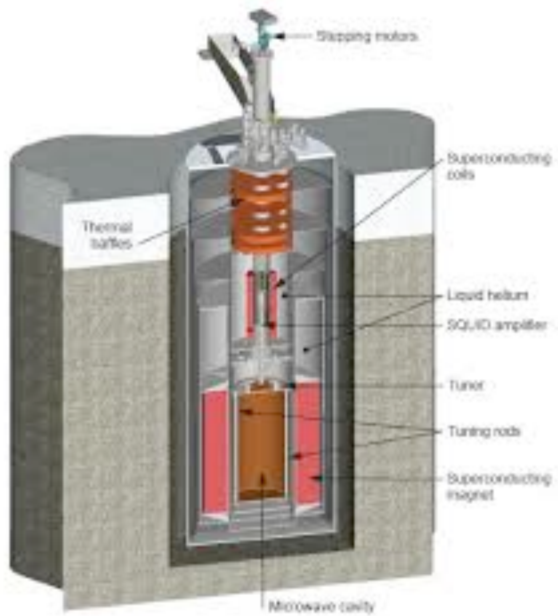
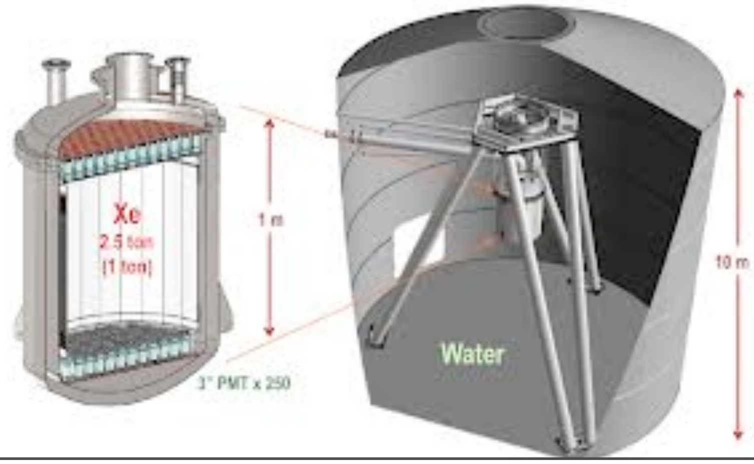
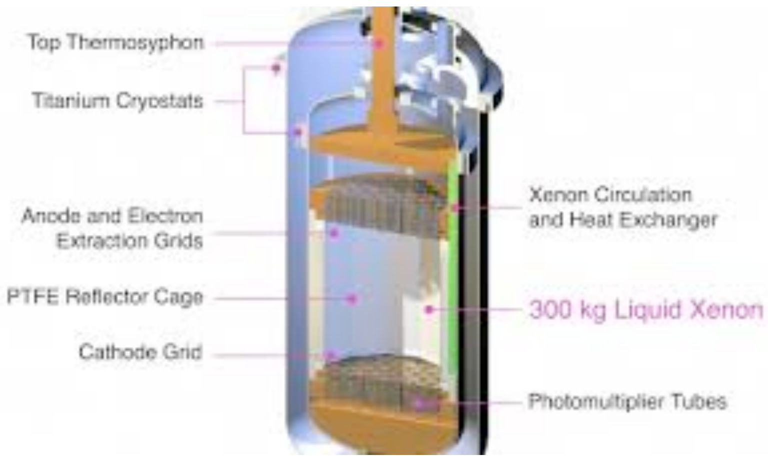
Mixed axion-higgsino CDM from natural SUSY

(Why we need LHC, ILC, wimp and axion detection)

Howard Baer
University of Oklahoma







- h(125.5+-0.5 GeV) discovered at LHC
- scalars need protective symmetry: SUSY
- m(h)~125.5 GeV falls within narrow MSSM expectation
- m(h) requires highly mixed TeV-scale stops
- LHC: no SUSY: m(glno)>1.3 TeV, m(sqrk)>1.7 TeV, t1 limits
- impression: then MSSM EW fine-tuned at .1%
- claims: SUSY as expected likely wrong (???)
- this perception arises due to mis-application of naturalness measures

A tale of three measures:
``and one ring shall rule them all"

J. R.R. Tolkien

- Simple electroweak fine-tuning Δ_{EW}
- Higgs mass fine-tuning Δ_{HS}
- Traditional EENZ/BG measure Δ_{BG}

We shall see that, if applied properly, then all three measures agree and imply a rich program of new physics at ILC:

ILC will be a Higgsino Factory!

First: Naturalness in the Standard Model

SM case: invoke a single Higgs doublet

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

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

$$m_h^2|_{tree} = 2\mu^2 \qquad \delta m_h^2|_{rad} \simeq \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

$m_h^2|_{tree}$ and $\delta m_h^2|_{rad}$ are *independent*,

If δm_h^2 blows up, can freely adjust (tune) $2\mu^2$ to maintain $m_h = 125.5$ GeV

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

#1: Simplest SUSY measure: Δ_{EW}

Working only at the weak scale, minimize scalar potential: calculate m(Z) or m(h)

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

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

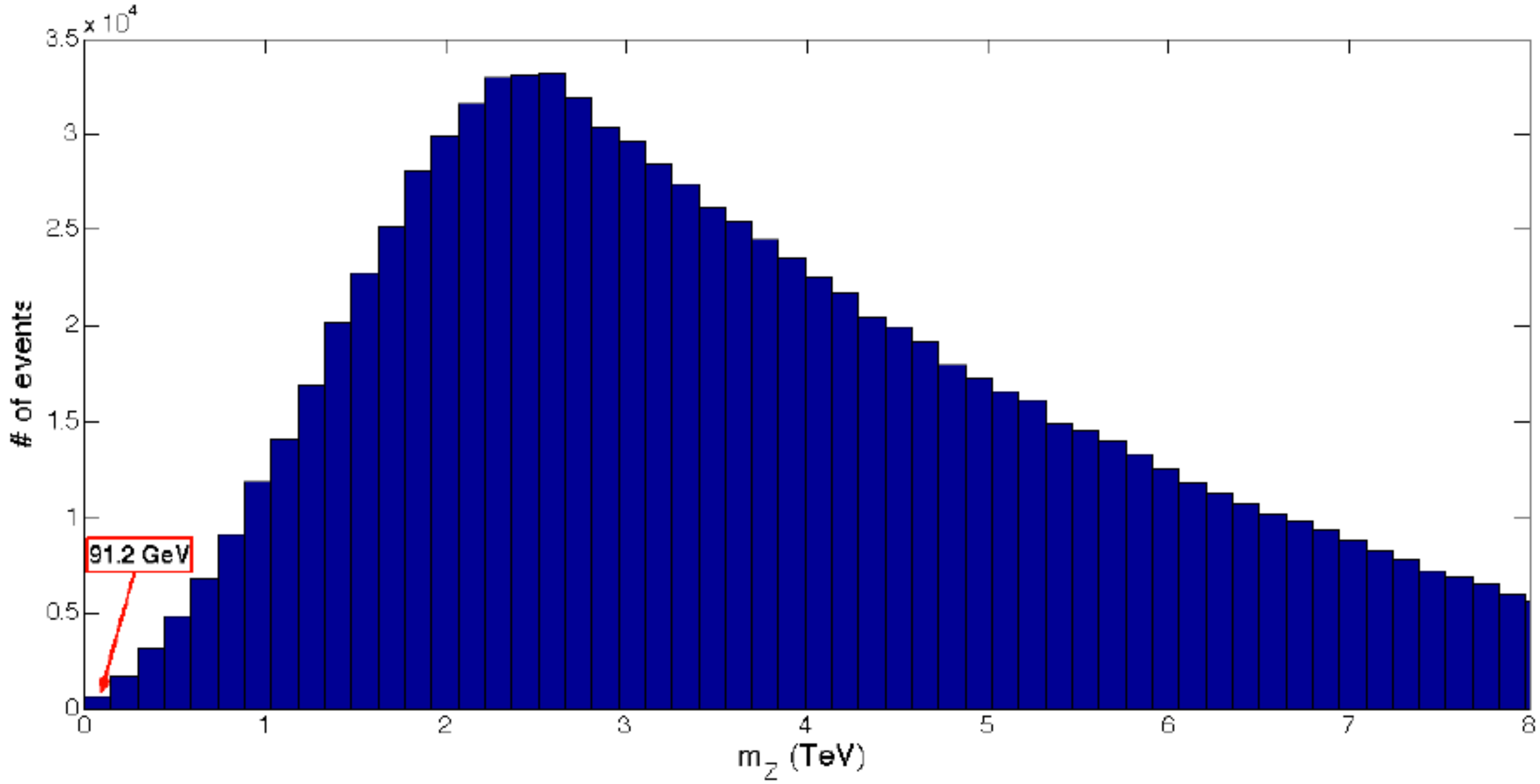
$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200$ GeV at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200$ GeV

Large A_t reduces $\Sigma_u^u(\tilde{t}_{1,2})$ whilst lifting m_h to 125.5 GeV

Is Δ_{EW} really a measure of fine-tuning?
What happens if one doesn't fine-tune $m^2_{H_u}/\mu^2$:



The 20 dimensional pMSSM parameter space then includes

$$
\begin{aligned}
&M_1,\ M_2,\ M_3,\\
&m_{Q_1},\ m_{U_1},\ m_{D_1},\ m_{L_1},\ m_{E_1},\\
&m_{Q_3},\ m_{U_3},\ m_{D_3},\ m_{L_3},\ m_{E_3},\\
&A_t,\ A_b,\ A_\tau,\\
&m^2_{H_u},\ m^2_{H_d},\ \mu,\ B.
\end{aligned}
$$

scan over parameters

Natural value of m(Z) from pMSSM is ~2-4 TeV

#2: Higgs mass or large-log fine-tuning Δ_{HS}

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

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

$$X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$$

neglect gauge pieces, S, mHu and running;
then we can integrate from mSUSY to Lambda

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

$\Delta_{HS} \sim \delta m_h^2/(m_h^2/2) < 10$ then $m_{\tilde{t}_{1,2},\tilde{b}_1} < 500\ \mathrm{GeV}$, $m_{\tilde{g}} < 1.5\ \mathrm{TeV}$

apparently in violation of LHC constraints!

What's wrong with this argument?

