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

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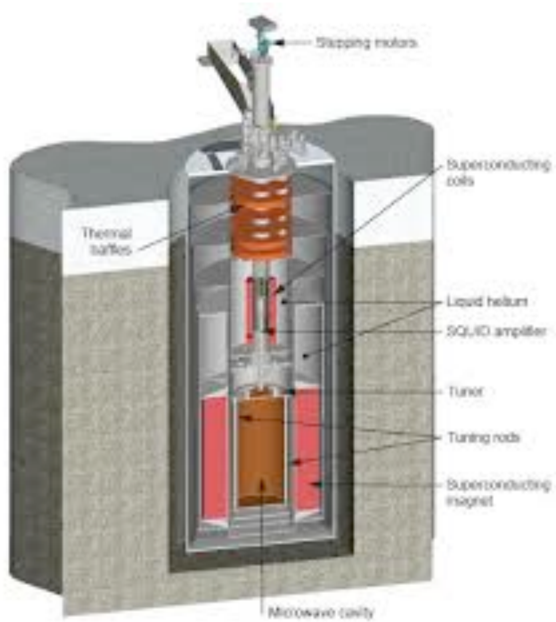
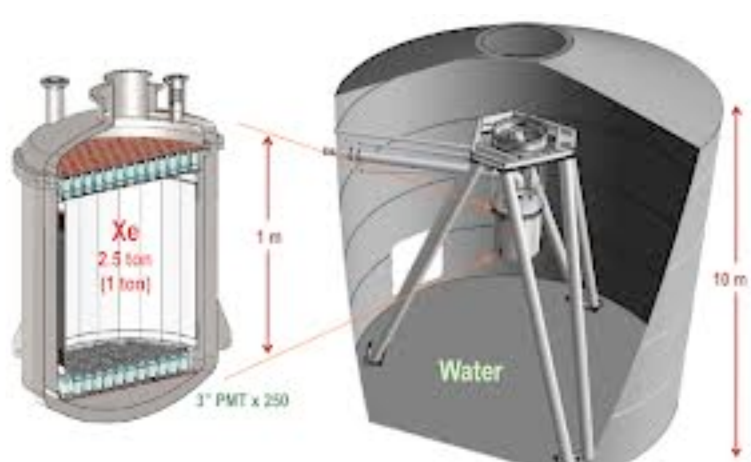


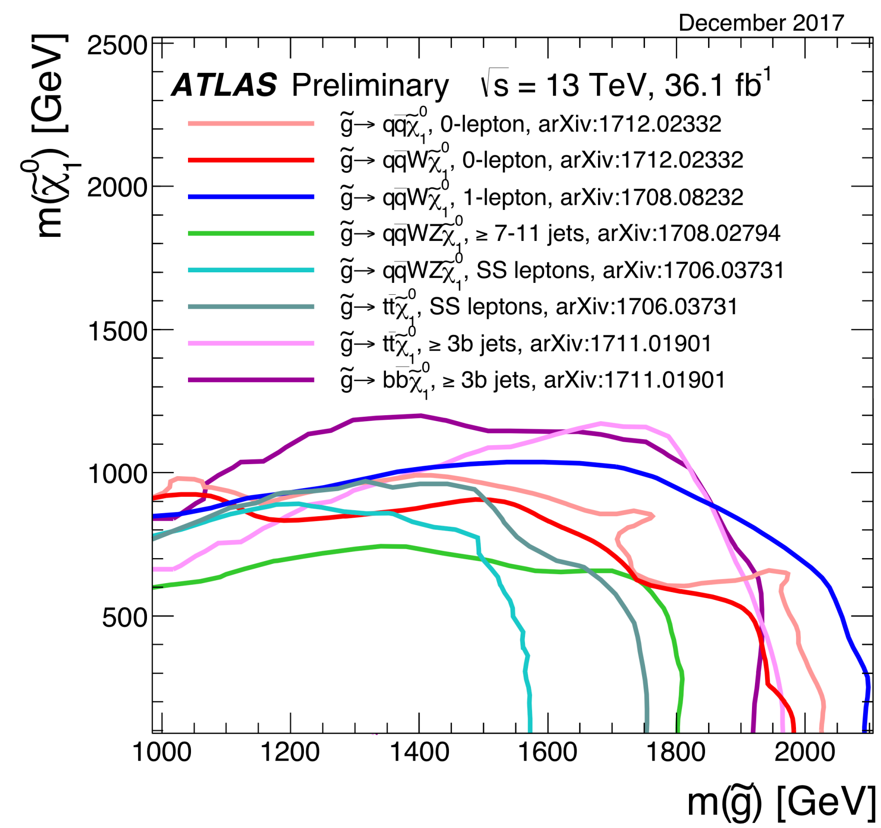




# Lots of problems with SM

- 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(gluino)>2 TeV
- LHC: m(t1)>1 TeV
- m(h)~125 GeV
- compare: Barbieri-Giudice naturalness: m(gluino)<350 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: $\Delta_{EW}$

