fermion masses:

$$M^f = \begin{pmatrix} 0 & 0 & m_{Z_x} \\ 0 & 0 & \mu' \\ m_{Z_x} & \mu' & 0 \end{pmatrix} \Rightarrow \boxed{\begin{array}{l} M^f_{2,3} = \sqrt{m^2_{Z_x} + |\mu'|^2} \\ M^f_1 = 0 \end{array}}$$

- Neglecting subleading $U(1)_R$-breaking terms, there is a massless "Goldstino" state!
  - Mass gets lifted to: $M^f_1 \sim \dfrac{B\mu'}{\mu'} \sim \epsilon^2 g^2_x M_1$
  - This state is problematic...
    - No efficient annihilation channels
    - Stable (< $m_{3/2}$) or *very* long-lived (> $m_{3/2}$)
- A possible fix is to go to the (incalculable) regime $m_{3/2}$~GeV

Hidden NMSSM

- Add a singlet S into the hidden sector

$$W = \lambda S H H^c$$

(To leading order in ϵ, we can ignore soft terms...)

$$V = |\lambda|^2 |H|^2 \left(|H^c|^2 + |S|^2\right) + |\lambda|^2 |H^c|^2 |S|^2 + \frac{g_x^2}{2}\left(x_H |H|^2 - x_H |H^c|^2 - \xi\right)^2$$

$$\xi = -\frac{\epsilon}{2}\frac{g_Y}{g_x} c_{2\beta} v^2$$

$$\langle H \rangle = \sqrt{\frac{\xi}{x_H}}, \ \langle H^c \rangle = \langle S \rangle = 0$$

Hidden NMSSM

- Only H gets a VEV, leading to a vacuum that *preserves supersymmetry* at leading order
  - $W = \lambda \langle H \rangle S H^c$ gives a supersymmetric mass to {S,H^c}
  - V_x and H combine to form massive vector multiplet

    ⇨ No light states!
  - LHP is either S scalar ($m_S^2 < 0$) or gauge-sector fermion

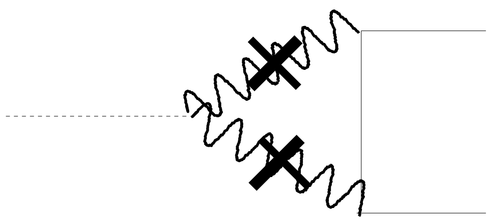
- However, there are still some dangers!
  - LHP could decay to gravitino+photon after BBN
  - If (meta)stable, still need efficient annihilation channel
- We can organize according to $m_{3/2}$...

Hidden NMSSM with $m_{3/2} << m_{LHP}$

- If the (stable) S scalar is lightest
  - No efficient annihilation channels
  - Only viable if higher dim operators allow decays

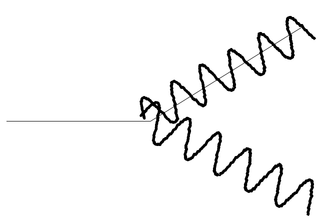
Hidden NMSSM with $m_{3/2} << m_{LHP}$

- If the (stable) S scalar is lightest
  - No efficient annihilation channels
  - Only viable if higher dim operators allow decays
- If the gauge sector is lightest [Cheung,Ruderman,Wang,Yavin '09]
  - S scalar annihilates to H scalar, which decays as:



$$\tau_{h\to ee} \sim \left(1\times 10^{-4}\, s\right)\left(\frac{0.1}{g_x x_H}\right)^2\left(\frac{GeV}{m_h}\right)\left(\frac{10^{-3}}{\epsilon}\right)^4$$

  - Fermion decays to gravitino+photon with lifetime:



$$\tau_{f\to\gamma\tilde{g}} \sim \left(3\times 10^{3}\, s\right)\left(\frac{\sqrt{\langle F\rangle}}{100\, TeV}\right)^4\left(\frac{GeV}{m_x}\right)^5\left(\frac{10^{-3}}{\epsilon}\right)^2$$

Messes up BBN unless F is very low!

Hidden NMSSM with $m_{3/2} \sim m_{LHP}$

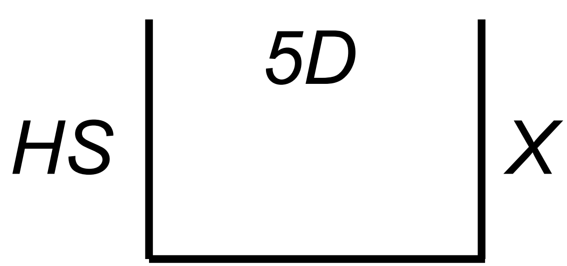
- We could attempt to avoid this problem by pushing the gravitino mass close to the fermion mass
- Generically, gravity effects make this incalculable
- Also, adding $U(1)_R$ breaking tends to push $M_f < M_{Zx}$, so it is easy to lose phase space for annihilation

Hidden NMSSM with $m_{3/2} \sim m_{LHP}$

- We could attempt to avoid this problem by pushing the gravitino mass close to the fermion mass
- Generically, gravity effects make this incalculable
- Also, adding $U(1)_R$ breaking tends to push $M_f < M_{Zx}$, so it is easy to lose phase space for annihilation

Both of these problems are absent if generic M_{pl}-suppressed operators are *sequestered*

[Randall, Sundrum '99]