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 $\delta m_{H_u}^2|_{rad}$

The dependent terms should be grouped together

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

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

After re-grouping: $\Delta_{HS} \simeq \Delta_{EW}$

#3: EENZ/BG traditional measure Δ_{BG}

Such a re-grouping is properly used in the EENZ/BG measure:

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

Here, the a_i are parameters of the theory

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

↑

express weak scale value in terms of high scale parameters

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

$$m_Z^2 \simeq -2m_{H_u}^2 - 2\mu^2$$ (weak scale relation)

$$-2\mu^2(m_{SUSY}) = -2.18\mu^2$$

all GUT scale parameters

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

Abe, Kobayashi, Omura; S. P. Martin

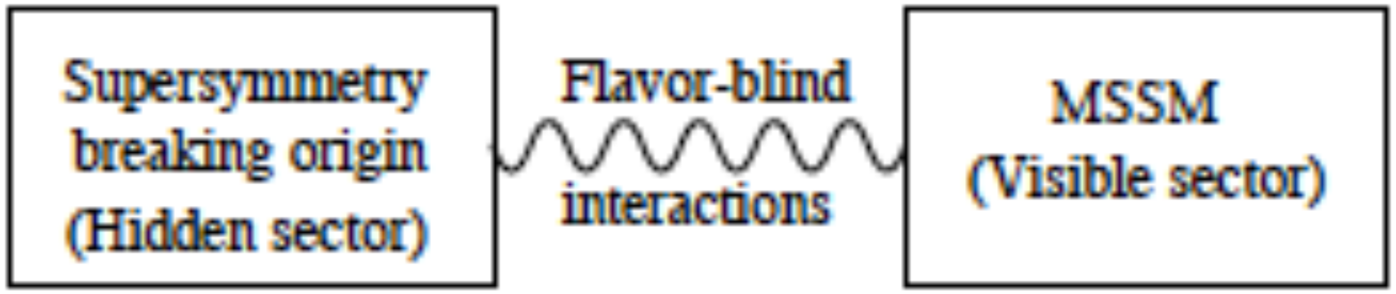
For generic parameter choices, Δ_{BG} *is large*

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!

To properly apply BG measure, need to identify independent soft breaking terms



examine gravity mediation

For any particular SUSY breaking hidden sector, each soft term is some multiple of gravitino mass m(3/2)

$$
\begin{aligned}
m_{H_u}^2 &= a_{H_u} \cdot m_{3/2}^2, \\
m_{Q_3}^2 &= a_{Q_3} \cdot m_{3/2}^2, \\
A_t &= a_{A_t} \cdot m_{3/2}, \\
M_i &= a_i \cdot m_{3/2}, \\
& \cdots .
\end{aligned}
$$

Since we don't know hidden sector, we impose parameters which parameterize our ignorance:

but this doesn't mean each parameter is independent

e.g. dilaton-dominated SUSY breaking: $m_0^2 = m_{3/2}^2$ with $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

Writing each soft term as a multiple of m(3/2) then we allow for maximal correlations/cancellations:

$$m_Z^2 = -2.18\mu^2 + a \cdot m_{3/2}^2$$

for naturalness, then

$\mu^2 \sim m_Z^2$ and $a \cdot m_{3/2}^2 \sim m_Z^2$

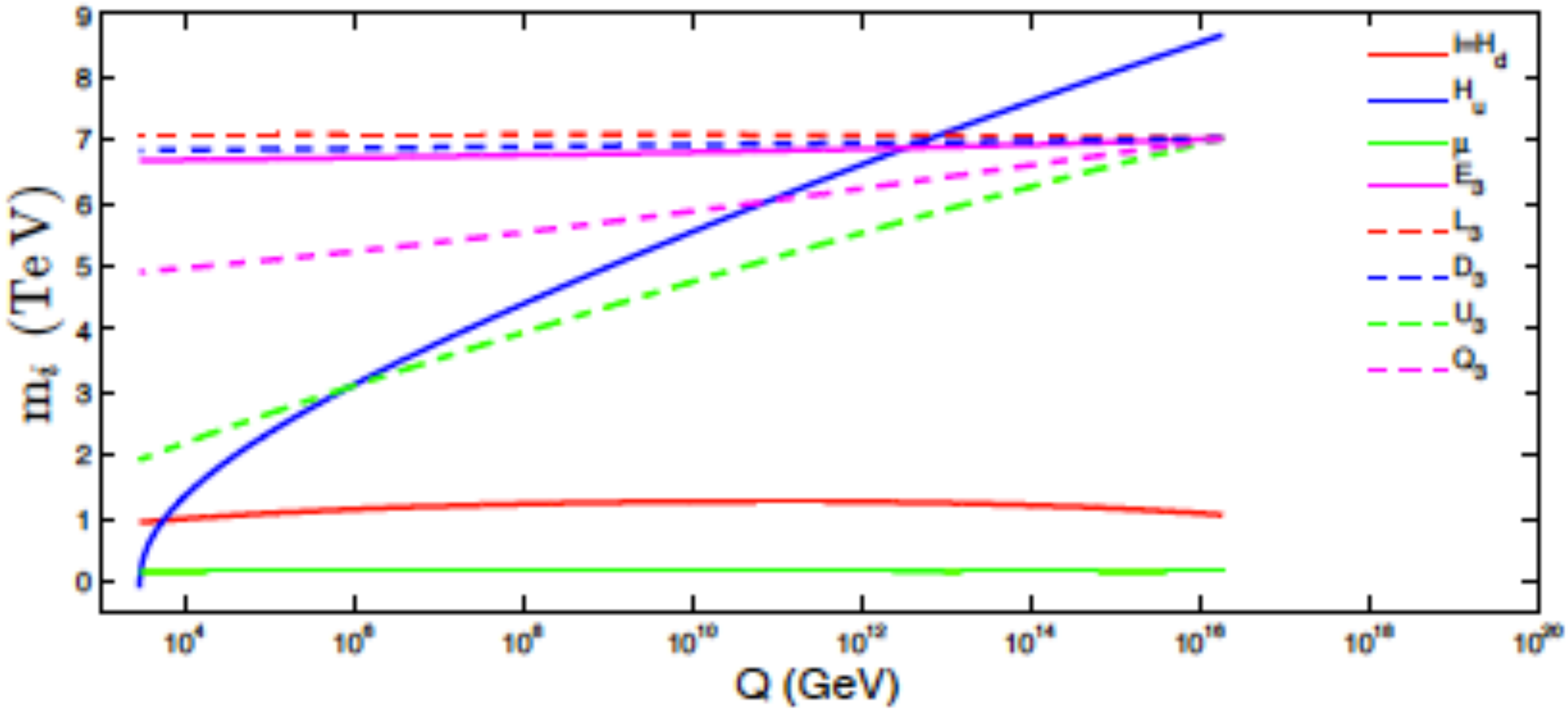
$$m_Z^2 \simeq -2\mu^2(weak) - 2m_{H_u}^2(weak) \simeq -2.18\mu^2(GUT) + a \cdot m_{3/2}^2$$

then $-m_{H_u}^2(weak) \sim a \cdot m_{3/2}^2 \sim m_Z^2$

$$\lim_{n_{SSB} \to 1} \Delta_{BG} \to \Delta_{EW}$$

Applied properly, all three measures agree:

naturalness is unambiguous and highly predictive!

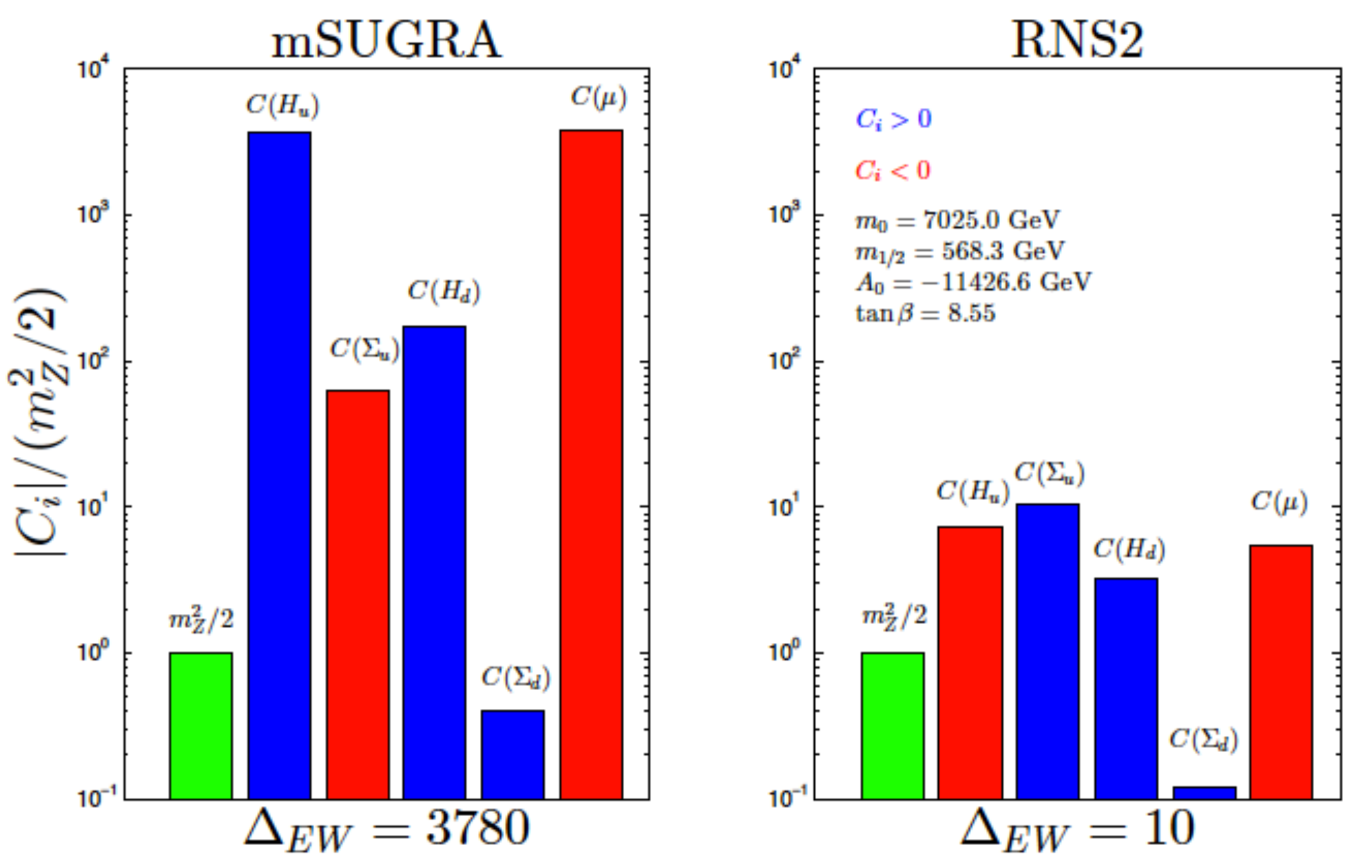


Radiatively-driven natural SUSY, or RNS:

H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, *Phys. Rev. Lett.* **109** (2012) 161802.

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, *Phys. Rev.* **D 87** (2013) 115028 [arXiv:1212.2655 [hep-ph]].

