DARK MATTER MEETS THE SUSY FLAVOR PROBLEM

Work with
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DARK MATTER

- Best evidence for new physics
  - Unambiguous
  - Intimately connected to central problems: electroweak symmetry breaking and structure formation

- Candidate masses and interactions span many orders of magnitude
THE WIMP MIRACLE

• Assume a new (heavy) particle $X$ is initially in thermal equilibrium

• Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

• $m_X \sim m_{\text{weak}} \sim 100 \text{ GeV} \quad g_X \sim g_{\text{weak}} \sim 0.6 \quad \{ \Omega_X \sim 0.1 \}$

• Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter
NEUTRALINO DARK MATTER

- Supersymmetry
  - Naturalness
  - Force unification
  - Radiative EWSB

- Neutralino naturally emerges as
  - Lightest (stable)
  - Weakly-interacting
  - ~100 GeV
  - Excellent DM candidate
Neutralinos must interact with the SM efficiently

Neutralinos

Efficient annihilation now
(Indirect detection)

Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)
NEUTRALINO IMPLICATIONS

Neutralinos must interact with the SM efficiently

EXCITING!
BACKGROUND CHECK: SKELETONS IN THE CLOSET

- Minor skeleton: thermal relic density

Majorana $\rightarrow$ P-wave suppressed

GUT/RGE $\rightarrow$ Bino suppressed

Feng, Matchev, Wilczek (2003)

Yellow: Before 2003
Red: After 2003

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MAJOR SKELETON: 
THE FLAVOR PROBLEM

• Neutralino DM $\Rightarrow m_{\tilde{G}} > m_{\chi}$

• $m_{\tilde{G}}$ characterizes the size of gravitational effects, which generically violate flavor symmetries

• Current bounds require $m_{\tilde{G}} < 0.01 m_{\chi}$

• There are ways to reconcile $\chi$ DM with flavor constraints, but none is especially compelling
There are well-known SUSY models that naturally conserve flavor: gauge-mediated SUSY-breaking models

Dine, Nelson, Nir, Shirman (1995); Dimopoulos, Dine, Raby, Thomas (1996); …

Can we find DM candidates in these models?

3 key features

- \( m_{\tilde{G}} \ll m_\chi \)
- Several sectors of particles
- Superpartner masses \( m \sim (\text{gauge couplings})^2 \)
Thermal gravitinos: the original SUSY DM scenario

Pagels, Primack (1982)

- Universe cools from $T \sim M_{Pl}$, gravitinos decouple while relativistic, expect $n_{\tilde{G}} \sim n_{eq}$ (cf. neutrinos)

- $\Omega_{\tilde{G}} h^2 \approx 0.1 \left( m_{\tilde{G}} / 80 \text{ eV} \right)$

- Lyman-\(\alpha\) constraints $\Rightarrow m_{\tilde{G}} > 2 \text{ keV}$
  Viel et al. (2006); Seljak et al. (2006)

- Could be saved by late entropy production
  Baltz, Murayama (2001)

- No use of WIMP miracle
PREVIOUS SUGGESTIONS 2

Messenger sneutrino DM

- Messenger sneutrino has right relic density for $m \sim 1-3$ TeV
- No use of WIMP miracle

Han, Hempfling (1997)
Goldilocks SUSY

Feng, Smith, Takayama, (2007)

- Eliminate both skeletons simultaneously: \( \chi \) overproduced, decays to gravitino that is light enough to solve the flavor problem, but heavy enough to be all of DM

- \( \Omega_\chi \sim m_\chi^2, \Omega_\tilde{G} \sim m_\chi m_\tilde{G} \); flavor \( \Rightarrow m_\tilde{G} / m_\chi < 0.01 \)

- Solution guaranteed for sufficiently large \( m_\chi, m_\tilde{G} \)

- But is it natural? Consider mGMSB
GOLDILOCKS SUSY

- $\Omega_\chi \sim 100$, $m_\chi \sim 1$ TeV, $m_{\tilde{G}} \sim 1$ GeV
- Uses the WIMP miracle
- Astrophysics constraints $\rightarrow$ CP solved, warm $\tilde{G}$ DM
A NEW APPROACH

- Consider standard GMSB with one or more hidden sectors
- Each hidden sector has its own matter content, gauge groups, couplings
THE WIMPLESS MIRACLE

• Particle Physics

\[ W = \lambda \Phi S \Phi + \lambda_X \bar{\Phi}_X S \Phi_X \]
\[ \langle S \rangle = M + \theta^2 F \]
\[ m \sim \frac{g^2}{16\pi^2} \frac{F}{M} \]

Superpartner masses depend on gauge couplings

• Cosmology

\[ \frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \]
\[ \Omega_X \sim \Omega_{\text{WIMP}} \sim \Omega_{\text{DM}} \]

\( \Omega \) depends only on the SUSY Breaking sector:

Hidden sector generically has the right relic density
THE WIMPLESS MIRACLE

• The thermal relic density constrains only one combination of $g_X$ and $m_X$

$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$

• These models map out the remaining degree of freedom

• This framework decouples the WIMP miracle from WIMPs, candidates have a range of masses/couplings, but always the right relic density

• The flavor problem becomes a virtue

• Naturally accommodates multi-component DM, all with relevant $\Omega$
HOW LARGE CAN HIDDEN SECTORS BE?

