Natural SUSY, mixed axion-higgsino dark matter and the gamma-ray sky

or

What the Higgs discovery implies for WIMP detection

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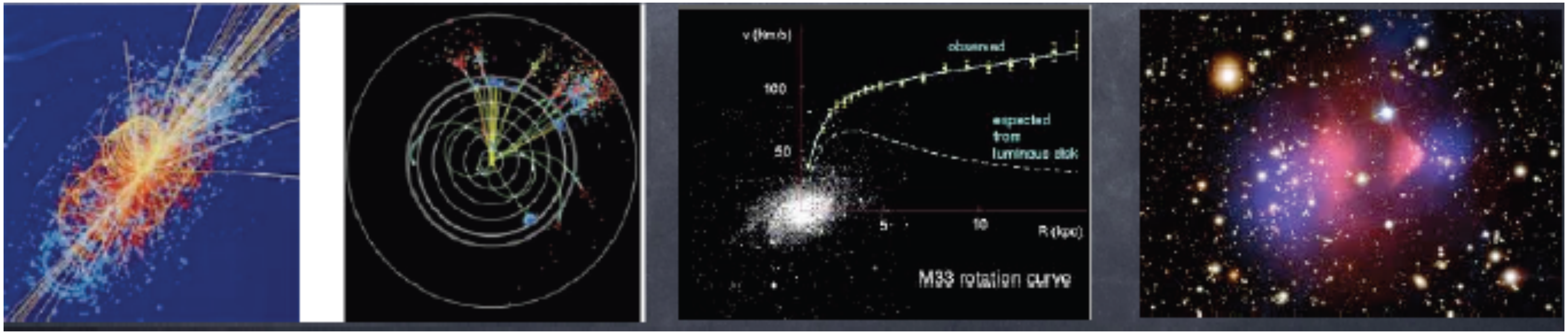


Discovery of Higgs at LHC vindicates SM!

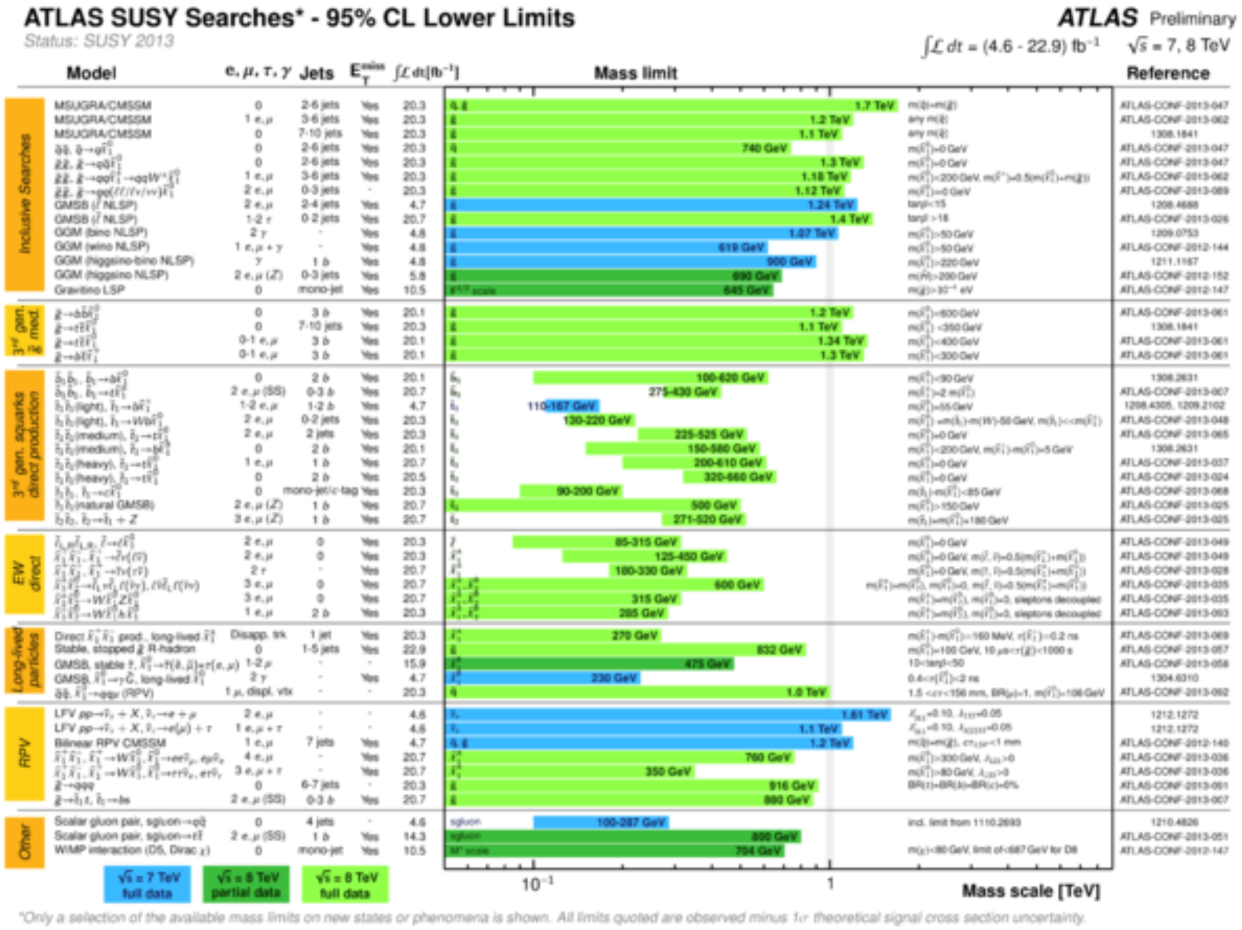
but....