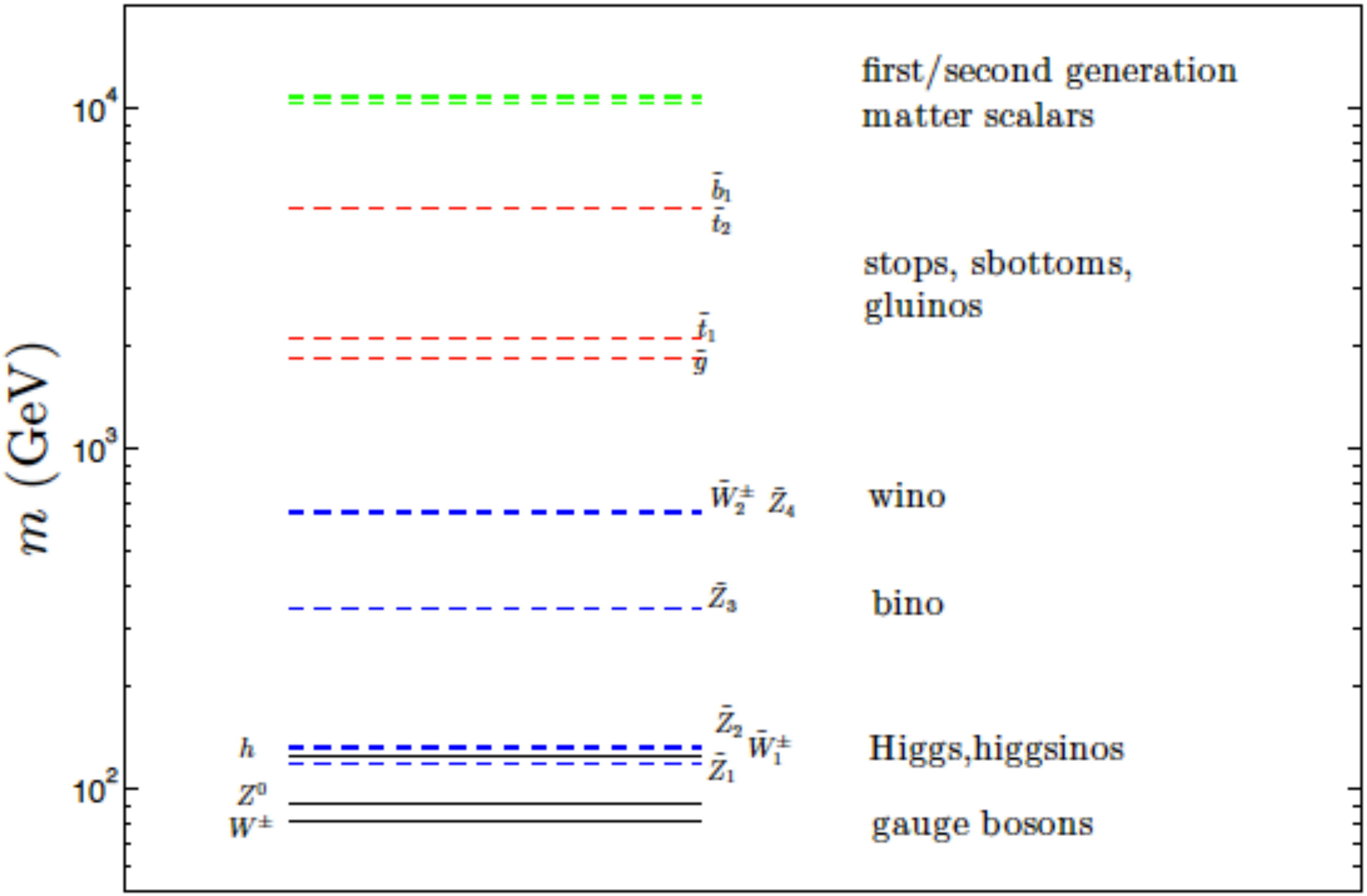
All contributions to m(Z) and m(h) are comparable to m(Z) and m(h): model is natural in EW sector!



unnatural model

natural model: all contributions to m(Z) are comparable to m(Z)

Typical spectrum for low Δ_{EW} models



There is a Little Hierarchy, but it is no problem

$$\mu \ll m_{3/2}$$

SUSY mu problem: mu term is SUSY, not SUSY breaking: expect mu~M(Pl) but phenomenology requires mu~m(Z)

- NMSSM: mu~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

$$\mu \sim \lambda f_a^2 / M_P$$

$$m_{3/2} \sim m_h^2 / M_P$$

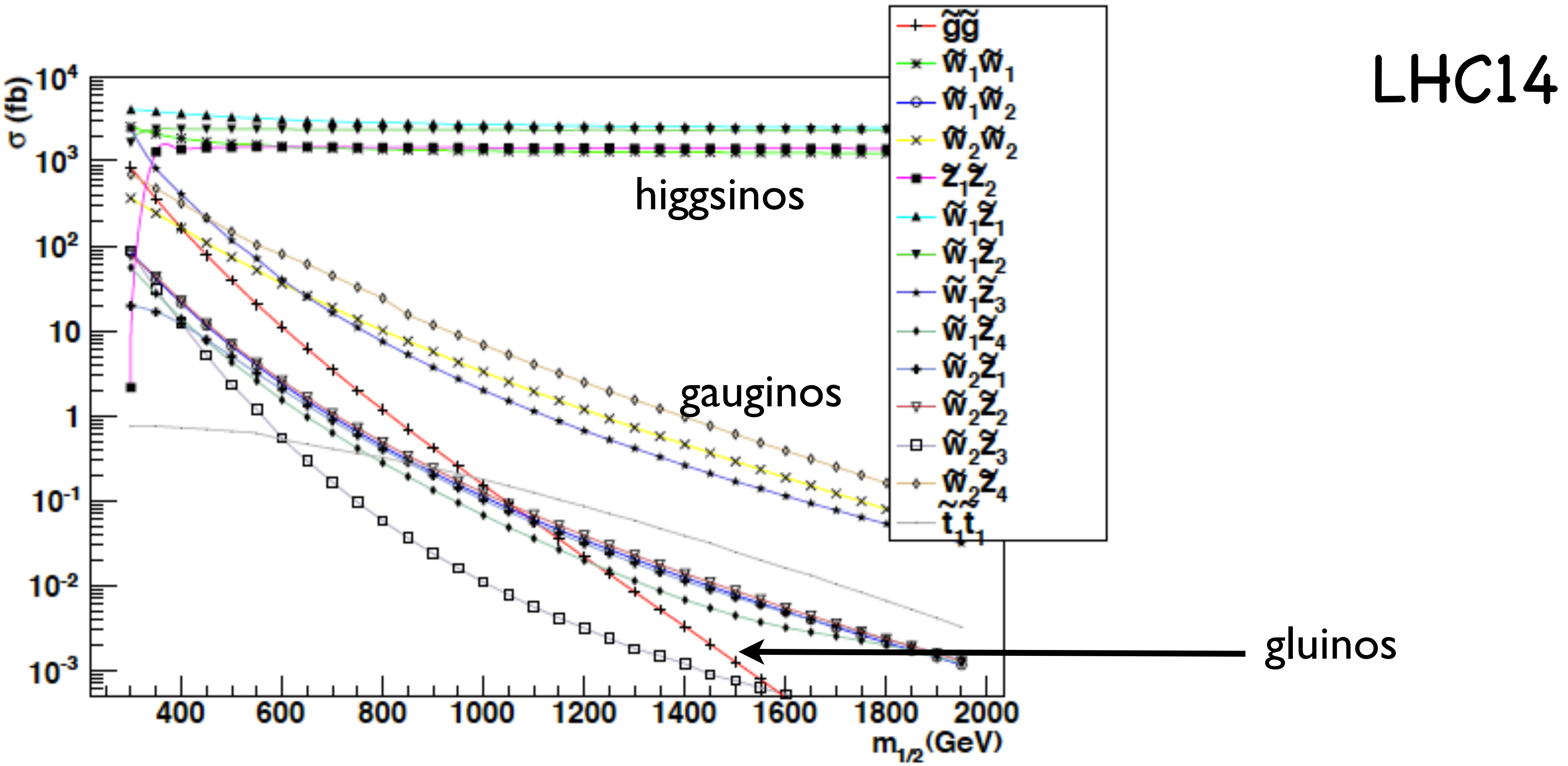
Little Hierarchy due to mismatch between SUSY breaking and PQ breaking scale?

$$f_a \ll m_h$$

Higgs mass tells us where to look for axion!

$$m_a \sim 6.2\mu\text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a} \right)$$

Sparticle production along RNS model-line:



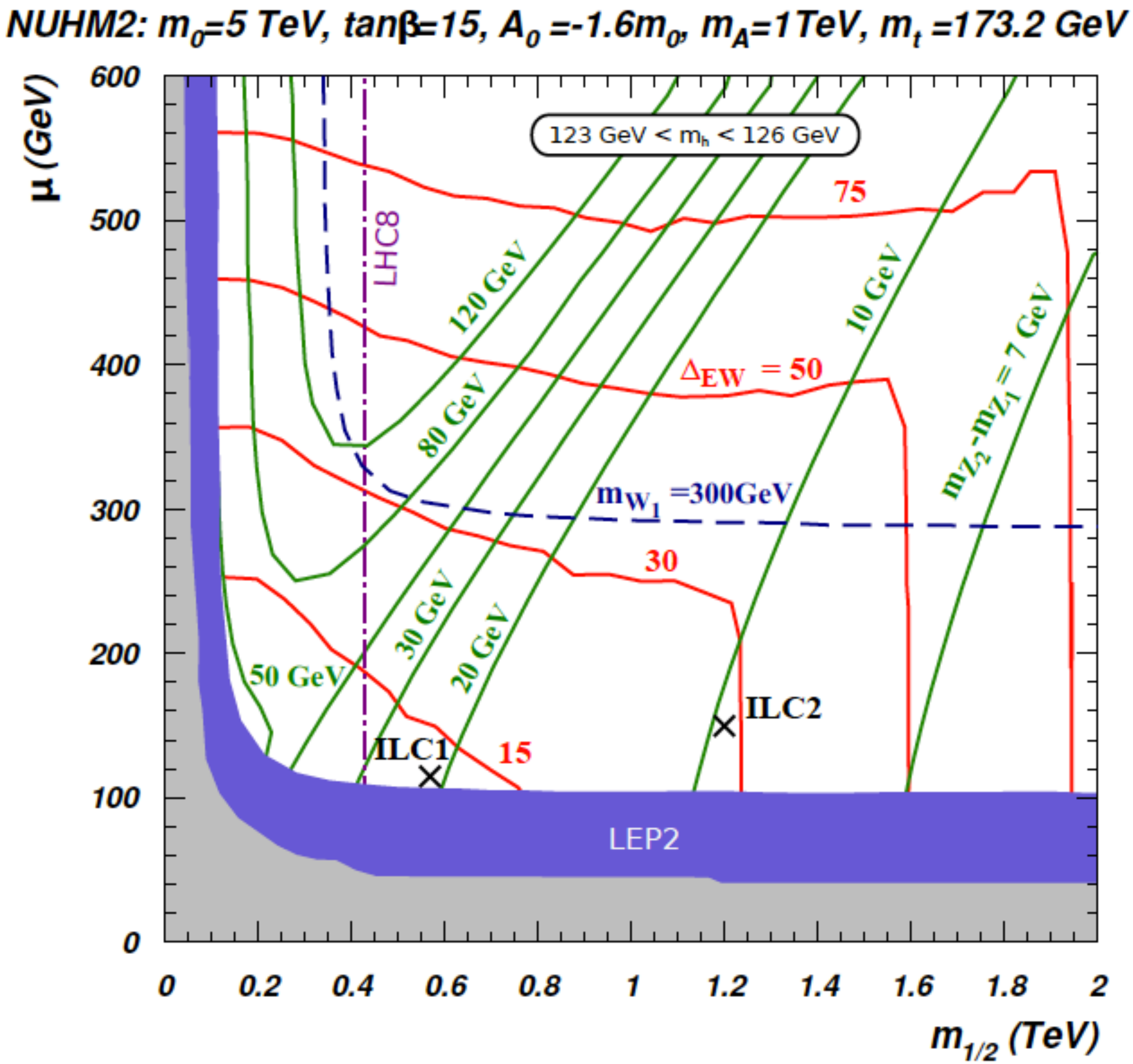
*higgsino pair production dominant-but only soft visible energy release from higgsino decays

*largest visible cross section: wino pairs=> SSdB

*gluino pairs sharply dropping

Radiatively-driven natural supersymmetry at the LHC (with V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata) JHEP**1312** (2013) 013.