- Hidden sectors contribute to expansion rate

- BBN: $N_\nu = 3.24 \pm 1.2$, excludes an identical copy of the MSSM
  
  Cyburt et al. (2004)

- But this is sensitive to temperature differences

\[ g^h_\nu \left( \frac{T^h_{BBN}}{T_{BBN}} \right)^4 = \frac{7}{8} \cdot 2 \cdot (N_{\text{eff}} - 3) \leq 2.52 \text{ (95\% CL)} \]
• WIMPless DM has no SM gauge interactions, but may interact through Yukawa couplings

• For example, introduce connectors Y with both MSSM and hidden charge

• Y particles mediate both annihilation to and scattering with MSSM particles

Feng, Kumar, Strigari (2008); Feng, Kumar, Learned, Strigari (2008)
EXAMPLE

• Assume WIMPless DM $X$ is a scalar, add fermion connectors $Y$, interacting through

\[ \mathcal{L} = \lambda_f X \bar{Y}_L f_L + \lambda_f X \bar{Y}_R f_R \]

• $XX \rightarrow ff$ preserves WIMPless miracle, as long as $\lambda_f < 1$

• For $f = b$, $Y$’s are “4th generation mirror quarks,” constrained by collider direct searches, precision electroweak, Yukawa perturbativity:

\[ 250 \text{ GeV} < m_Y < 500 \text{ GeV} \]

Kribs, Plehn, Spannowsky, Tait (2007); Fok, Kribs (2008)
Collision rate should change as Earth’s velocity adds constructively/destructively with the Sun’s.

Drukier, Freese, Spergel (1986)

DAMA: $8\sigma$ signal with $T \sim 1$ year, max $\sim$ June 2
CHANNELING

- DAMA’s result is puzzling, in part because the favored region was considered excluded by others.

- This may be ameliorated by astrophysics and channeling: in crystalline detectors, efficiency for nuclear recoil energy → photons depends on direction.

- Channeling reduces threshold, shifts allowed region to lower masses. Consistency possible, but requires uncomfortably low WIMP masses (~ GeV).

Gondolo, Gelmini (2005)

DAMA AND WIMPLESS DM

- WIMPless DM naturally explains DAMA with $\lambda_b \sim 0.3-1$ (cf. typical neutralino: $m \sim 100$ GeV, $\sigma_{SI} \sim 10^{-8}$ pb)
INDIRECT DETECTION

• Indirect searches also promising for low masses, even for smooth halos
HIDDEN CHARGED DM

- This requires that an $m_X$ particle be stable. Is this natural?

<table>
<thead>
<tr>
<th>MSSM</th>
<th>Flavor-free MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_w$ sparticles, $W$, $Z$, $t$</td>
<td>$m_X$ sparticles, $W$, $Z$, $q$, $l$, $\tilde{t}$ (or $\tau$)</td>
</tr>
<tr>
<td>$\sim$GeV $q$, $l$</td>
<td></td>
</tr>
<tr>
<td>0 $p$, $e$, $\gamma$, $\nu$, $\tilde{G}$</td>
<td>0 $g$, $\gamma$, $\nu$, $\tilde{G}$</td>
</tr>
</tbody>
</table>

- If the hidden sector is a flavor-free MSSM, natural DM candidate is any hidden charged particle, stabilized by exact $U(1)_{EM}$ symmetry
HIDDEN CHARGED DM

- Hidden charged particles exchange energy through Rutherford scattering

- Non-spherical galaxy cores → DM can’t be too collisional, require $E/(dE/dt) > 10^{10}$ years

- Annihilates through weak (to neutrinos) and EM (to photons)

- $m_X \sim 10$ GeV ($100$ MeV) allowed for $\tan \theta = 1$ (10)

See also Ackerman, Buckley, Carroll, Kamionkowski (2008)
ANNIHILATION

- Annihilation is Sommerfeld enhanced by $\alpha/v$

- Strong constraint from protohaloes, formed at $z \sim 200$ with low velocity dispersion
  
  Kamionkowski, Profumo (2008)

- Can $m_\gamma = 0$? Yes!
  - $T_{kd}$ is lower than for WIMPs
  - $\alpha \sim 10^{-6}$ for $m_X \sim \text{GeV}$

\[ M_c \simeq 33 \left( \frac{T_{kd}}{10 \text{ MeV}} \right)^{-3} M_\oplus \]

\[ (v/c) \sim 6.0 \times 10^{-9} \left( \frac{M_c}{M_\oplus} \right)^{1/3} \left( \frac{z_c}{200} \right)^{1/2} \]
CONCLUSIONS

• Neutralino DM has a flavor problem

• Reconciliation $\Rightarrow$ qualitatively new DM candidates

• WIMPless dark matter
  – No flavor problem (GMSB)
  – Preserves WIMP miracle
  – Large direct, indirect signals
  – Explains DAMA, with testable implications
  – Motivates hidden charged DM with exact hidden $U(1)_{EM}$
  – Collisional, implications for structure formation