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

**naturalness: no large unnatural cancellations on RHS**

HB,Barger, Huang, Mustafayev, Tata, PRL109 (2012)161802

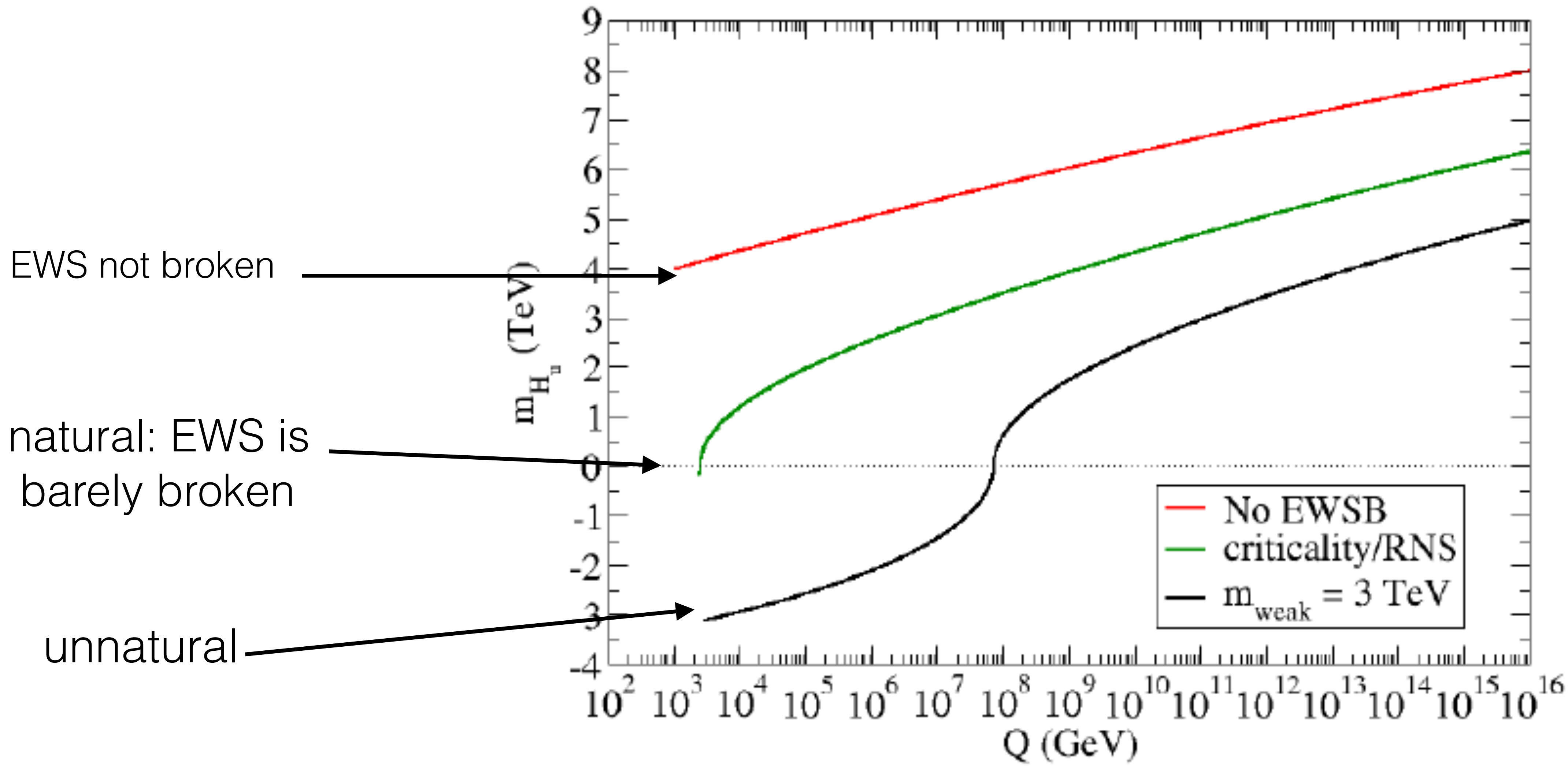
then:

- $\mu \sim 100 - 200$ GeV
- $m_{H_u}^2$ can be driven to natural via large top Yukawa
- radiative corrections not too large  m(t1)~1-3 TeV fine

naturalness: only higgsinos need be ~100-200 GeV

higgsino is LSP

higgsino-like WIMP~100-200 GeV thermally underproduced as DM 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 $sign(m_{H_u}^2)\sqrt{|m_{H_u}^2|}$ vs. $Q$

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:

$$W \ni \lambda \phi_{PQ}^2 H_u H_d / M_P$$

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking

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

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

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

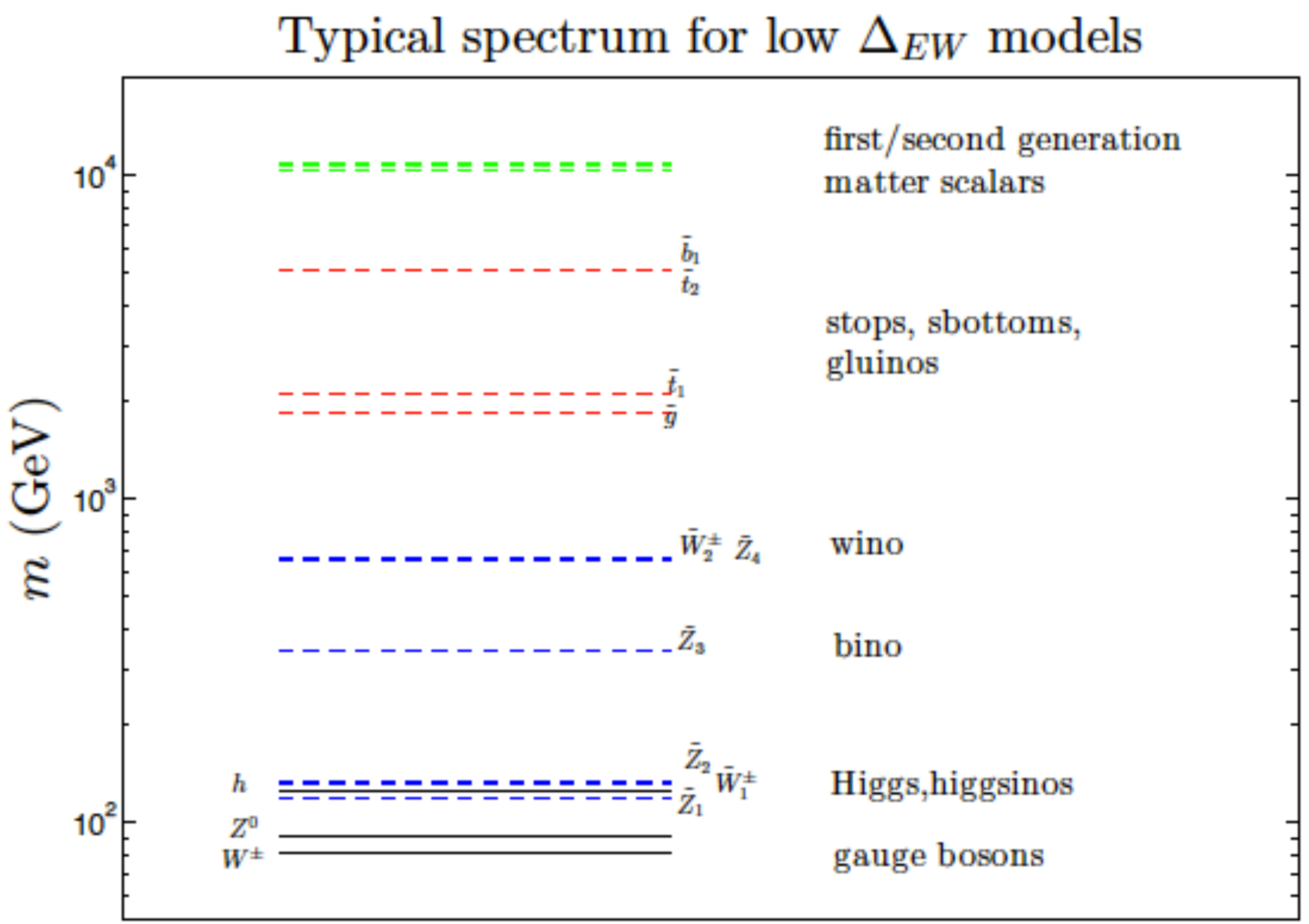
$$f_a \ll m_{hid}$$

Higgs mass tells us where to look for axion!

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

| bounds from naturalness (3%) | old BG/DG | Delta_EW |
|---|---|---|
| **mu** | 350 GeV | 350 GeV |
| **gluino** | 400-600 GeV | 5000 GeV |
| **t1** | 450 GeV | 3000 GeV |
| **sq/sl** | 550-700 GeV | 10-20 TeV |

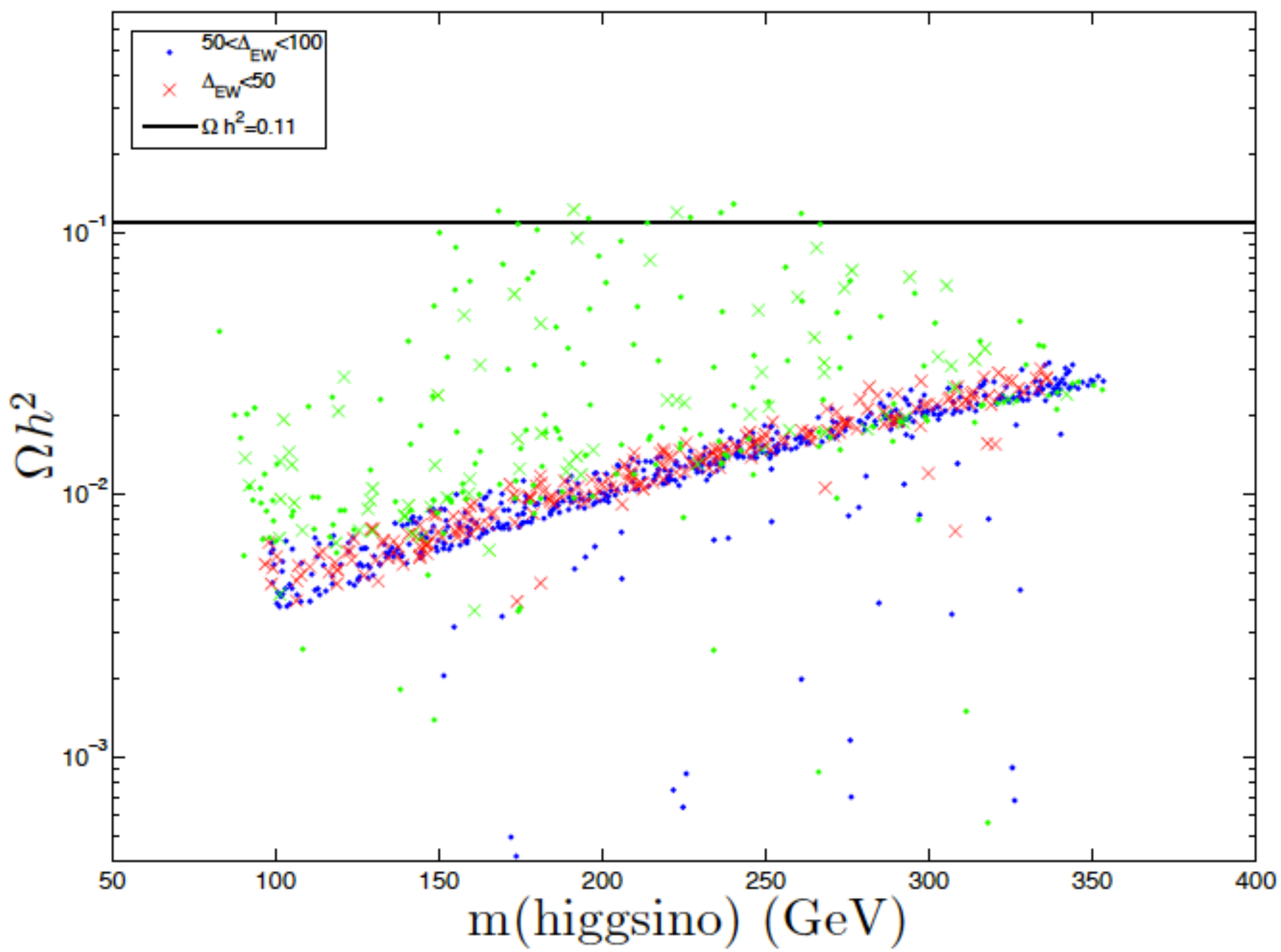
h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis!