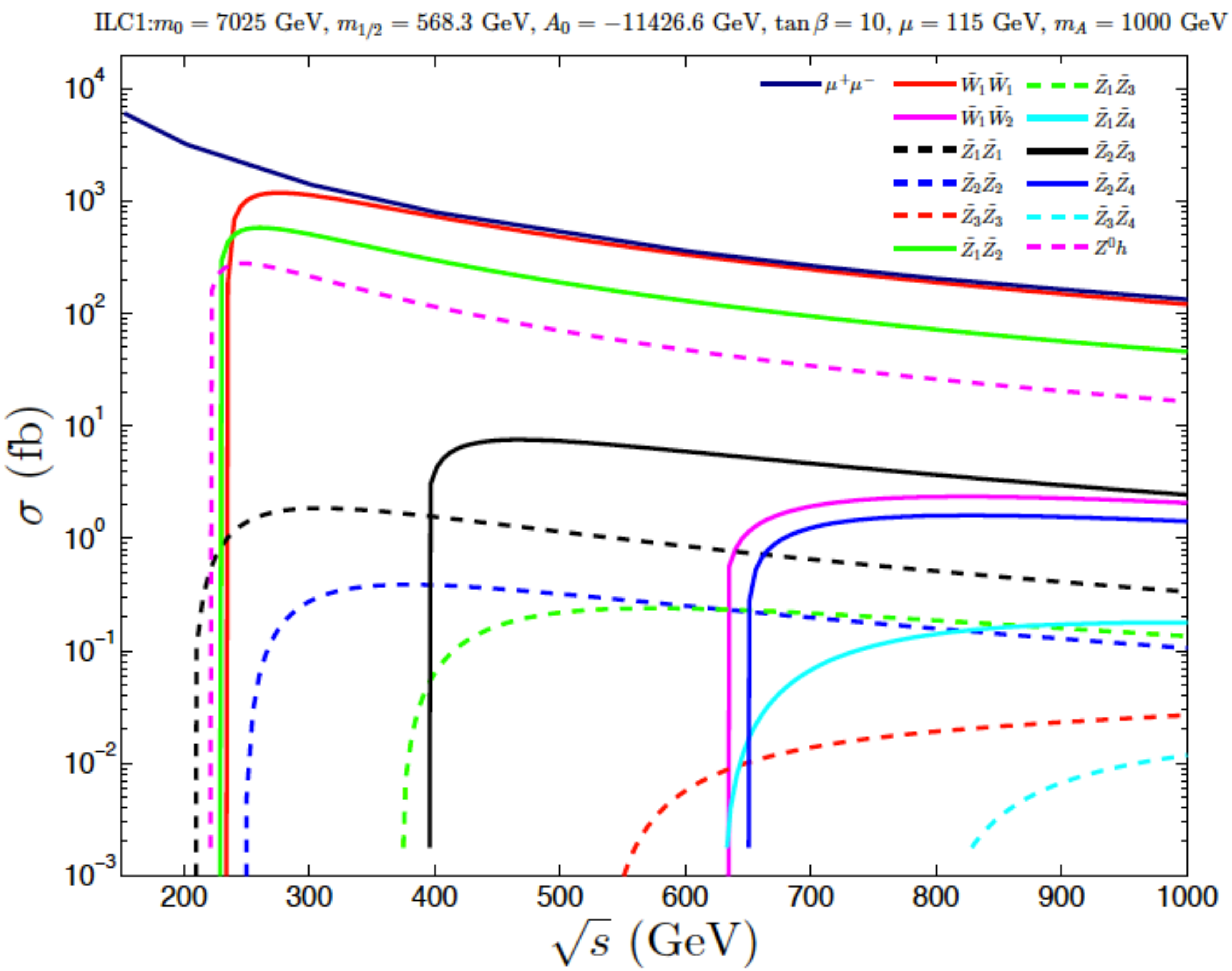
Landscape of RNS



Physics at a Higgsino Factory (with V. Barger, D. Mickelson, A. Mustafayev and Xerxes Tata), arXiv:1404.7510.

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



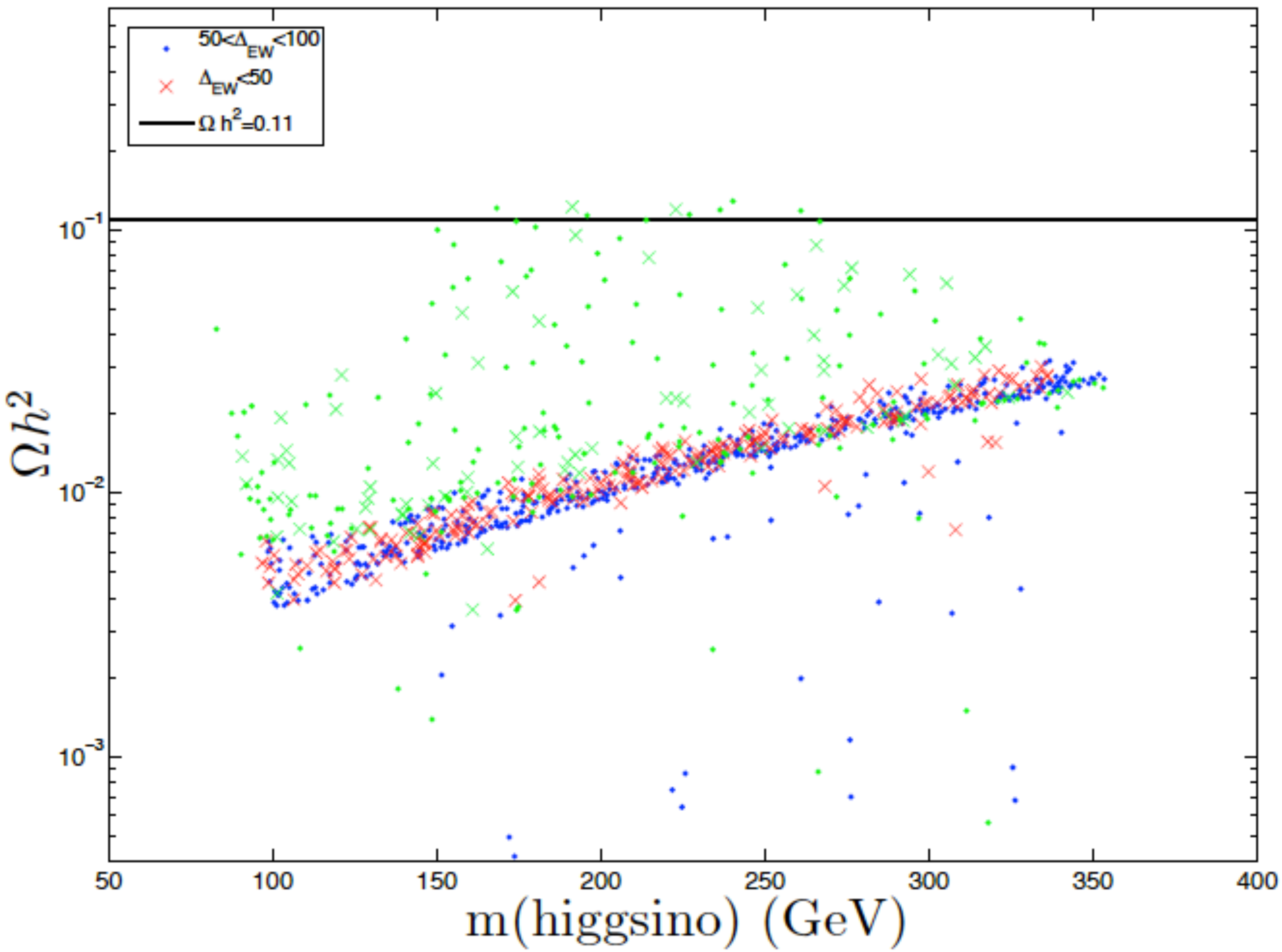
$$\sigma(higgsino) \gg \sigma(Zh)$$

10-15 GeV higgsino mass
gaps no problem
in clean ILC environment

ILC either sees light higgsinos or natural SUSY dead

Dark matter from RNS: thermally-produced higgsinos can't comprise all CDM!

$\Omega_\chi^{TP} h^2$ low by factor 10-15



The QCD fine-tuning problem

- QCD chiral symmetry: expect 4 light pions
- 't Hooft solution: θ-vacuum but then additional term:
- $\bar{\theta} = \theta + arg(det\mathcal{M})$

$$\frac{\bar{\theta}}{32\pi^2} F_{A\mu\nu} \tilde{F}^{\mu\nu}_A$$

- $\bar{\theta} < 10^{-10}$ (neutron EDM)
- solution: PQ symmetry and axion a

For DM abundance calculus,
presence of axion changes everything:
spin-0 saxion and spin-1/2 axino with mass ~ TeV

expect mixed axion-higgsino CDM: 2 particles!