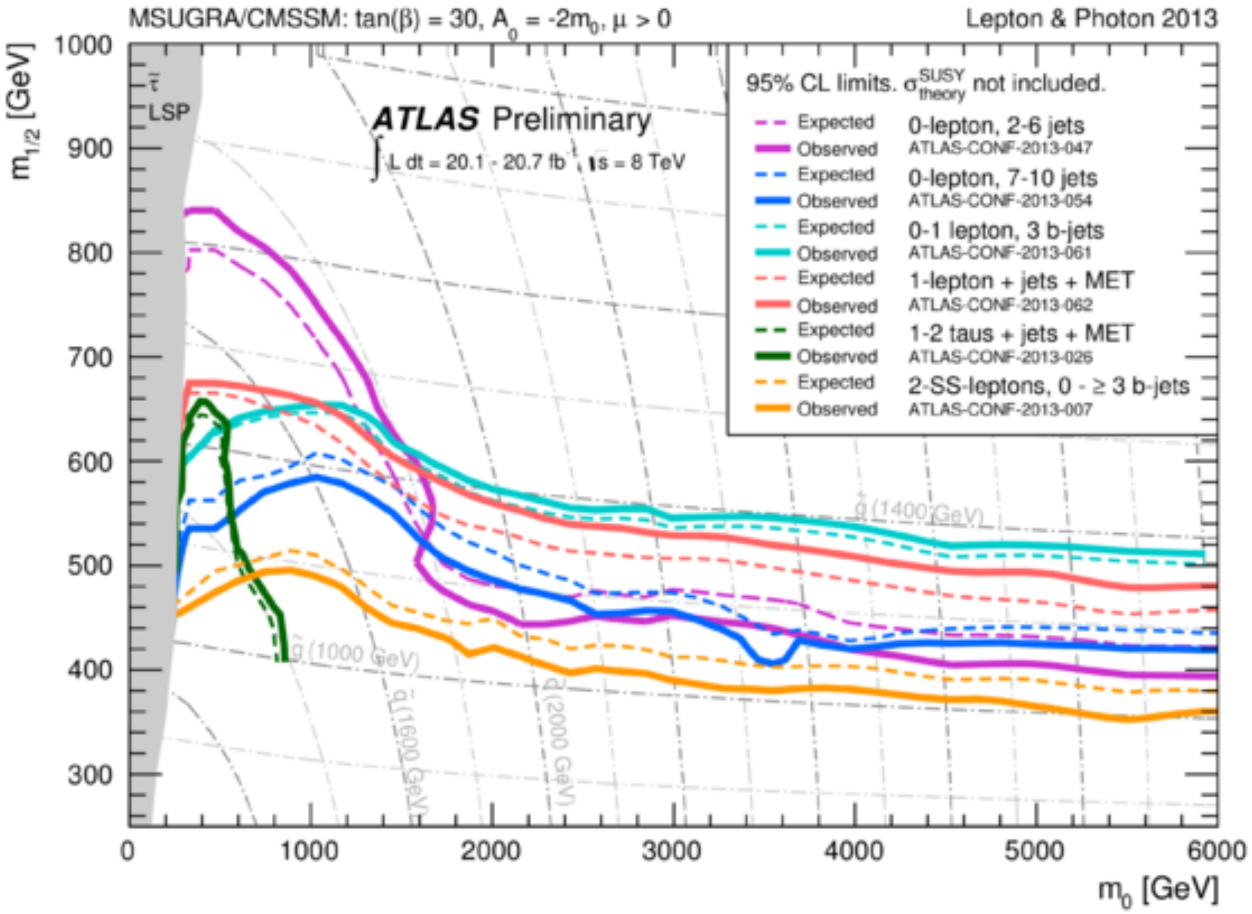
- Scalar particles contain quadratic divergences
- No dark matter candidates
- no valid baryogenesis mechanism

SUSY extension of SM

- Tames quadratic divergences: stable hierarchies
- Supported by gauge coupling unification
- m(t)~173 GeV needed to drive EWSB
- m(h)~126 GeV falls within narrow predicted SUSY window
- a variety of DM candidates:
  neutralino (WIMP), axino, sneutrino_R, gravitino...

But where are the SUSY particles?





$$m_{\tilde g} > 1.4\ TeV\ \ for\ m_{\tilde g} \ll m_{\tilde q}$$

$$m_{\tilde g} > 1.8\ TeV\ \ for\ m_{\tilde g} \sim m_{\tilde q}$$

Impression from past year and summer conferences: crisis of SUSY naturalness!

SM case: $V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$

$$m_h^2 = m_h^2|_{tree} + \delta m_h^2|_{rad}$$

$m_h^2|_{tree} = \sqrt{2}\mu^2$ $\delta m_h^2|_{rad} = \frac{c}{16\pi^2}\Lambda^2$ $m_h^2|_{tree}$ and $\delta m_h^2|_{rad}$ are *independent*,

$\Delta_{SM} \equiv \delta m_h^2|_{rad}/(m_h^2/2)$ $\Delta_{SM} < 1 \Rightarrow \Lambda \sim 1\; TeV$

MSSM case: $m_h^2 \simeq \mu^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{rad}$

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$\delta m_{H_u}^2|_{rad} \sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/m_{SUSY}^2\right)$$

$\Delta \equiv \delta m_{H_u}^2/(m_h^2/2) \lesssim 10$ then $m_{\tilde{t}_{1,2}}, m_{\tilde{b}_1} \lesssim 200$ GeV and $m_{\tilde{g}} \lesssim 600$ GeV

apparently in violation of LHC constraints!

In zeal for simplicity, have neglected that in SUSY

$m_{H_u}^2$ and $\delta m_{H_u}^2|_{rad}$ are not independent

the larger the value of $m_{H_u}^2(\Lambda)$, then the larger is the cancelling correction $\delta m_{H_u}^2|_{rad}$

This suggests a re-grouping

$$m_h^2|_{phys} = \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$$

where instead both μ^2 and $(m_{H_u}^2 + \delta m_{H_u}^2)$ should be comparable to $m_h^2|_{phys}$.

Such a re-grouping is used in Barbieri-Giudice measure:

$$\Delta_{BG} \equiv max_i\,[c_i] \quad \text{where} \quad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln a_i}\right|$$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -\underset{\uparrow}{m_{H_u}^2} - \mu^2$$

express weak scale value in terms of high scale parameters

Express m(Z) in terms of high scale parameters:

$$m_Z^2 \simeq -2m_{H_u}^2 - 2\mu^2 \qquad\qquad -2\mu^2(m_{SUSY}) \;=\; -2.18\mu^2$$

$$\begin{aligned}
-2m_{H_u}^2(m_{SUSY}) \;=\;& 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
&+0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
&-0.025M_1A_t + 0.22A_t^2 + 0.004m_3A_b \\
&-1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
&+0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
&+0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
&+0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2,
\end{aligned}$$

For generic parameter choices, $\Delta_{BG}\ is\ large$

But if: $m_{Q_{1,2}} = m_{U_{1,2}} = m_{D_{1,2}} = m_{L_{1,2}} = m_{E_{1,2}} \equiv m_{16}(1,2)$ then $\sim 0.007m_{16}^2(1,2)$

Even better: $m_{H_u}^2 = m_{H_d}^2 = m_{16}^2(3) \equiv m_0^2$ => $-0.017m_0^2$

For correlated parameters, EWFT collapses in 3rd gen. sector!

Lessons:

- Large log finetuning selectively picks out one term to exclusion of others; gives gross overestimate by orders of magnitude
- Δ_{BG} properly uses $m_h^2|_{phys} = \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2)$
- But Δ_{BG} usually applied to general effective theories.
- The hope is that eff. theory contains the ultimate theory (UTH).
- Due to high scale parameter correlations, UTH can have far less EWFT than effective theories which may contain it.