There is a Little Hierarchy, but it is no problem

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

# Mainly higgsino-like WIMPs thermally underproduce DM




green: excluded;
red/blue:allowed

HB, Barger, Mickelson

IsaReD

$$\Omega_\chi^{TP} h^2 \sim 10 - 15 \text{ too low!}$$

but axion may constitute bulk of DM

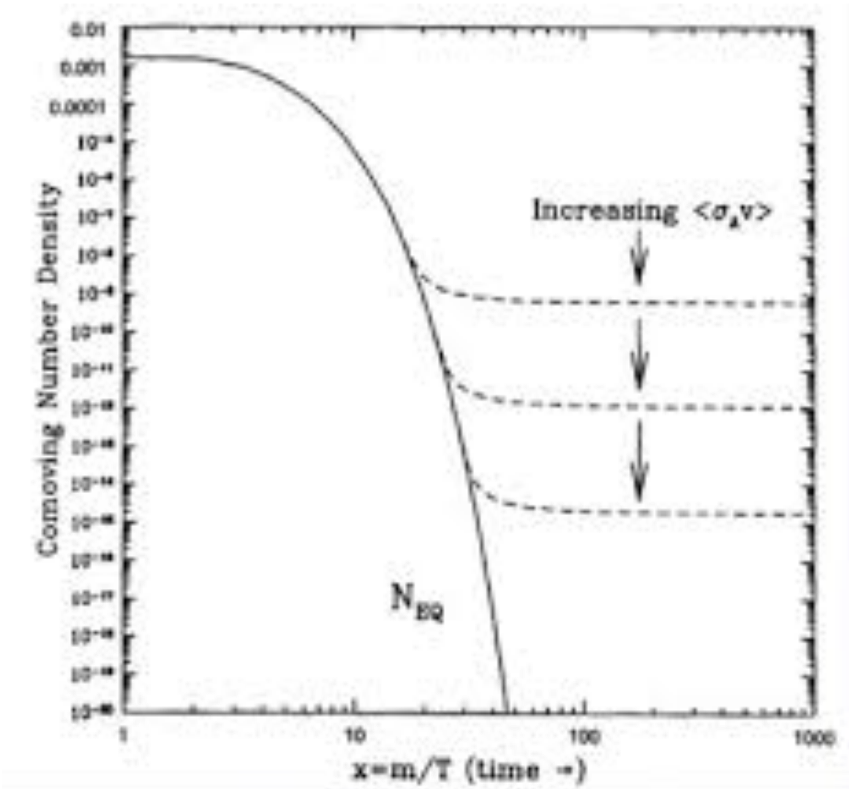
# mixed axion-neutralino production in early universe