As a bonus: axion provides elegant solution to the SUSY mu problem:

In MSSM, Higgs/higgsino mass mu is supersymmetric and not soft breaking:
expect mu~M_P but m(h,Z) require mu~m(weak)

PQ charges for H(d), H(u) forbid mu term,
but H(d), H(u) can couple to axion supermultiplet:
SUSY DFSZ axion model

Kim-Nilles

PQ symmetry breaking:

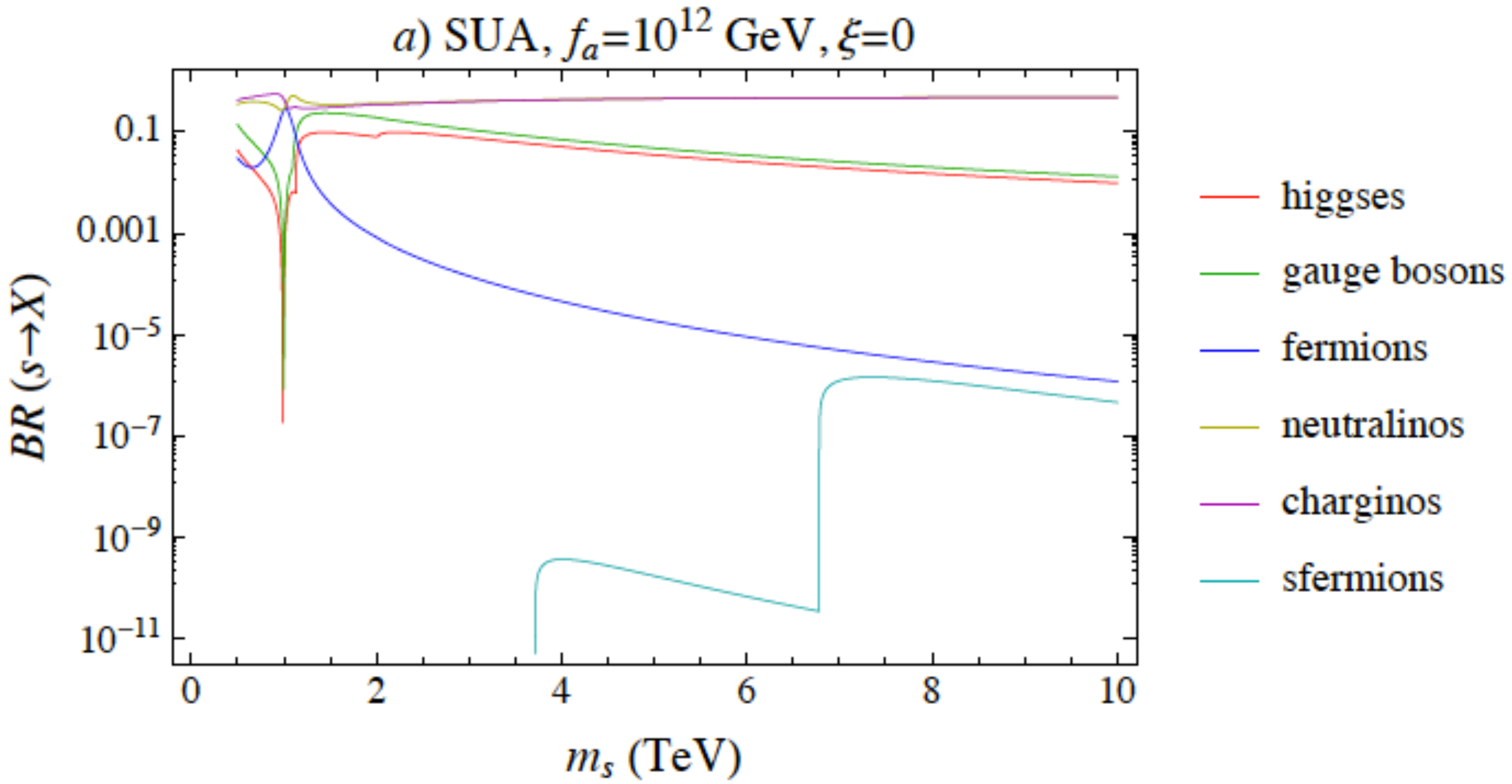
$$\mu \sim f_a^2/M_P \sim 100 \text{ GeV } for \ f_a \sim 10^{11} \text{ GeV}$$

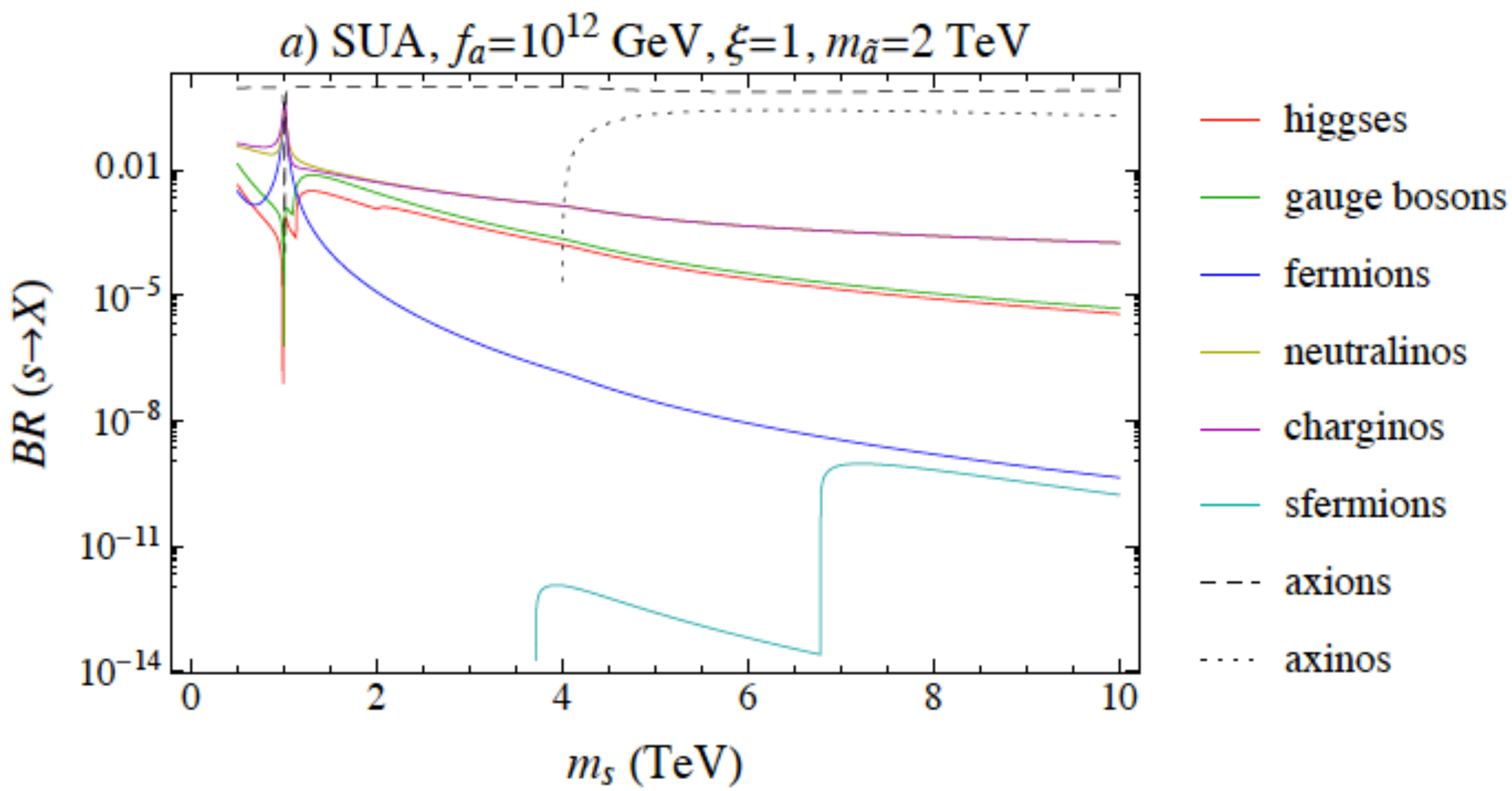
Higgs mass tells us where to look for axion and wimp!

mixed axion-neutralino production in early universe

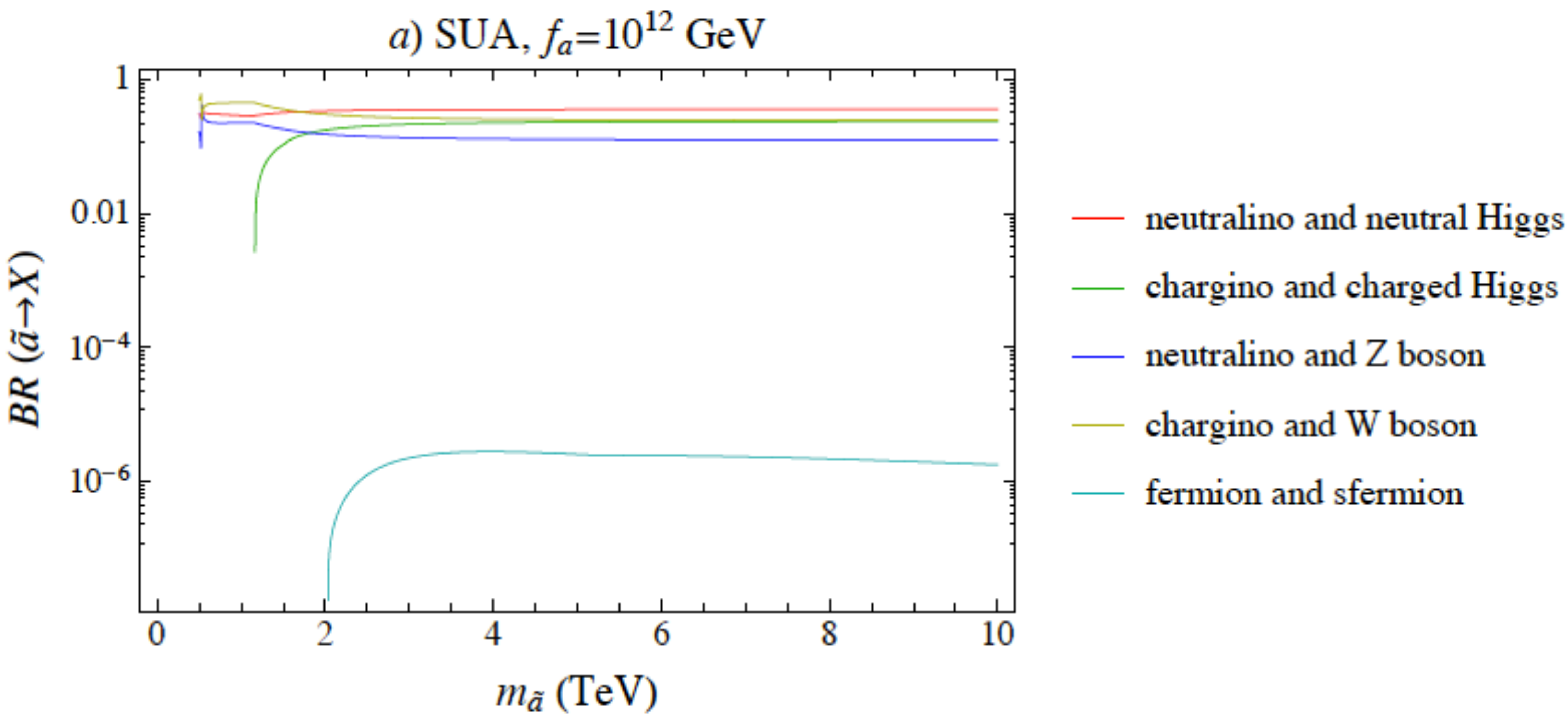
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: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