What we really want to know is if nature is fine-tuned, (and by implication the UTH which describes it), and not whether-or-not the more general effective theories
(which might contain the UTH) are fine-tuned

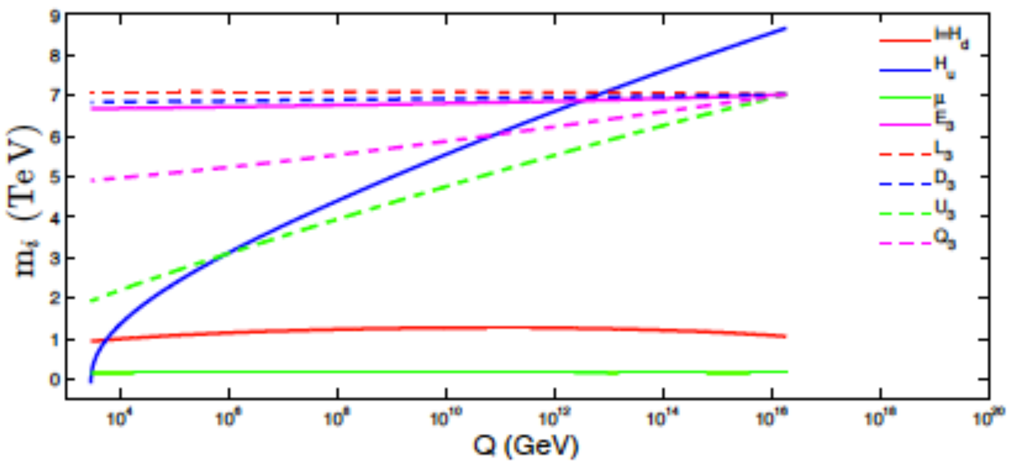
Model-independent EWFT measure: Δ_{EW}

No large uncorrelated cancellations in m(Z) or m(h)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$\Delta_{EW} \equiv max_i\left|C_i\right|/(m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

Since Δ_{EW} model-independent (within MSSM), expect same value for Eff. theory as for UTH!



In order to achieve low Δ_{EW}, it is necessary that $-m_{H_u}^2$, μ^2 and $-\Sigma_u^u$ all be nearby to $m_Z^2/2$ to within a factor of a few[12, 13]:

1. μ is required to lie in the $100 - 300$ GeV range,
2. a value of $m_{H_u}^2(m_{GUT}) \sim (1.3 - 2.5)m_0$ may be chosen so that $m_{H_u}^2$ is driven radiatively to slightly negative at the weak scale, leading to $m_{H_u}^2(weak) \sim -m_Z^2/2$, and
3. with large stop mixing from $A_0 \sim \pm 1.6 m_0$, the top-squark radiative corrections are softened while m_h is raised to the ~ 125 GeV level.