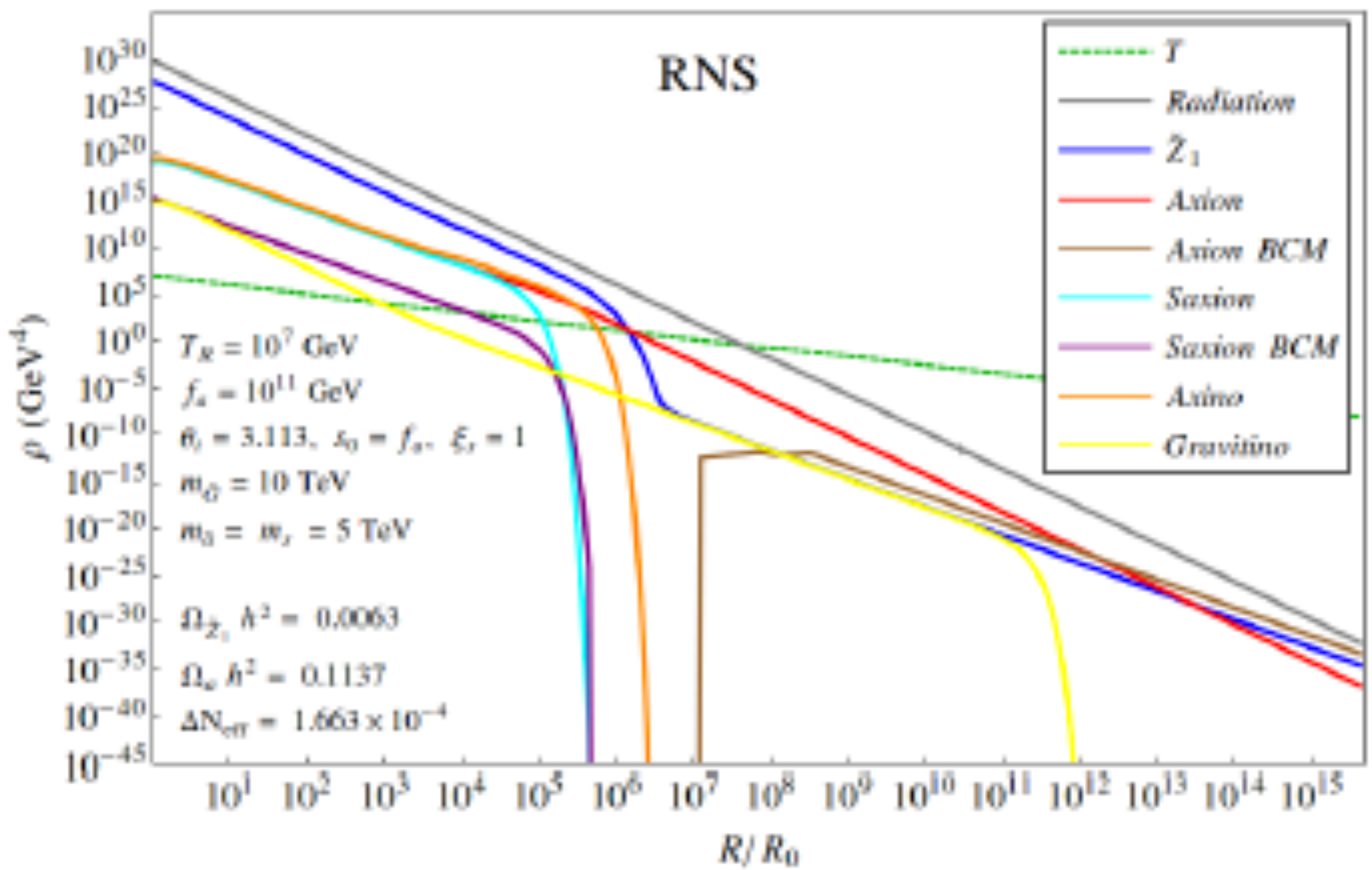
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, $s$ or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: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