saxion decays in susy dfsz





axino decays in susy dfsz for rns



coupled Boltzmann equations

$$\frac{dn_{\widetilde{Z}_1}}{dt} = -3Hn_{\widetilde{Z}_1} + \left[\bar{n}^2_{\widetilde{Z}_1} - n^2_{\widetilde{Z}_1}\right] \langle\sigma v\rangle_{\widetilde{Z}_1}(T) + \sum_j BR(j \to \widetilde{Z}_1)\Gamma_j m_j \left(n_j - \bar{n}_j \frac{n_{\widetilde{Z}_1}}{\bar{n}_{\widetilde{Z}_1}}\right) \frac{n_{\widetilde{Z}_1}}{\rho_{\widetilde{Z}_1}} \quad (3.2)$$

$$\frac{dn_{\widetilde{G}}}{dt} = -3Hn_{\widetilde{G}} + \left[\bar{n}^2_{\widetilde{G}} - n^2_{\widetilde{G}}\right] \langle\sigma v\rangle_{\widetilde{G}} + \sum_j BR(j \to \widetilde{G})\Gamma_j m_j \left(n_j - \bar{n}_j \frac{n_{\widetilde{G}}}{\bar{n}_{\widetilde{G}}}\right) \frac{n_j}{\rho_j}$$

$$-\sum_j BR(\widetilde{G} \to j)\Gamma_{\widetilde{G}} m_{\widetilde{G}} \left(n_{\widetilde{G}} - \bar{n}_{\widetilde{G}} \frac{n_j}{\bar{n}_j}\right) \frac{n_{\widetilde{G}}}{\rho_{\widetilde{G}}}, \quad (3.3)$$

$$\frac{dn_s}{dt} = -3Hn_s + \left[\bar{n}^2_s - n^2_s\right] \langle\sigma v\rangle_s - \sum_j 2BR(s \to j)\Gamma_s m_s \left(n_s - \bar{n}_s (\frac{n_j}{\bar{n}_s})^2\right) \frac{n_s}{\rho_s}, \quad (3.4)$$

$$\frac{dn_s^{CO}}{dt} = -3Hn_s^{CO} - \Gamma_s n_s^{CO}/\gamma_s, \quad (3.5)$$

$$\frac{dn_{\tilde{a}}}{dt} = -3Hn_{\tilde{a}} + \left[\bar{n}^2_{\tilde{a}} - n^2_{\tilde{a}}\right] \langle\sigma v\rangle_{\tilde{a}} + \sum_j BR(j \to \tilde{a})\Gamma_j m_j \left(n_j - \bar{n}_j \frac{n_{\tilde{a}}}{\bar{n}_{\tilde{a}}}\right) \frac{n_j}{\rho_j}$$

$$-BR(\tilde{a} \to j)\Gamma_{\tilde{a}} m_{\tilde{a}} \left(n_{\tilde{a}} - \bar{n}_{\tilde{a}} \frac{n_j}{\bar{n}_j}\right) \frac{n_{\tilde{a}}}{\rho_{\tilde{a}}}, \quad (3.6)$$

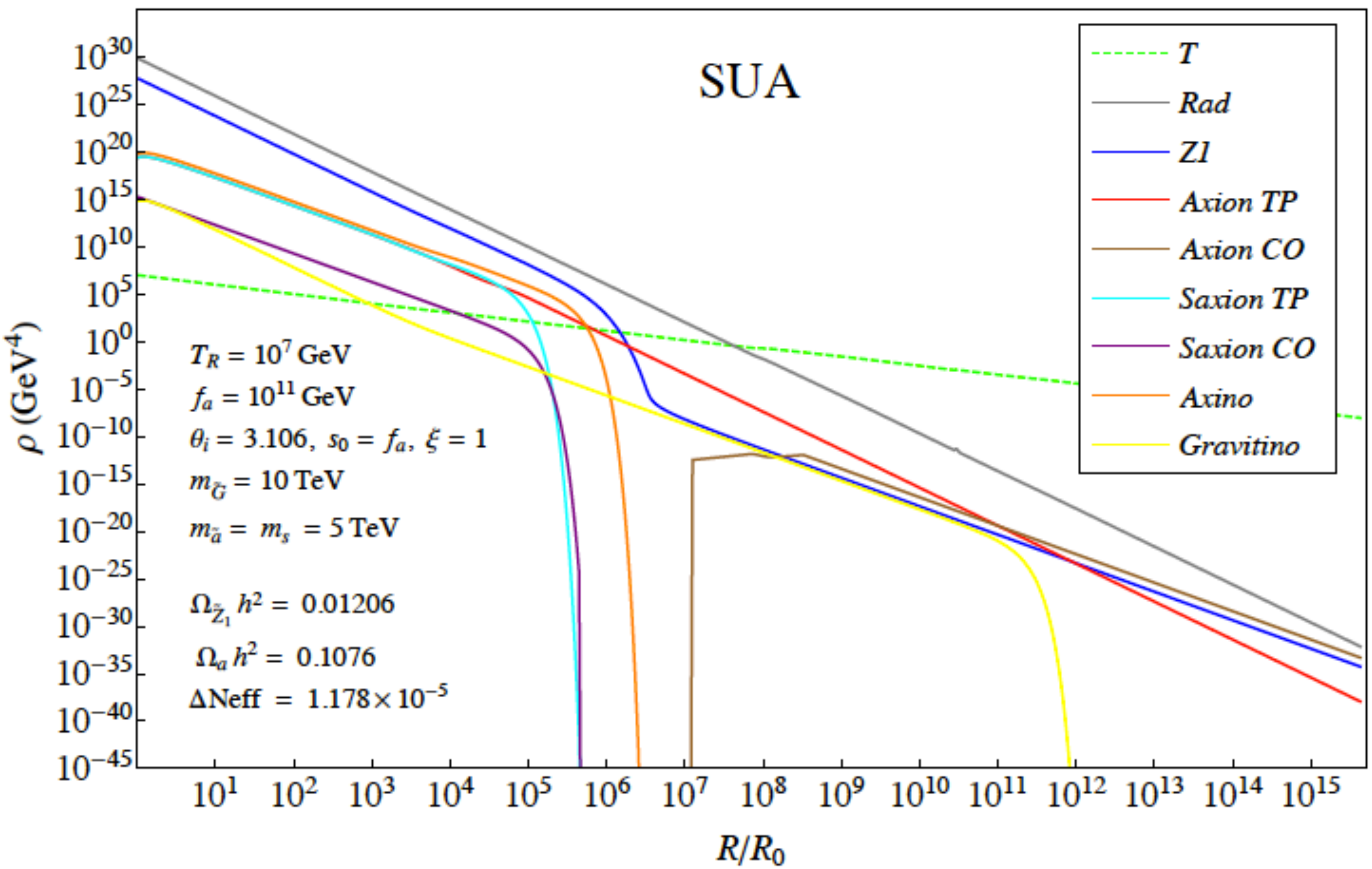
$$\frac{dn_a}{dt} = -3Hn_a + \left[\bar{n}^2_a - n^2_a\right] \langle\sigma v\rangle_a + \sum_j 2BR(j \to a)\Gamma_j m_j \left(n_j - \bar{n}_j \frac{n_a}{\bar{n}_a}\right) \frac{n_j}{\rho_j}, \quad (3.7)$$

$$\frac{dn_a^{CO}}{dt} = -3Hn_a^{CO} + \sum_j BR(j \to a)\Gamma_j n_j/\gamma_j, \quad (3.8)$$

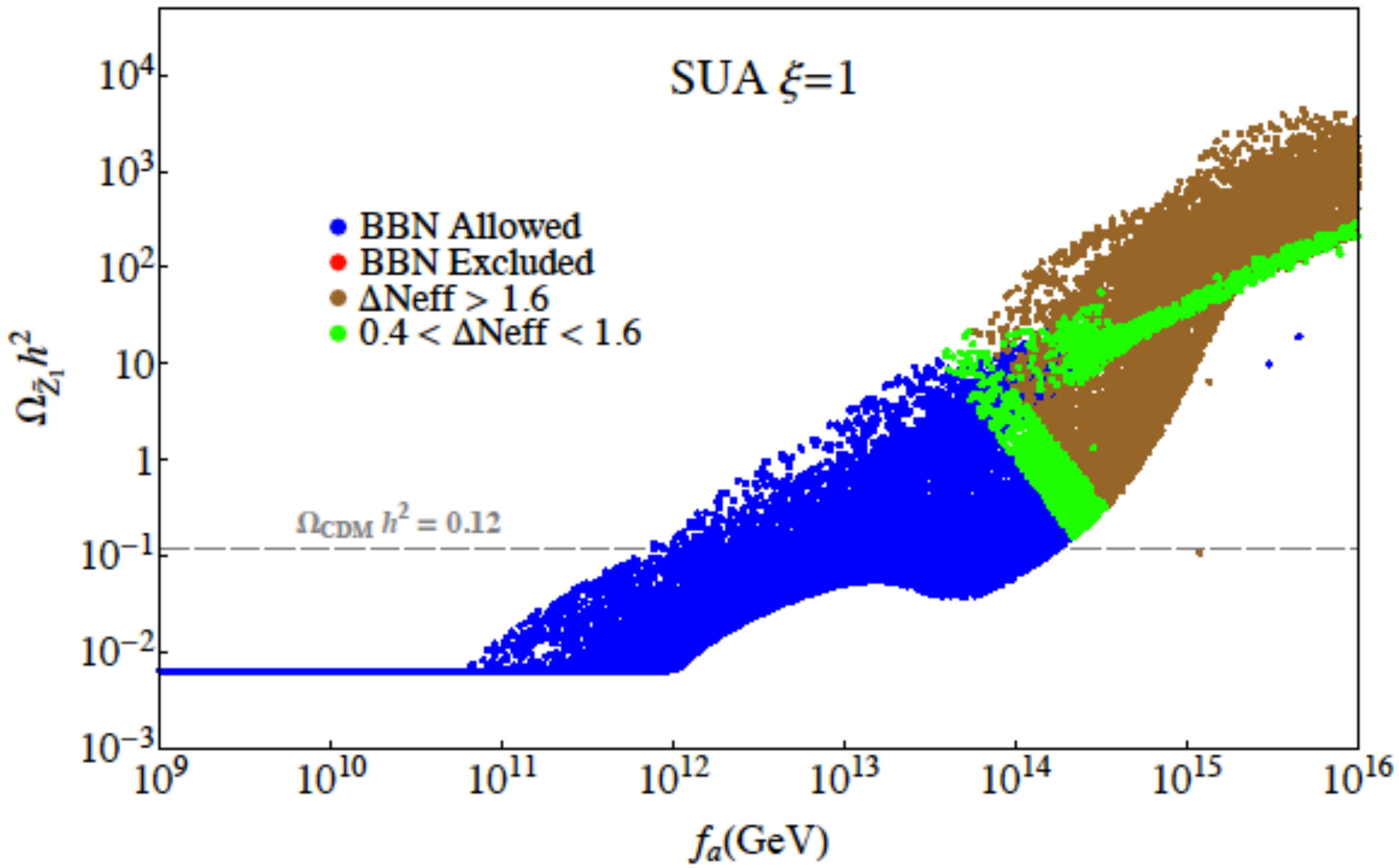
$$\frac{dS}{dt} = \frac{R^3}{T} \sum_i BR(i \to X)\Gamma_i m_i \left(n_i - \bar{n}_i \sum_{i \to \cdots} B_{ab\cdots} \frac{n_a n_b \cdots}{\bar{n}_a \bar{n}_b \cdots}\right) \quad (3.9)$$