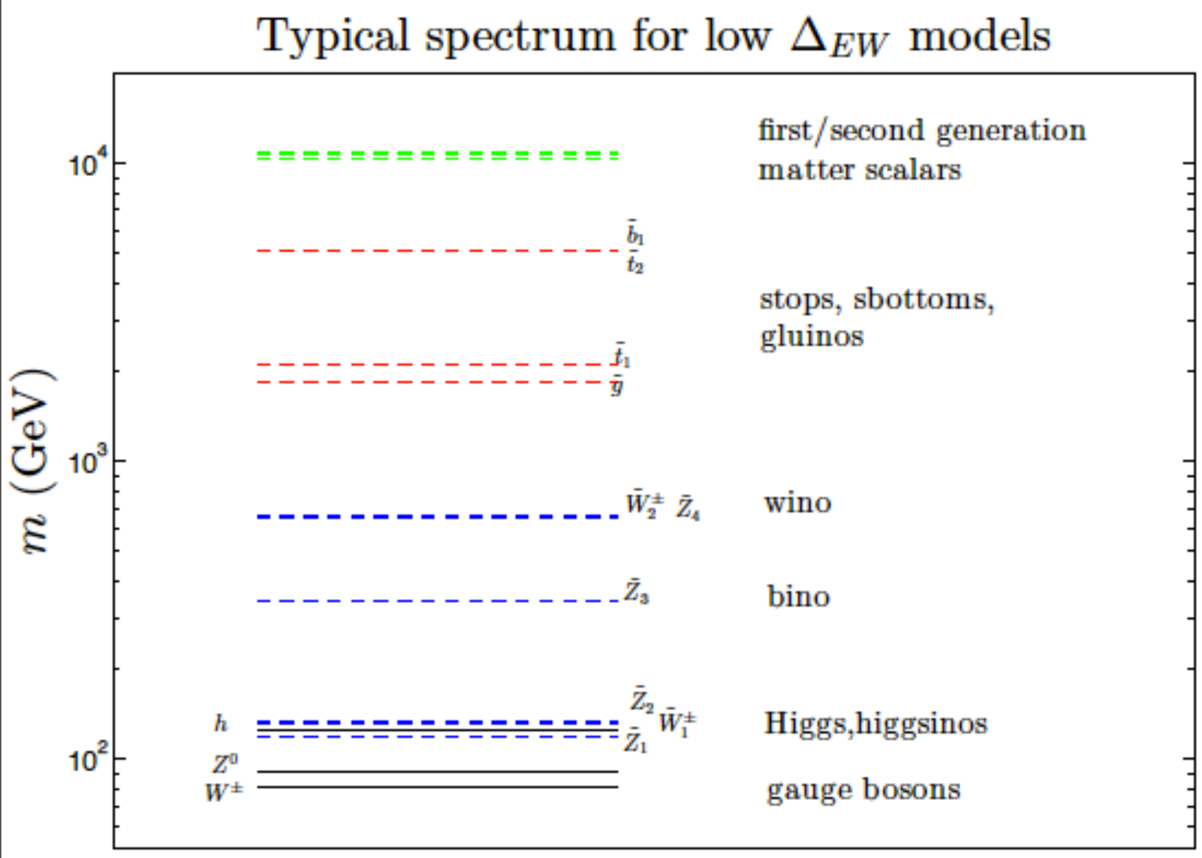
Radiatively-driven natural SUSY

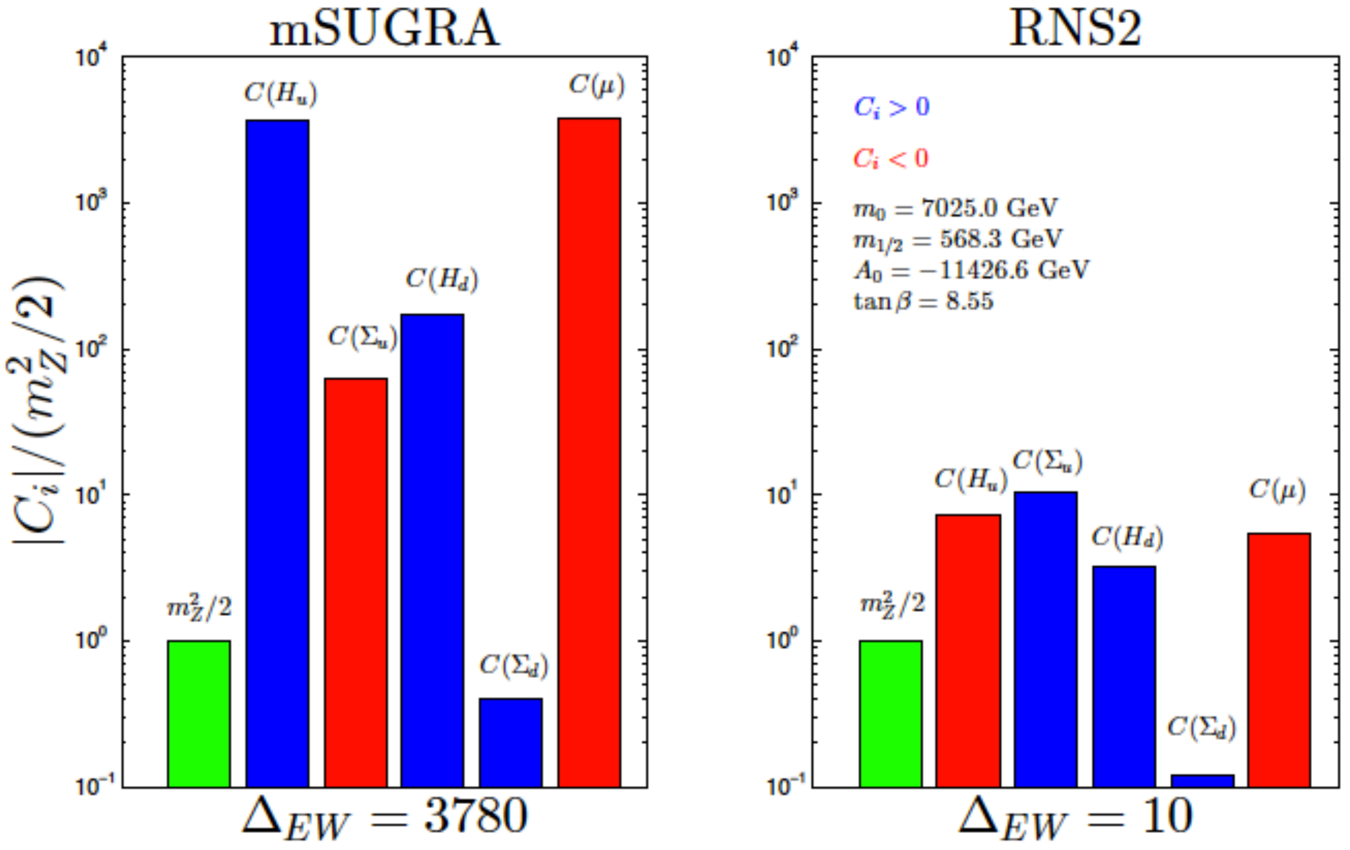
WIMP=mainly higgsino!

Models where m_Hu^2 correlated with m0 (such as mSUGRA) are fine-tuned

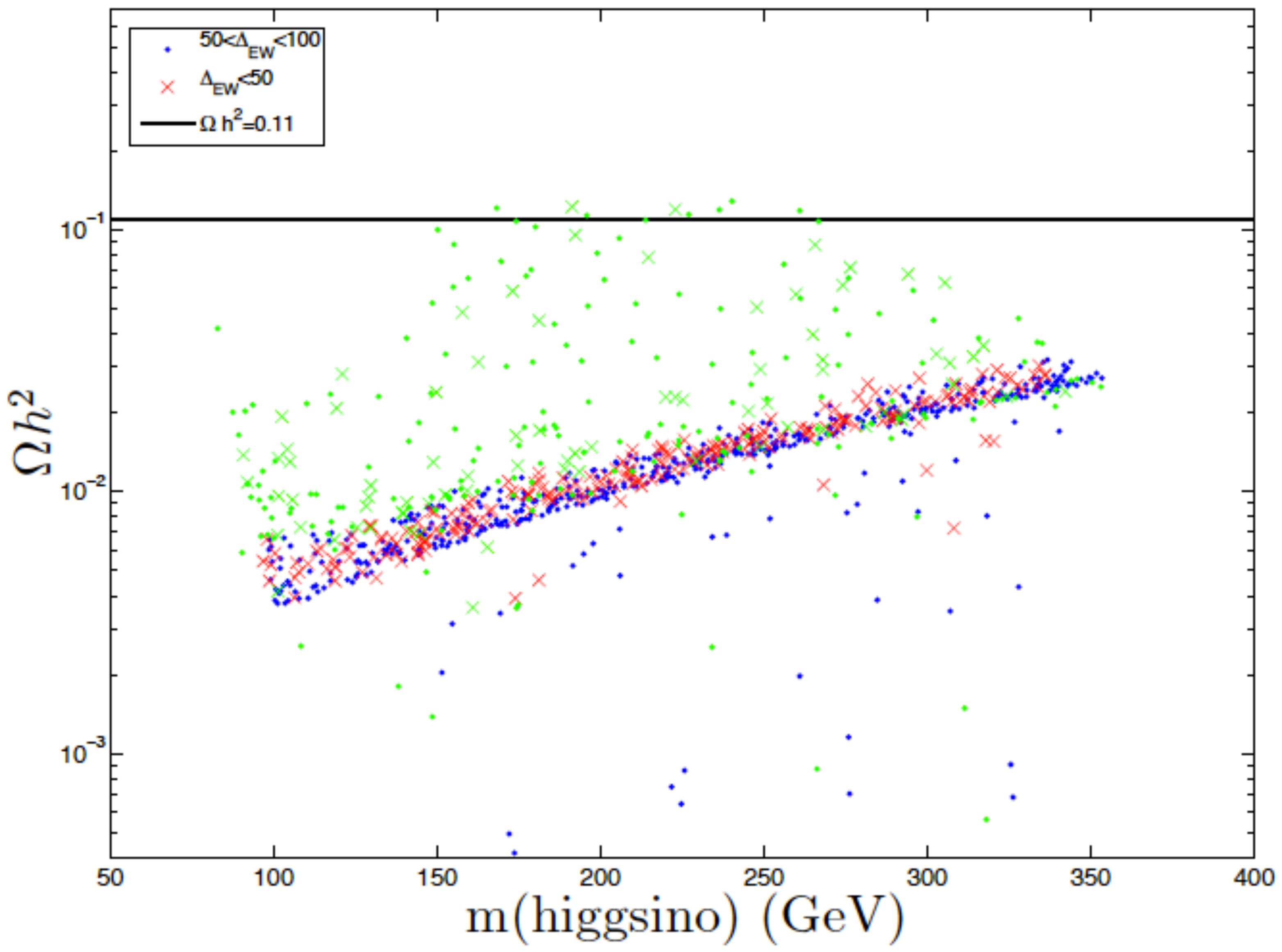
Models such as NUHM2 can allow for
low mu~m(Z) while maintaining not-too-heavy but
highly mixed stops

NUHM2 by J. Ellis, K. Olive and Y. Santoso, *Phys. Lett.* B **539** (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys.* B **652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *J. High Energy Phys.* **0507** (2005) 065.