**to calculate: solve 8 coupled Boltzmann equation**

Bae, HB, Serce

usual picture => mixed axion/WIMP

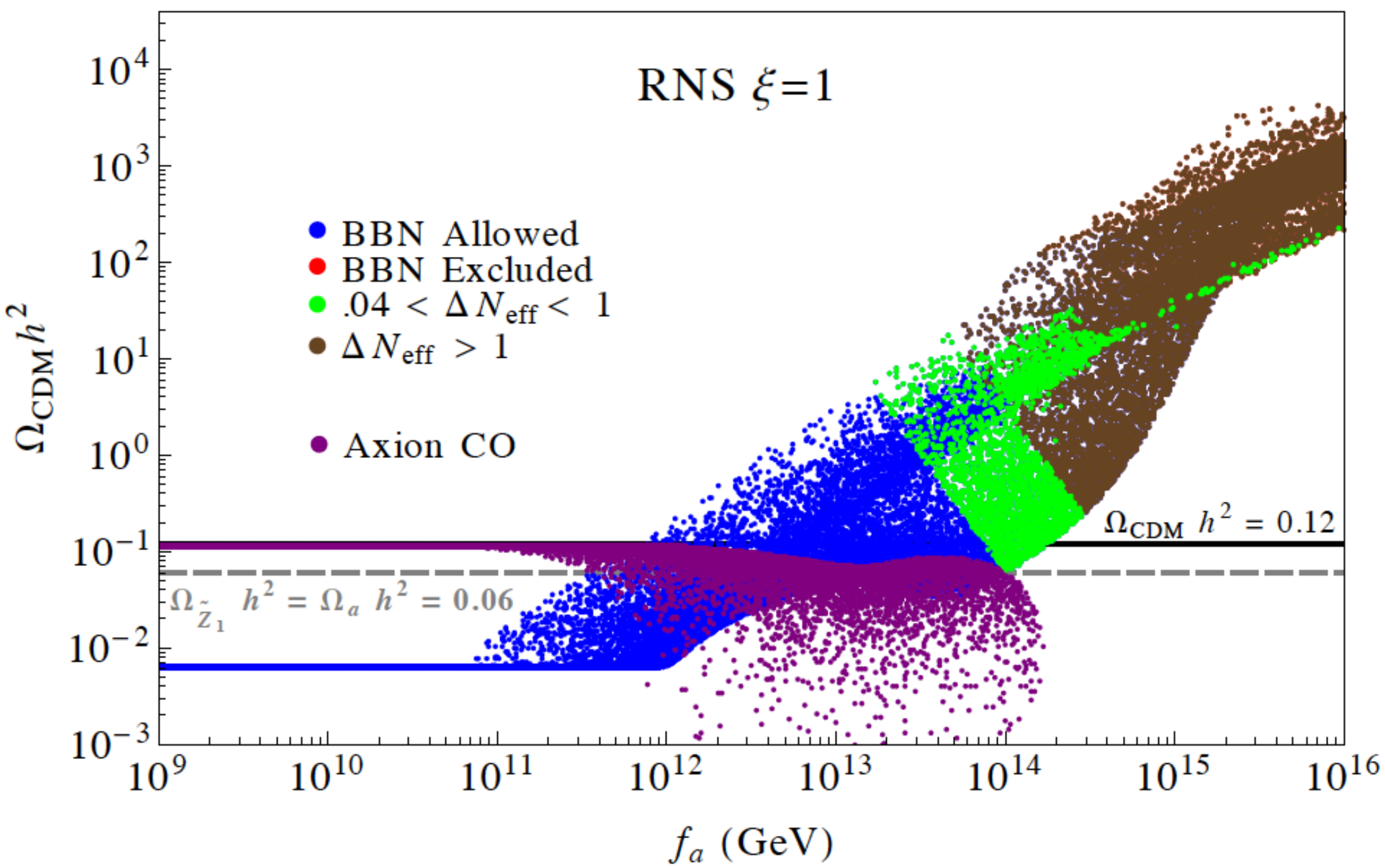



KJ Bae, HB, Lessa, Serce

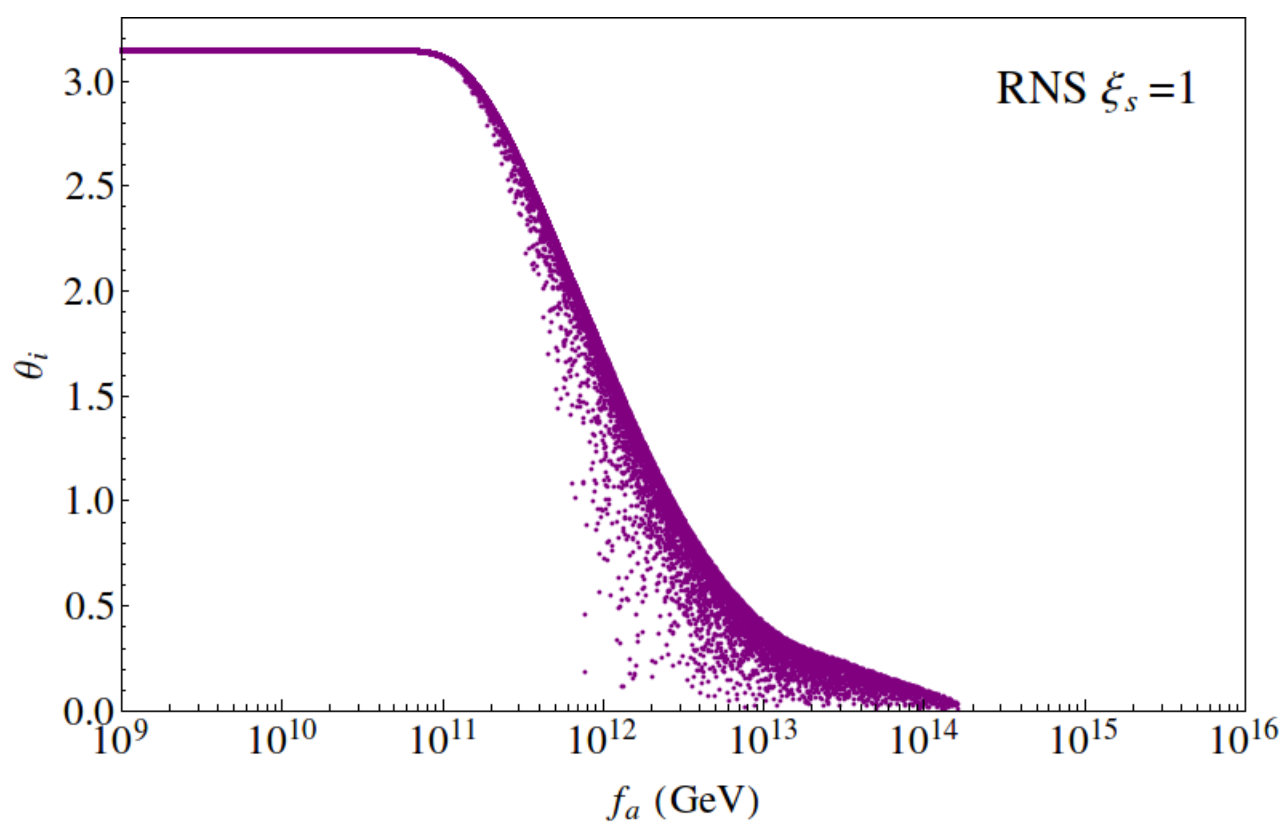
much of parameter space is axion-dominated
with 10-15% WIMPs