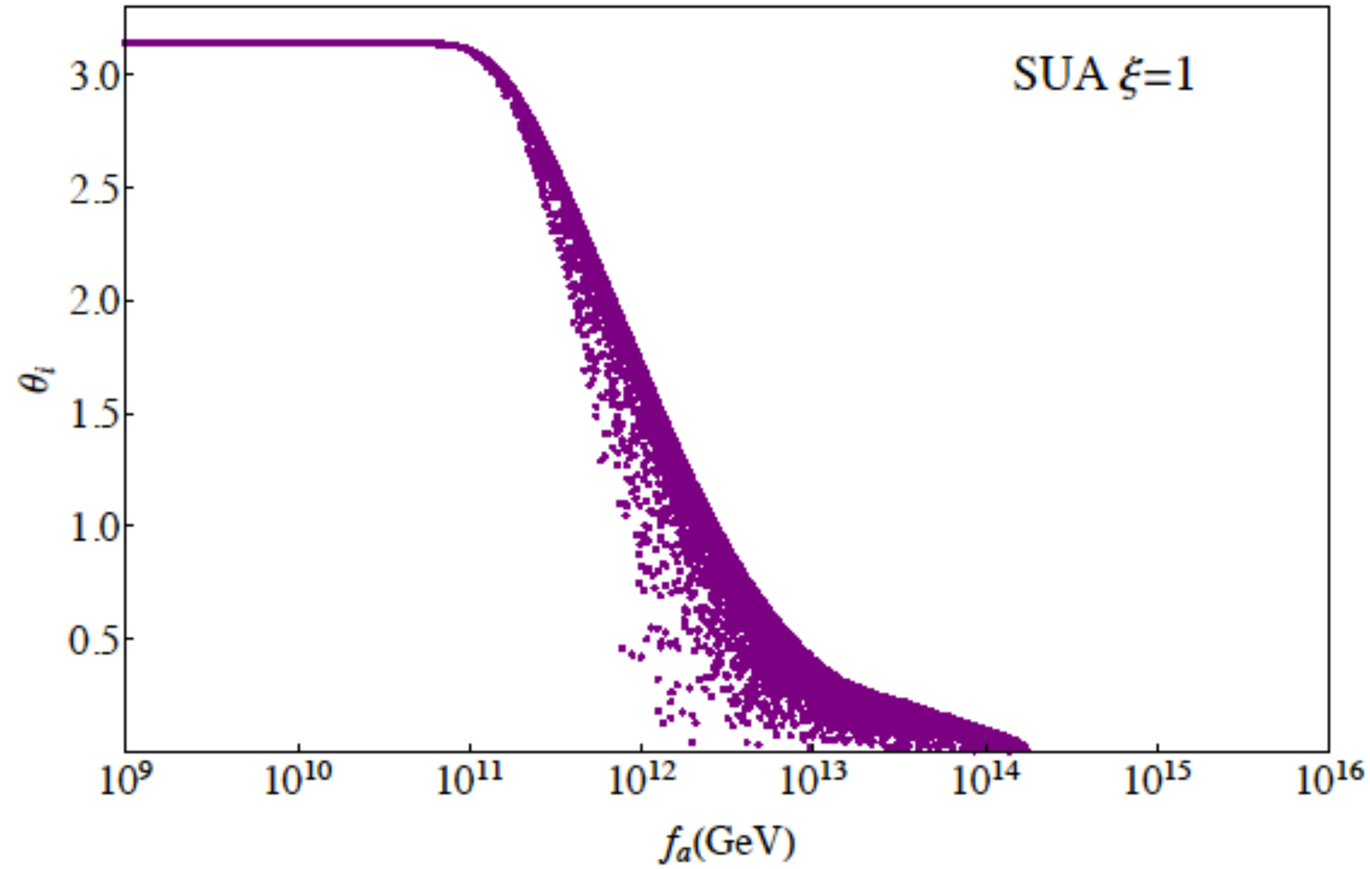
$$H \equiv \dot{R}/R = \sqrt{\rho_T / 3M_P^2}$$

DM production in SUSY DFSZ: solve eight coupled Boltzmann equation



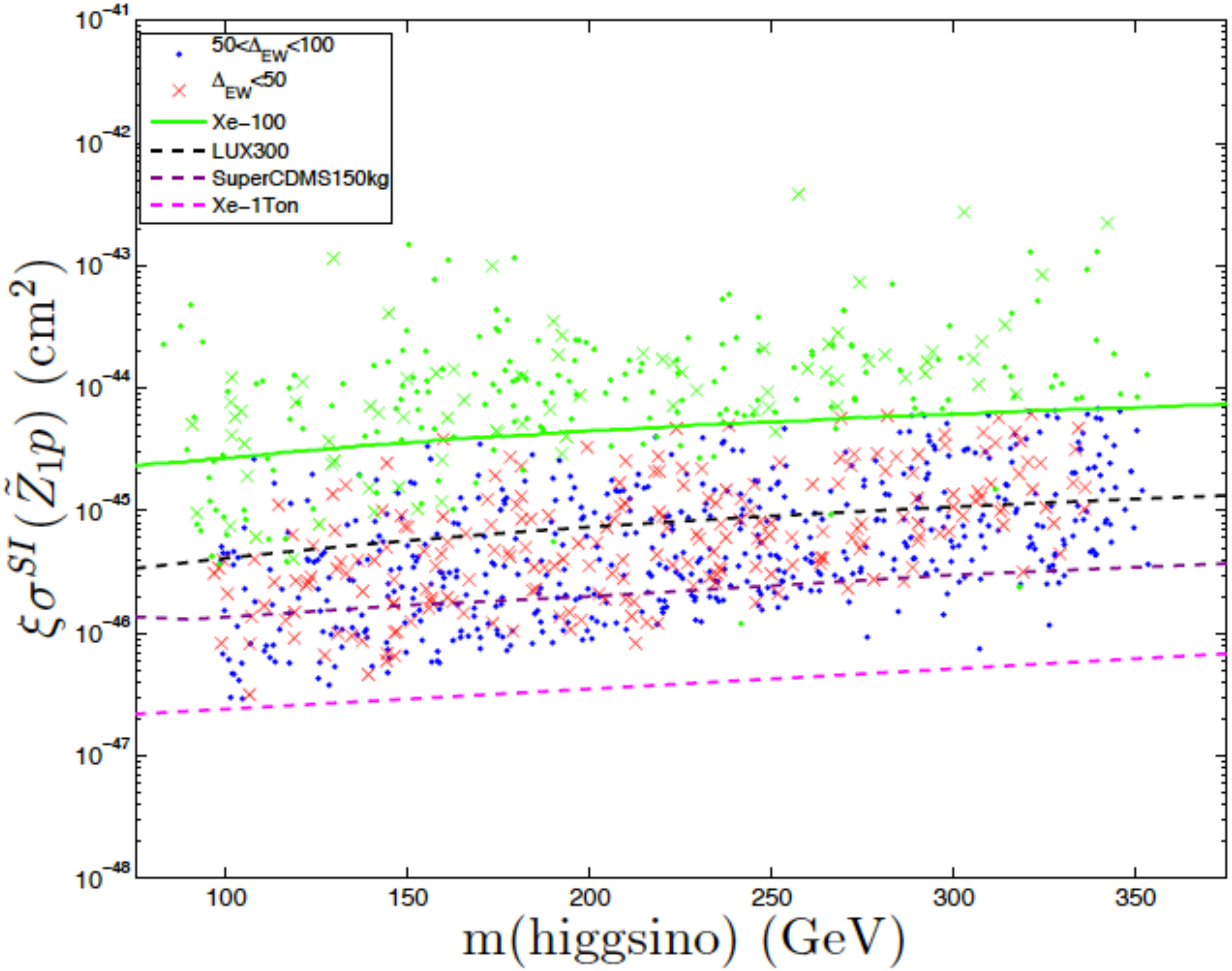
HB, Bae, Chun;
HB, Bae, Lessa, Serce





mainly axion CDM for fa<10^11 GeV; for higher fa, then get increasing wimp abundance