Mainly higgsino-like WIMPs underproduce DM



Factor of 10-15 too low

But so far we have addressed only Part 1 of finetuning problem:

In QCD sector, the term $\frac{\bar{\theta}}{32\pi^2} F_{A\mu\nu} \tilde{F}_A^{\mu\nu}$ must occur

But neutron EDM says it is not there: strong CP problem

(frequently ignored by SUSY types)

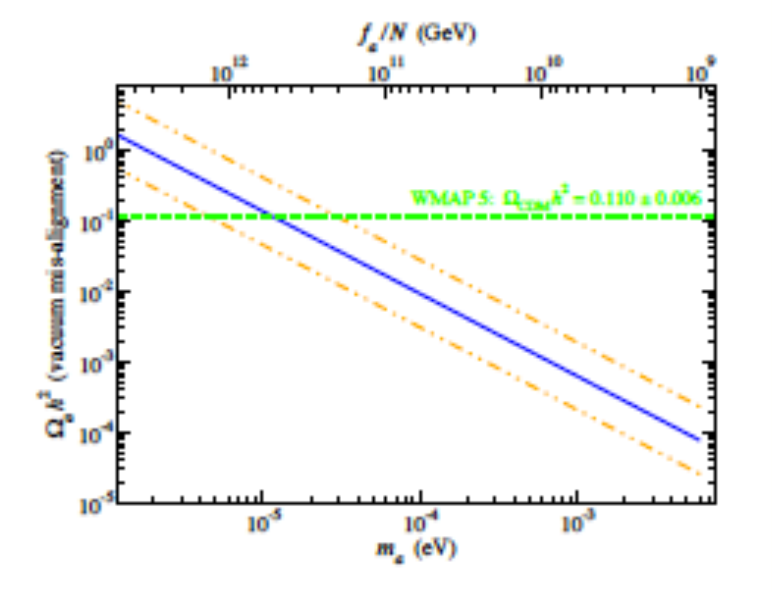
Best solution after 35 years: PQWW invisible axion

In SUSY, axion accompanied by axino and saxion

Changes DM calculus: expect mixed WIMP/axion DM (2 particles)

Axion cosmology

- Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$:
    $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- a(x) oscillates,
  creates axions with $\vec{p} \sim 0$:
  production via vacuum mis-alignment



- $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times10^{-6} eV}{m_a}\right]^{7/6} \theta_i^2 h^2$
- astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 GeV$

Axino/saxion decays

Decays very model-dependent;
also depend on KSVZ or DFSZ model

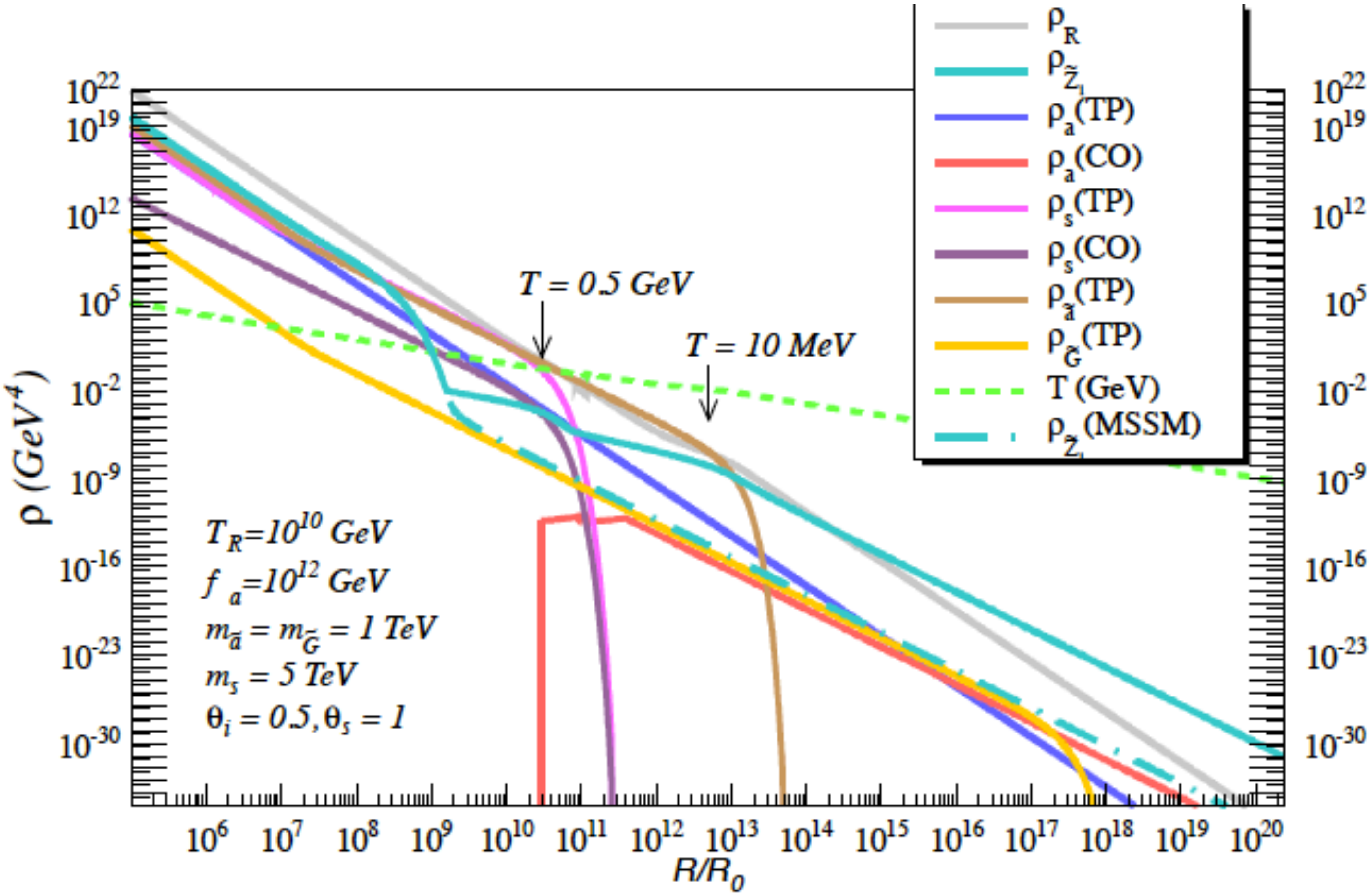
axino-> particle+sparticle: augment LSP abundance but also provide late-time entropy injection

saxion-> gg, hh, etc SM particles (entropy dilution)

saxion-> glno+gno, hgno+hgno, etc (SUSY particles, augment)

saxion->aa, dark radiation, ΔN_{eff} *bounds*

Coupled Boltzmann KSVZ $\xi = 0$



HB, Lessa, Sreethawong

mu problem: why is mu~m(weak) and not Mp?