=>




higgsino abundance

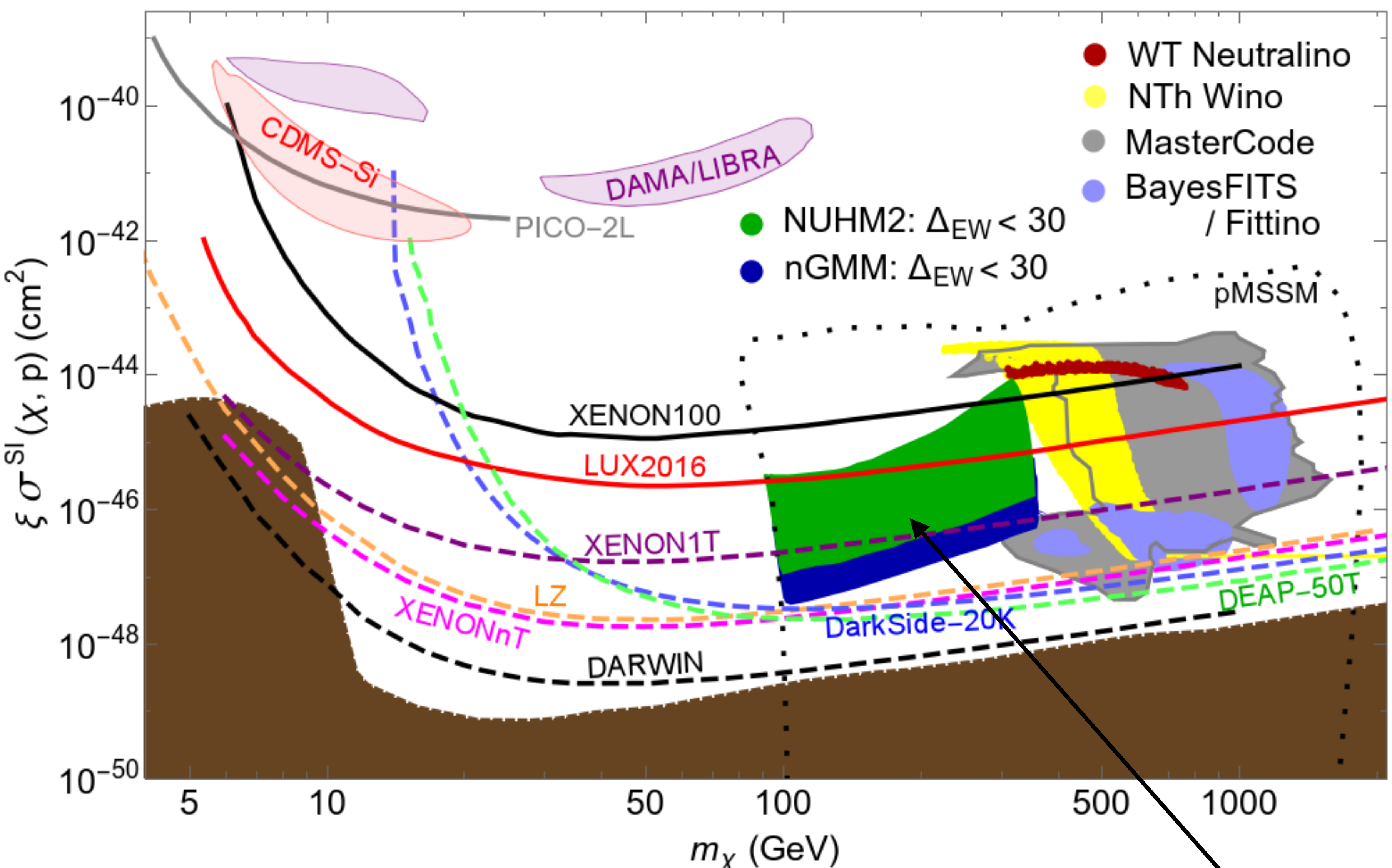
axion abundance




mainly axion CDM for fa<~10^12 GeV; for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce

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




natural SUSY

Bae, HB, Barger, Savoy, Serce

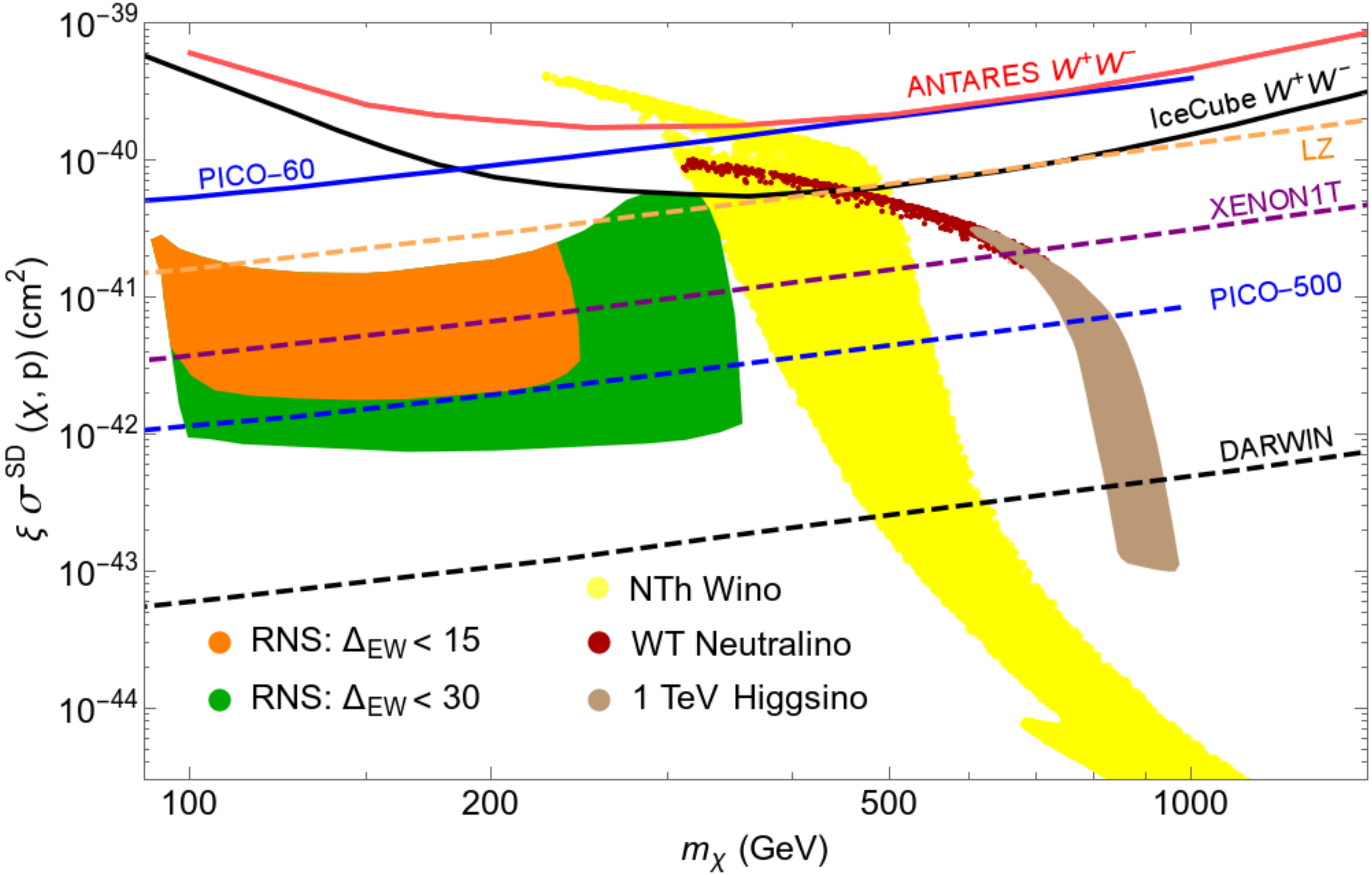
$$\mathcal{L} \ni -X_{11}^h \overline{\widetilde{Z}}_1 \widetilde{Z}_1 h$$