Direct higgsino detection rescaled for minimal local abundance



HB, Barger, Mickelson
arXiv:1303.3816

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

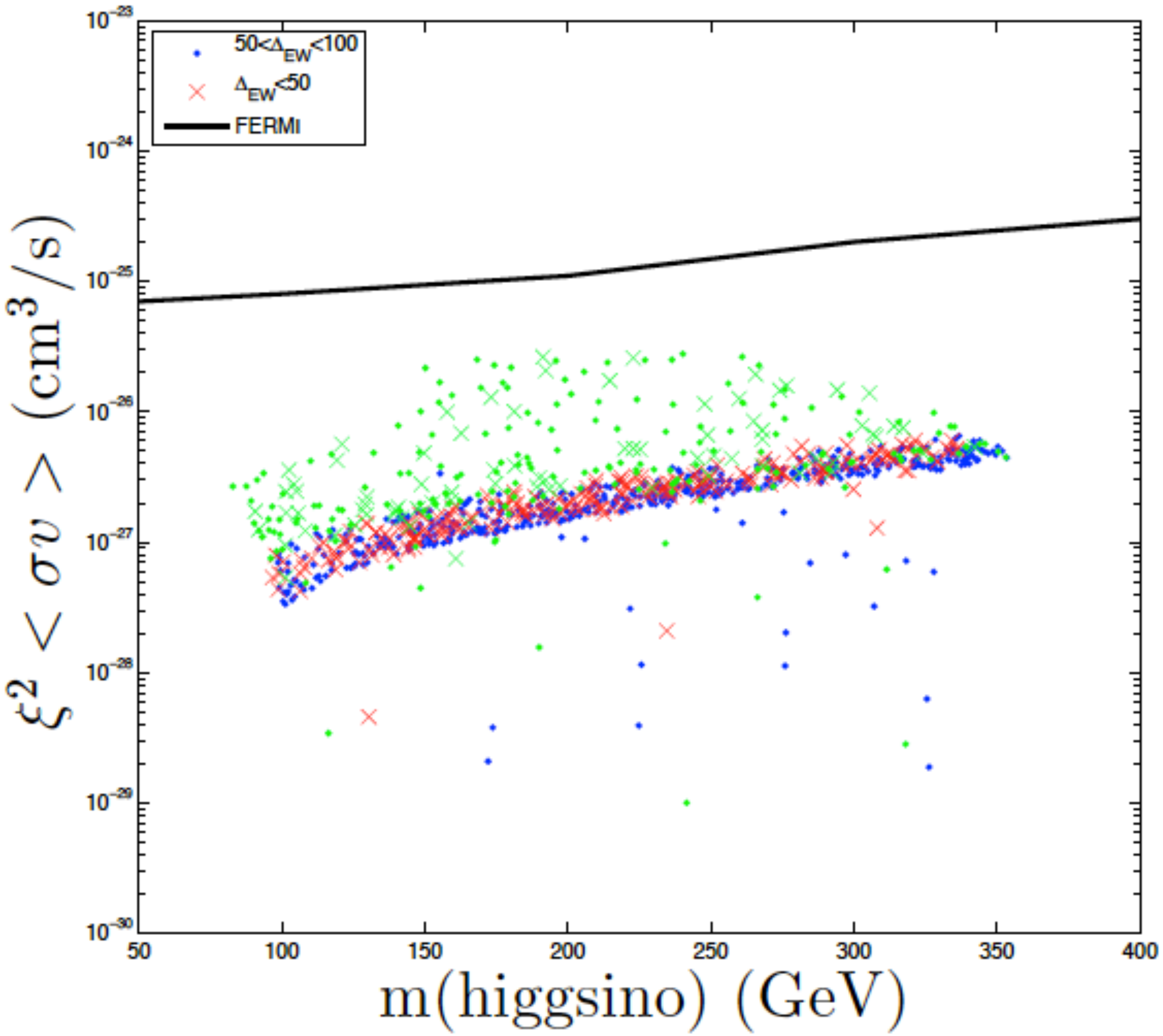
$$X^h_{11} = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(gv_3^{(1)} - g'v_4^{(1)}\right)$$

new LUX results

Deployment of Xe-1ton coming soon!

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

Indirect detection via wimp annihilation suppressed by square of reduced local abundance

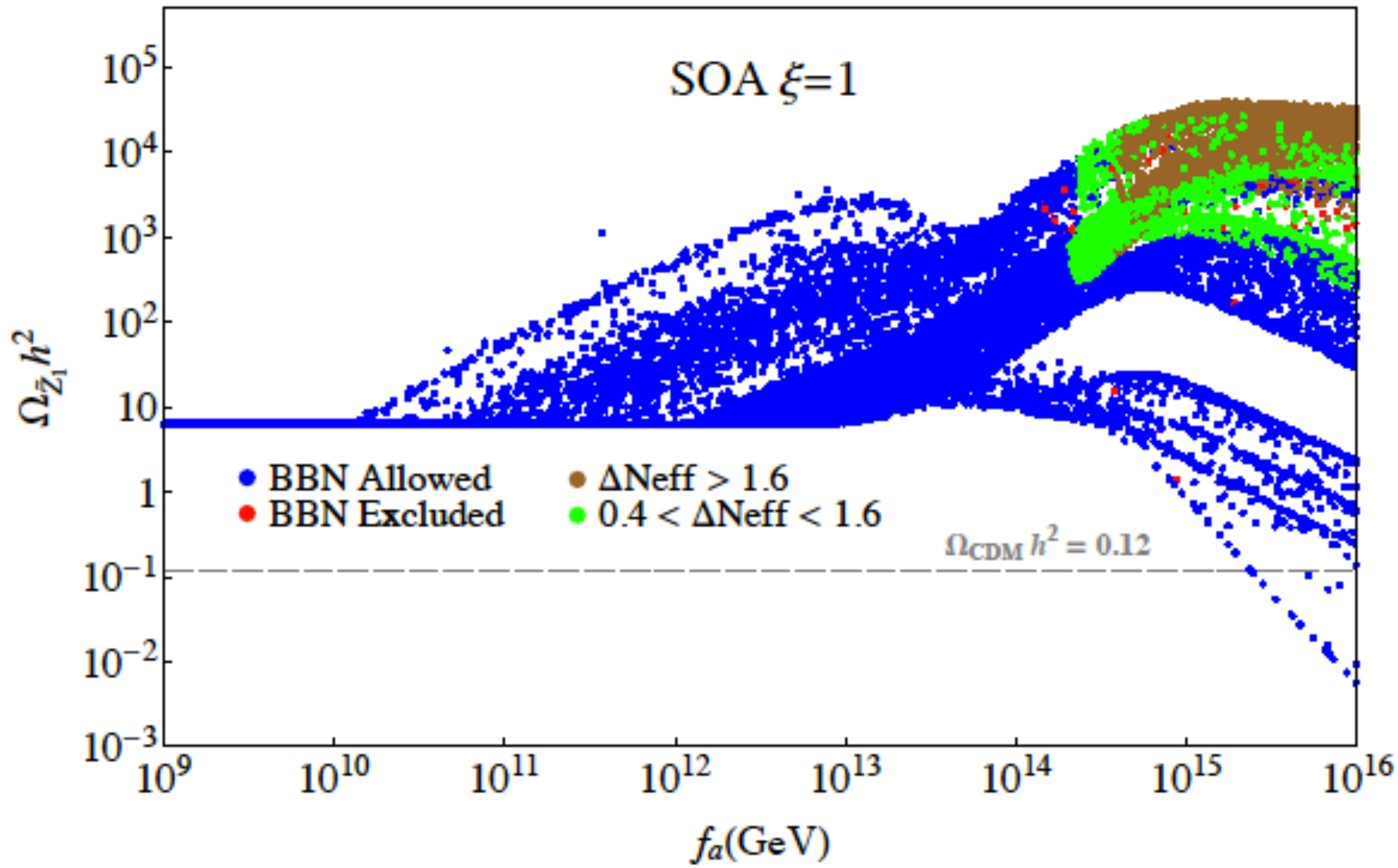


Conclusions: status of SUSY post LHC8

- SUSY EWFT non-crisis: EWFT allowed at 10% level in radiatively-driven natural SUSY: SUGRA GUT paradigm is just fine
- naturalness maintained for mu~100-200 GeV; t1~1-2 TeV, t2~2-4 TeV, highly mixed; m(glno)~1-5 TeV
- RNS spectra characterized by mainly higgsino-like WIMP: standard relic underabundance
- 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
- Discovery of and precision measurements of light higgsinos!
- DFSZ invisible axion model: solves strong Cp and mu problems while allowing for mu~m(Z)
- Expect mainly axion CDM with 5-10% higgsino-like WIMPs over much of p-space
- Ultimately detect both axion and higgsino-like WIMP

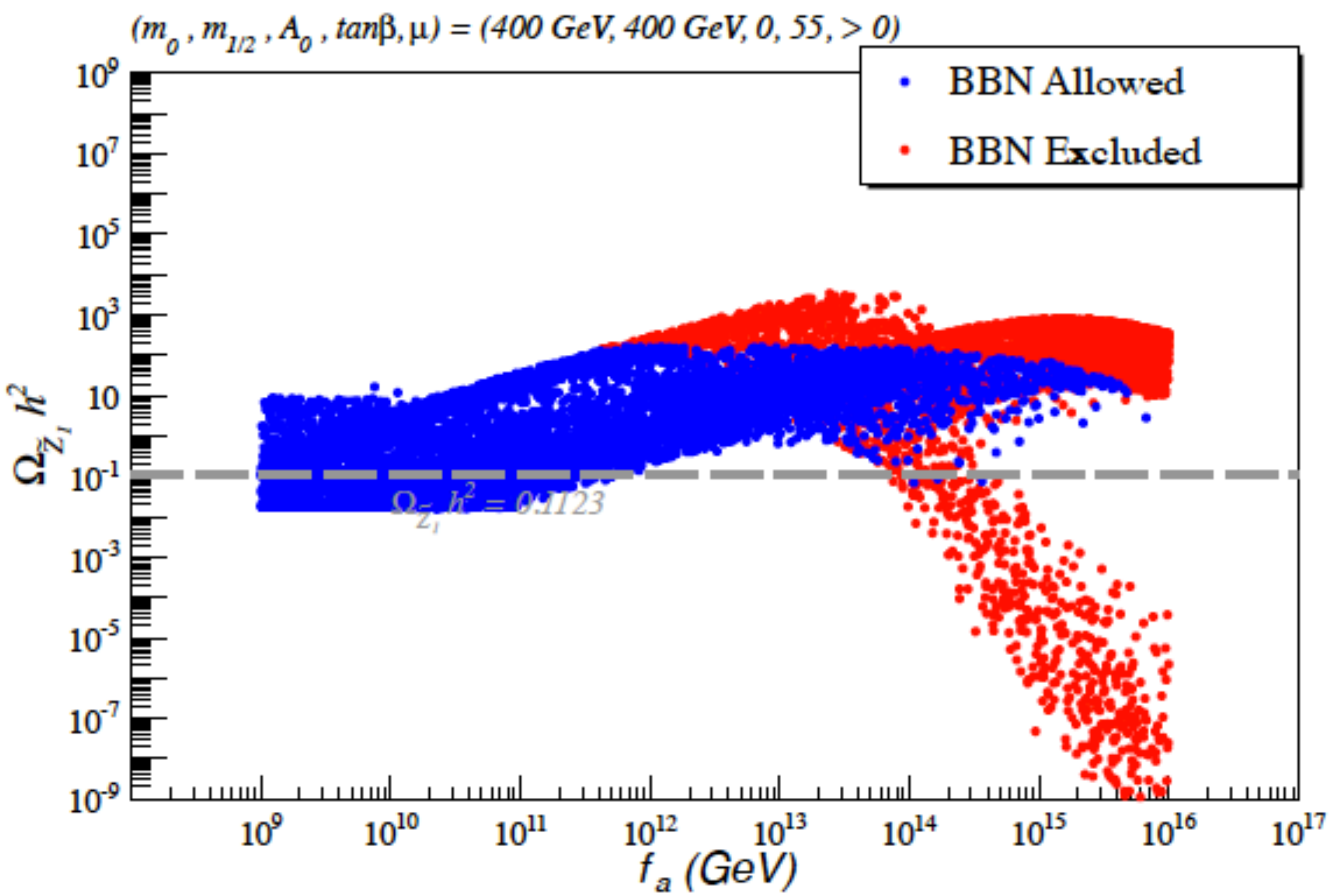
Backup

Case with standard overabundance of bino-like WIMPs



Excluded over most of f_a range except $f_a > 2 \times 10^{15}$ GeV where there can be significant entropy dilution so long as $m_s < 2m_{\tilde{Z}_1}$

Mixed axion/higgsino DM in KSVZ with xi=0



mixed axion/higgsino DM in KSVZ with xi=1