Kim-Nilles solution to SUSY mu problem

SUSY DFSZ model

(Dine-Fischler-Srednicki-Zhitnitsky, 1983)

Higgs fields Hu and Hd carry PQ charge: mu term forbidden

Field S carries PQ charge and contains axion-axino-saxion

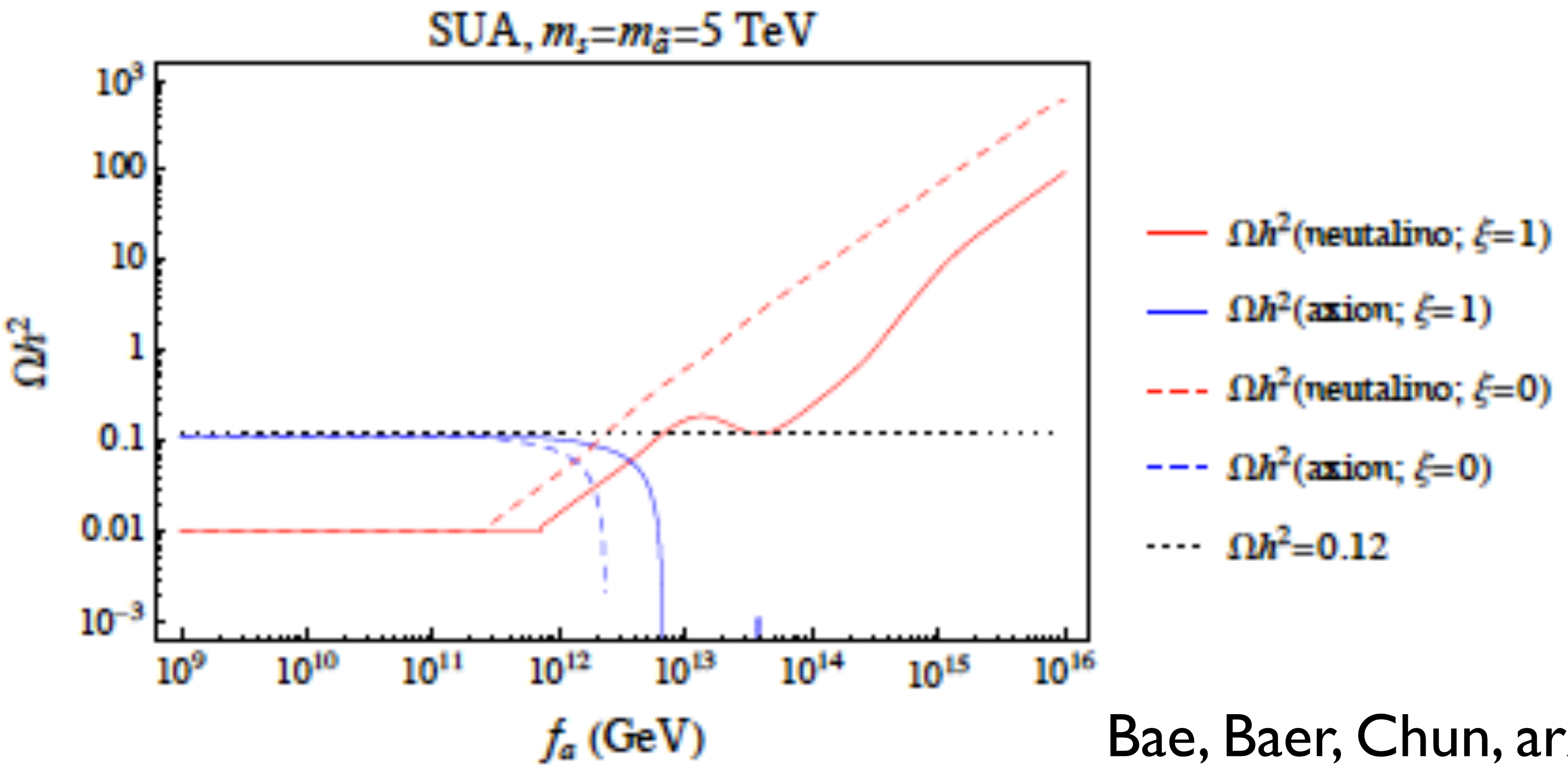
$$W_{\rm DFSZ} \ni \lambda \frac{S^2}{M_P} H_u H_d$$

If S develops vev ~ f_a, then weak scale mu generated!

$$\mu \sim \lambda f_a^2 / M_P \sim \lambda m_{3/2}$$

Tree level axion superfield couplings to higgs/higgsinos: axino/saxion decay before WIMP freezeout for f_a<10^12 GeV

Then usual WIMP abundance obtains but supplemented by axion CDM!



Bae, Baer, Chun, arXiv:1309.0519

Get 90-95% axion CDM plus 5-10% higgsino-like WIMPs

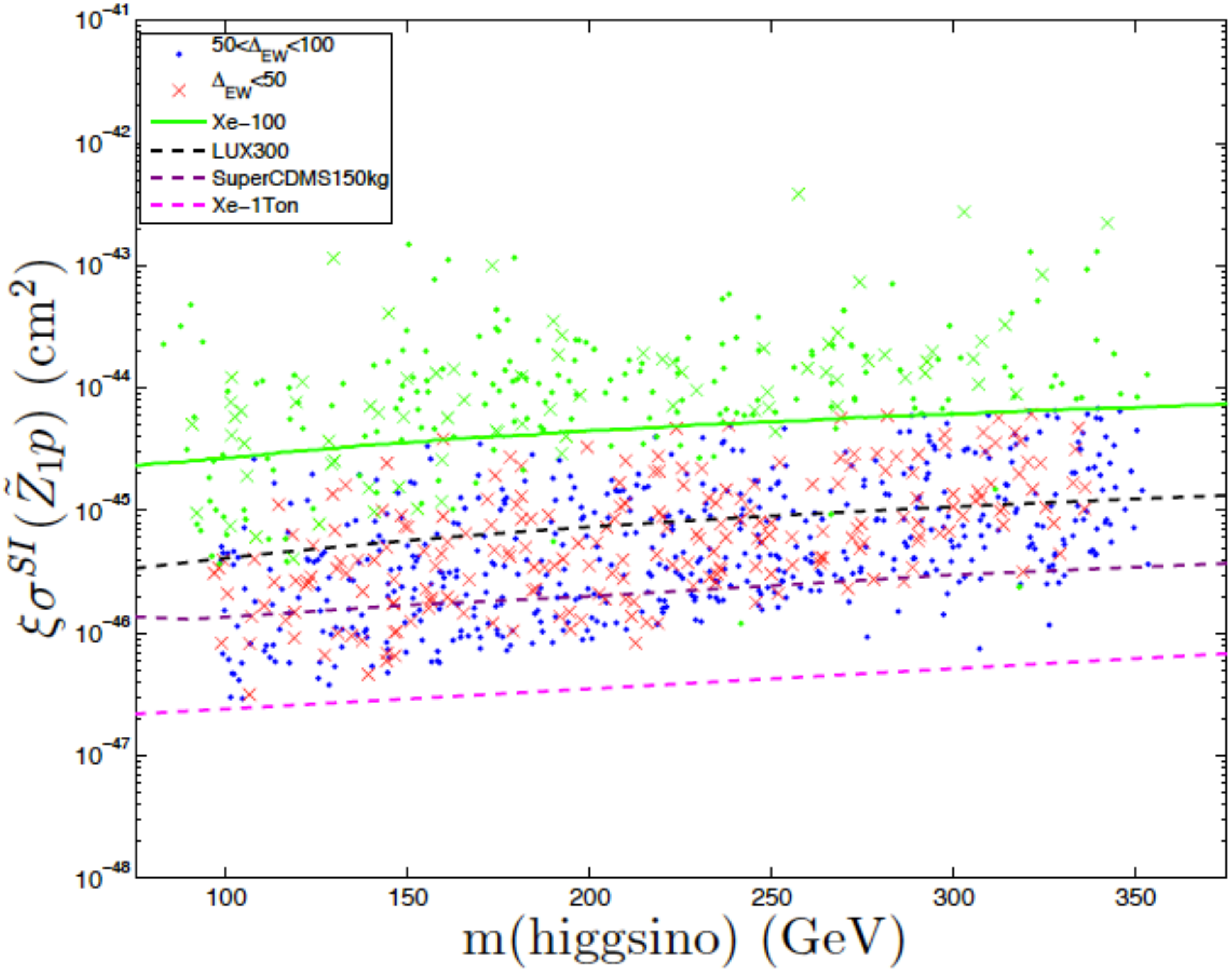
Detection of mixed a/Z1 DM in natural SUSY with DFSZ axion