Hidden NMSSM with *Sequestering*

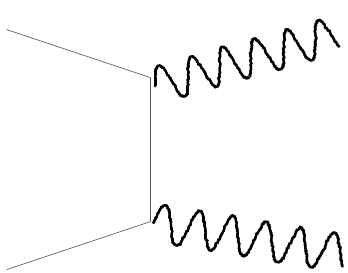
- In this case hidden-sector parameters receive contributions from anomaly mediation:

$$\Delta m_{hid} \sim M_x \sim \frac{g_x^2 m_{3/2}}{(4\pi)^2}$$

- With $m_{3/2} \sim m_{hid}$, the spectrum is only slightly perturbed
  - Still only H gets a VEV, gauge fermion mass becomes

$$M^f = \begin{pmatrix} M_x & m_{Z_x} \\ m_{Z_x} & 0 \end{pmatrix} \quad \Longrightarrow \quad M_1^f \sim m_{Z_x} - \frac{1}{2} M_x$$

  - Mass splitting is smaller than temperature at thermal freeze-out, allowing annihilation to gauge bosons:



$$\langle \sigma v \rangle \sim \left(7 \times 10^{-24}\, cm^3/s\right) \left(\frac{g_x x_H}{0.1}\right)^4 \left(\frac{GeV}{m_{Z_x}}\right)^2 \left(\frac{v_{f.o.}}{0.3}\right)$$

Hidden NMSSM with *Sequestering*

- To summarize...
  - Before gravity effects, the LHP is either the gauge fermion or singlet scalar
  - If the singlet is lightest, it has no efficient annihilation channels and is not viable without higher dim ops
  - If the fermion is lightest, decays to gravitino+photon are problematic for BBN unless F is very low
  - Making $m_{3/2} \sim m_{hid}$ forbids this decay, and sequestering gravity effects allows the fermion to efficiently annihilate

- Note that if the scalar *can* decay through higher dim ops, one can also go to the regime $m_{3/2} \sim 100\, GeV$ [Katz, Sundrum '09]
  - Easy to add weak-scale DM to this scenario

A few words on DAMA...

- Annual modulation seen in NaI detectors at 8σ
- Light (few GeV) elastic dark matter scattering possible, though constrained by spectral shape
- Heavy (100's of GeV) inelastic dark matter with ~ 100 keV mass splitting possible, but we run into a couple problems:
  - Heavier state too long-lived if decays occur through kinetic mixing $\Rightarrow$ problematic down-scattering
    - One possible solution is to charge the DM state under SU(2) as well as $U(1)_x$
  - Scattering cross section a bit too large if we assume FI term generated through visible Higgs VEVs
    - May work if ξ_Y has additional contributions

Closing Thoughts

- Light hidden sectors are generic in gauge mediation
- Simple U(1) HS models often have problems with overabundance or BBN constraints
- These can be avoided either by:
  - Allowing for fast LHP decays (low F or higher dim ops)
  - Forbidding the LHP decay in a way that preserves an annihilation channel (larger $m_{3/2}$ + seq)
- These hidden sectors are perhaps the simplest examples of hidden valleys [Strassler]
  - Lots of fun collider phenomenology!
- We should have an open mind
  - Many things that may generically occur in BSM physics may not be relevant to existing problems

Singlet Mediation

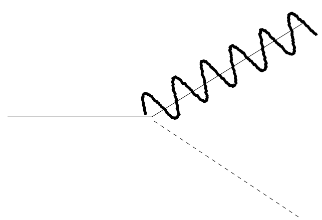
- So far $U(1)_x$ breaking has been driven by kinetic mixing...
- Another possibility is to let a singlet couple more directly to SUSY breaking and (somewhat) weakly to the HS
  - Take $W = \lambda S H H^c$ as before, but suppose $m_S^2 \sim (100\,GeV)^2$
  - RGE running induces *negative* soft masses for H and H^c

$$m_H^2 = m_{H^c}^2 \simeq -\frac{\lambda^2}{8\pi^2} m_S^2 \ln\left(\frac{\Lambda}{m_{hid}}\right) \Longrightarrow \langle H \rangle^2 \simeq \langle H^c \rangle^2 \simeq -\frac{m_H^2}{\lambda^2}$$

  - This spontaneously breaks both $U(1)_R$ and $U(1)_{PQ}$
    - Massless axion in spectrum, lifted by explicit breaking from $W \supset \kappa S^3$ and $A_{\lambda,\kappa}$
  - Axion can decay through a small coupling $W \supset \zeta S H_u H_d$

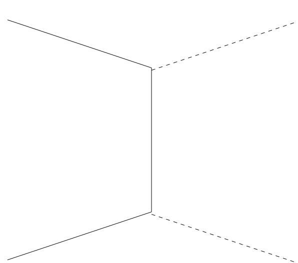
Singlet Mediation

- If $m_{3/2} << m_{hid}$
  - Lightest fermion can decay to axion+gravitino



$$\tau_{f\to a\tilde{g}} \sim (3\times 10^{-3}\, s)\left(\frac{\sqrt{\langle F\rangle}}{100\,TeV}\right)^4\left(\frac{GeV}{m_x}\right)^5\frac{1}{|P_{f\tilde{a}}|^2}$$

  - Viable for somewhat low F
- If $m_{3/2} > m_{hid}$ (and spectrum isn't *too* perturbed)
  - Lightest fermion now stable (due to R-parity), and can efficiently annihilate to axions



$$\langle \sigma v\rangle \sim \left(1\times 10^{-23}\, cm^3/s\right)\left(\frac{\lambda}{0.1}\right)^4\left(\frac{3\,GeV}{m_{hid}}\right)^2$$