Prospects for WIMP and axion detection in SUSY with radiatively-driven naturalness

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Lots of problems with SM

- nu mass
- gauge hierarchy, why m(h) so small
- strong CP: why 3 not 4 light pions from QCD?
- dark matter?
- dark energy?
- baryogenesis?

SUSY either solves or improves all of these and is supported by data: gauge couplings, mt, mh
But where is SUSY

- LHC: \( m(\text{gluino}) > 2 \text{ TeV} \)
- LHC: \( m(t_1) > 1 \text{ TeV} \)
- \( m(h) \sim 125 \text{ GeV} \)
- compare: Barbieri-Giudice naturalness: \( m(\text{gluino}) < 350 \text{ GeV} \)
- LHC limits way beyond naturalness bounds
- is SUSY unnatural? Is SUSY dead?
No

- BG naturalness computed in multi-parameter effective theories

- In more fundamental theories (e.g. SUGRA/string) all soft terms inter-dependent: computed as multiples of more fundamental gravitino mass $m(3/2)$

- Then large cancellations in fine-tuning computation (e.g. focus point SUSY, but now via all soft terms)

- More conservative measure which allows for cancellations: $\Delta_{EW}$
\[ m_Z^2/2 = \frac{m_{Hd}^2 + \Sigma_d - (m_{Hu}^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \sim -m_{Hu}^2 - \Sigma_u - \mu^2 \]

naturalness: no large unnatural cancellations on RHS

then:

- \( \mu \sim 100 - 200 \) GeV
- \( m_{Hu}^2 \) can be driven to natural via large top Yukawa
- radiative corrections not too large

naturalness: only higgsinos need be \( \sim 100-200 \) GeV

higgsino is LSP

higgsino-like WIMP\( \sim 100-200 \) GeV thermally underproduced as DM

HB, Barger, Huang, Mustafayev, Tata, PRL109 (2012)161802
radiative corrections drive $m_{H_u}^2$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness

Evolution of the soft SUSY breaking mass squared term $\text{sign}(m_{H_u}^2)\sqrt{|m_{H_u}^2|}$ vs. $Q$
SUSY mu problem: mu term is SUSY, not SUSY breaking: expect $\mu \sim M(\text{Pl})$ but phenomenology requires $\mu \sim m(Z)$

- NMSSM: $\mu \sim m(3/2)$; beware singlets!
- Giudice-Masiero: $\mu$ forbidden by some symmetry: generate via Higgs coupling to hidden sector
- Kim-Nilles: invoke SUSY version of DFSZ axion solution to strong CP:
  
  - KN: PQ symmetry forbids $\mu$ term, but then it is generated via PQ breaking

Little Hierarchy due to mismatch between PQ breaking and SUSY breaking scales?

Higgs mass tells us where to look for axion!

\[
\begin{align*}
W & \ni \lambda \phi_{PQ}^2 H_u H_d / M_P \\
\mu & \sim \lambda f_a / M_P \\
m_{3/2} & \sim m_{hid}^2 / M_P \\
f_a & \ll m_{hid}
\end{align*}
\]

\[
m_a \sim 6.2 \mu eV \left( \frac{10^{12} \text{ GeV}}{f_a} \right)
\]
<table>
<thead>
<tr>
<th>bounds from naturalness (3%)</th>
<th>old BG/DG</th>
<th>Delta_EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu</td>
<td>350 GeV</td>
<td>350 GeV</td>
</tr>
<tr>
<td>gluino</td>
<td>400-600 GeV</td>
<td>5000 GeV</td>
</tr>
<tr>
<td>t1</td>
<td>450 GeV</td>
<td>3000 GeV</td>
</tr>
<tr>
<td>sq/sl</td>
<td>550-700 GeV</td>
<td>10-20 TeV</td>
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</tbody>
</table>

h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis!
There is a Little Hierarchy, but it is no problem

\[ \mu \ll m_{3/2} \]
Mainly higgsino-like WIMPs thermally underproduce DM

\[ \Omega^T P h^2 \sim 10 - 15 \text{ too low!} \]

but axion may constitute bulk of DM
mixed axion-neutralino production in early universe

- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, $s$ or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \rightarrow aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \rightarrow gg$: entropy dilution
  - $s \rightarrow SUSY$: augment neutralinos
  - $s \rightarrow aa$: dark radiation ($\Delta N_{\text{eff}} < 1.6$)
- axinos: TP
  - $\tilde{a} \rightarrow SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

to calculate: solve 8 coupled Boltzmann equation

Bae, HB, Serce
usual picture  =>  mixed axion/WIMP

much of parameter space is axion-dominated with 10-15% WIMPs
=>
mainly axion CDM for $f_a \sim 10^{12}$ GeV; for higher $f_a$, then get increasing wimp abundance

higgsino abundance

axion abundance
Direct higgsino detection rescaled for minimal local abundance \( \xi \equiv \Omega_{\chi}^{TP} h^2 / 0.12 \)