detection of axion as usual: range of PQ scale f_a:
10^9-10^12 favored in SUSY DFSZ

detection of WIMPs same as usual but theory projections should be scaled to account for WIMPs making only a fraction of total DM density

use Bottino, Fornengo et al. $\xi \equiv \Omega_\chi h^2/0.12$ rescaling factor

Direct higgsino detection rescaled for minimal local abundance



HB, Barger, Mickelson
arXiv:1303.3816

$$\mathcal{L} \ni -X^h_{11}\overline{\widetilde{Z}}_1\widetilde{Z}_1 h$$

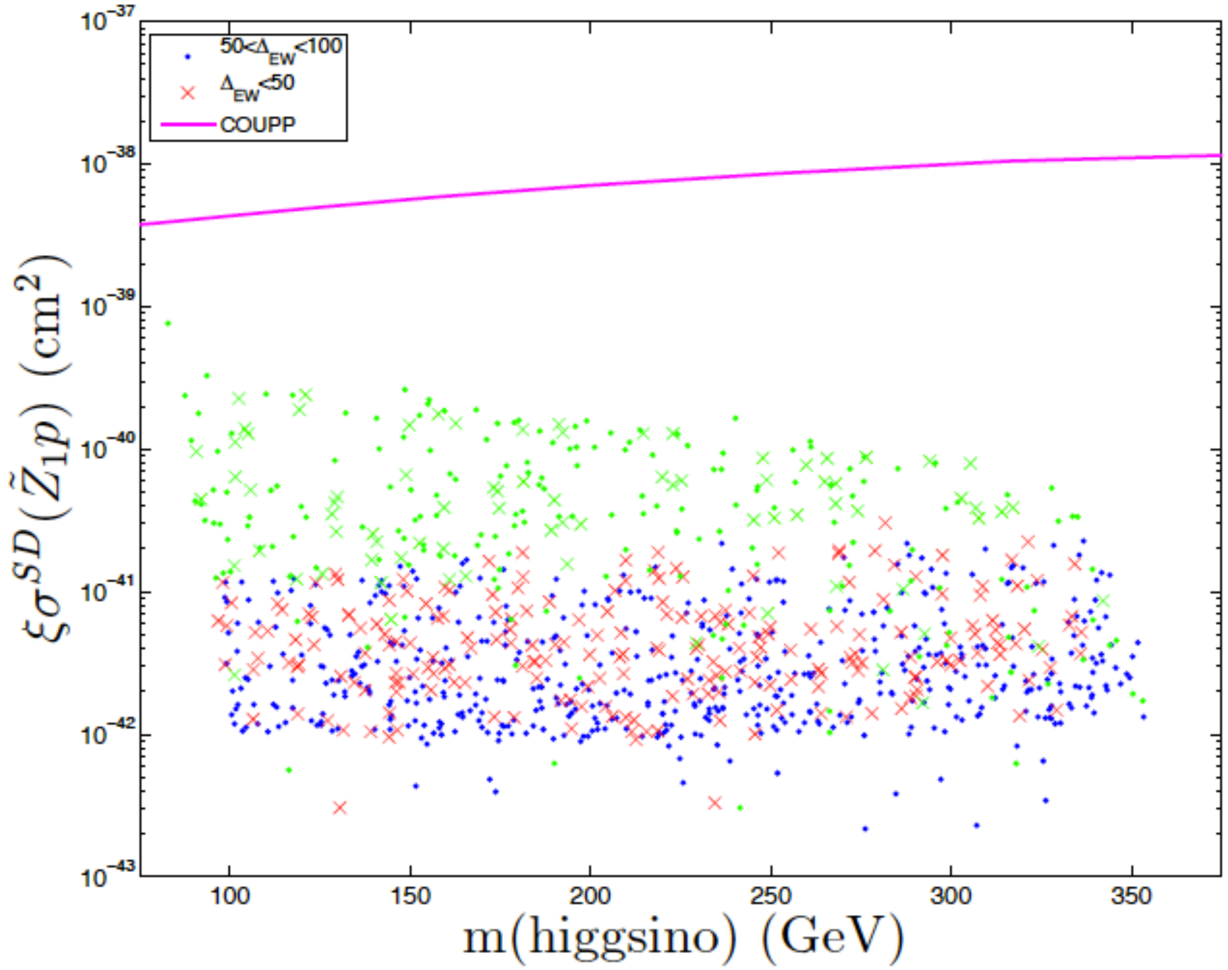
$$X^h_{11} = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(gv_3^{(1)} - g'v_4^{(1)}\right)$$

LUX has been deployed!

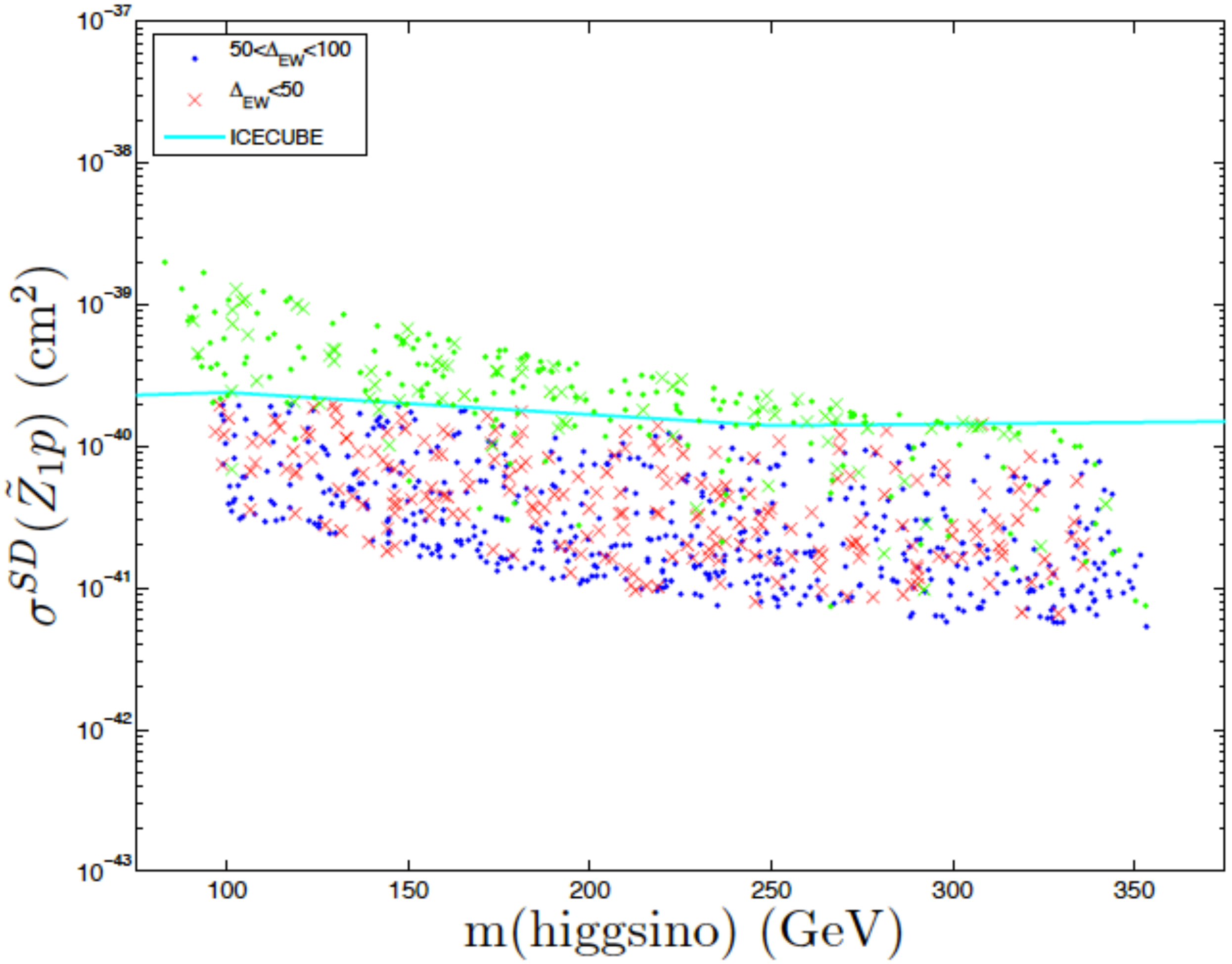
Deployment of Xe-1ton
coming soon!

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

Spin-dependent higgsino detection:

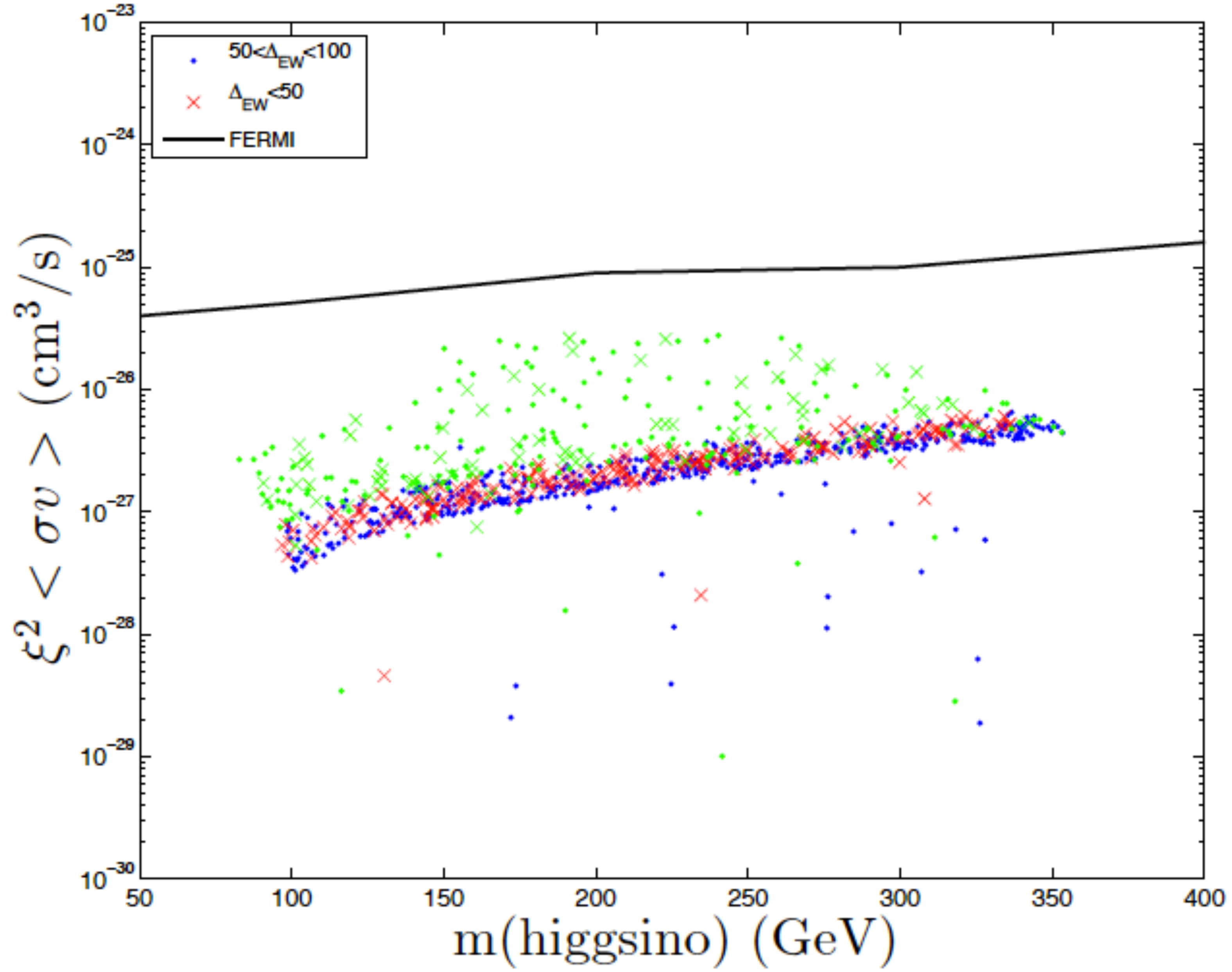


10^2 below current bounds



no rescaling for IceCube if equilibration between solar capture/annihilation has occurred

Higgsino detection via halo annihilations:



green: excluded by Xe-100

annihilation rate is high but rescaling is squared

Gamma-ray sky signal is factor 10-20 below current limits

Conclusions: SUSY dark matter post LHC8

- SUSY EWFT non-crisis: EWFT allowed at 10% level in radiatively-driven natural SUSY
- RNS spectra characterized by mainly higgsino-like WIMP: standard relic underabundance
- Also address strong CP problem via axion-axino-saxion
- DFSZ invisible axion model: solves mu problem while allowing for mu~m(Z)
- Expect mainly axion CDM with 5-10% higgsino-like WIMPs over much of p-space
- Direct detect both axion and higgsino-like WIMP
- Gamma-ray signal below bounds by 10-20: ways to go...
- LHC14 w/ 300 fb^-1 can see about half of RNS parameter space
- e+e- collider with sqrt(s)~500-600 GeV needed to find predicted light higgsino states