Can test completely with ton scale detector or equivalent (subject to minor caveats)

Bae, HB, Barger, Savoy, Serce

\[ \mathcal{L} \supset -X_{11}^{h} \overline{Z}_1 \tilde{Z}_1 h \]

\[ X_{11}^{h} = \frac{1}{2} \left( v_2^{(1)} \sin \alpha - v_1^{(1)} \cos \alpha \right) \left( gv_3^{(1)} - g'v_4^{(1)} \right) \]

Xe-1-ton now operating!

natural SUSY

Can test completely with ton scale detector or equivalent (subject to minor caveats)
Prospects for SD WIMP searches:
Prospects for IDD WIMP searches:

suppressed by square of diminished WIMP abundance
SUSY DFSZ axion: large range in $m(a)$ but coupling reduced may need to probe broader and deeper!
• Solve gauge hierarchy (SUSY)

• Solve strong CP (axion)

• Solve SUSY mu problem (SUSY DFSZ axion)

• Allow/generate Little Hierarchy \([\mu \ll m(\text{soft})]\]

• Expect mixed higgsino/(SUSY) DFSZ axion DM

• natural higgsino LSP should be covered by n-ton scale DD search

• \(m(a)\) for SUSY DFSZ axion spread across vast range

• \(a\)-gamma-gamma coupling reduced compared to non-SUSY DFSZ

• Deeper and broader probes in axion p-space are required/encouraged

• natural SUSY: maybe see at HL-LHC but may need HE-LHC (gl/t1)

• ILC500 is ideal for light higgsinos
How much is too much fine-tuning?

Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

higgsinos should be accessible to ILC!
Little Hierarchy from radiative PQ breaking? exhibited within context of MSY model

Murayama, Suzuki, Yanagida (1992); Gherghetta, Kane (1995); Choi, Chun, Kim (1996)

Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

\[ f' = \frac{1}{2} h_{ij} \hat{X} \hat{N}_i^{\text{c}} \hat{N}_j^{\text{c}} + \frac{f}{M_P} \hat{X}^3 \hat{Y} + \frac{g}{M_P} \hat{X} \hat{Y} \hat{H}_u \hat{H}_d. \]

\[ M_{N_i} = v_X h_i|_{Q=v_X} \]

\[ \mu = \frac{g v_X v_Y}{M_P}. \]

Large \( m_{3/2} \) generates small \( \mu \sim 100 - 200 \text{ GeV}! \)
\[ \log_{10}(\Lambda/\Lambda_P^4) \]

\( \Lambda_{\text{SM}}^{\text{expected}} \)  
\( \Lambda_{\text{SUSY}}^{\text{expected}} \)  
\( \Lambda_{\text{measured}} \)

too large for galaxy condensation
Why do soft terms take on values needed for natural (barely-broken) EWSB? string theory landscape?

• assume model like MSY/CCK where $\mu \sim 100$ GeV

• then $m(weak)^2 \sim |m_{H_u}^2|

• If all values of SUSY breaking field $\langle F_X \rangle$ equally likely, then mild (linear) statistical draw towards large soft terms

• This is balanced by anthropic requirement of weak scale $m_{weak} \sim 100$ GEV

**Anthropic selection of $m_{weak} \sim 100$ GeV**: If $m_W$ too large, then weak interactions $\sim (1/m_W^4)$ too weak, weak decays, fusion reactions suppressed, elements not as we know them
statistical draw to large soft terms balanced by anthropic draw toward red \((m(\text{weak}) \sim 100 \text{ GeV})\):
then \(m(\text{Higgs}) \sim 125 \text{ GeV}\) and natural SUSY spectrum!

Giudice, Rattazzi, 2006
HB, Barger, Savoy, Serce, PLB758 (2016) 113
statistical/anthropic draw toward FP-like region
Expectations for SUSY from statistical analysis of II-B string landscape: power law selection of soft terms anthropic draw of m(weak)~100 GeV

HB, Barger, Serce, Sinha
Conclusions:

• SUSY very much alive: natural for $\mu \sim 100-200$ GeV
• EW naturalness: higgsino-like WIMP
• QCD naturalness: axion
• SUSY $\mu$ problem/Little Hierarchy: SUSY DFSZ axion
• DM=higgsino-like WIMP+DFSZ axion admixture?
• n-ton SI noble liquid detectors should probe all p-space
• axions: must probe broader and deeper!
• (HL)-LHC: maybe see SUSY, maybe not
• HE-LHC 3.3 TeV may be required
• ILC500 is ideal for light higgsinos