$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

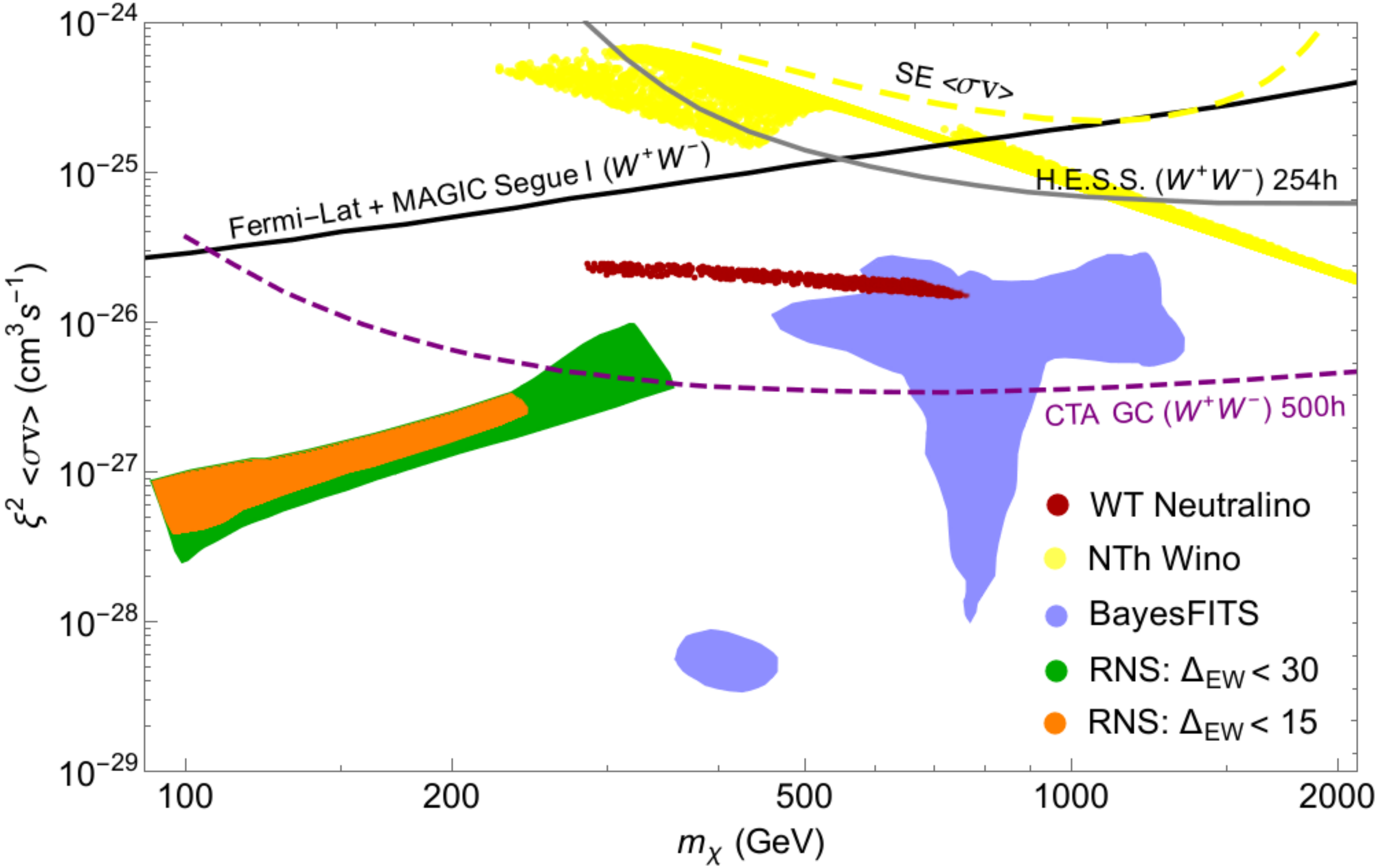
Xe-1-ton now operating!

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

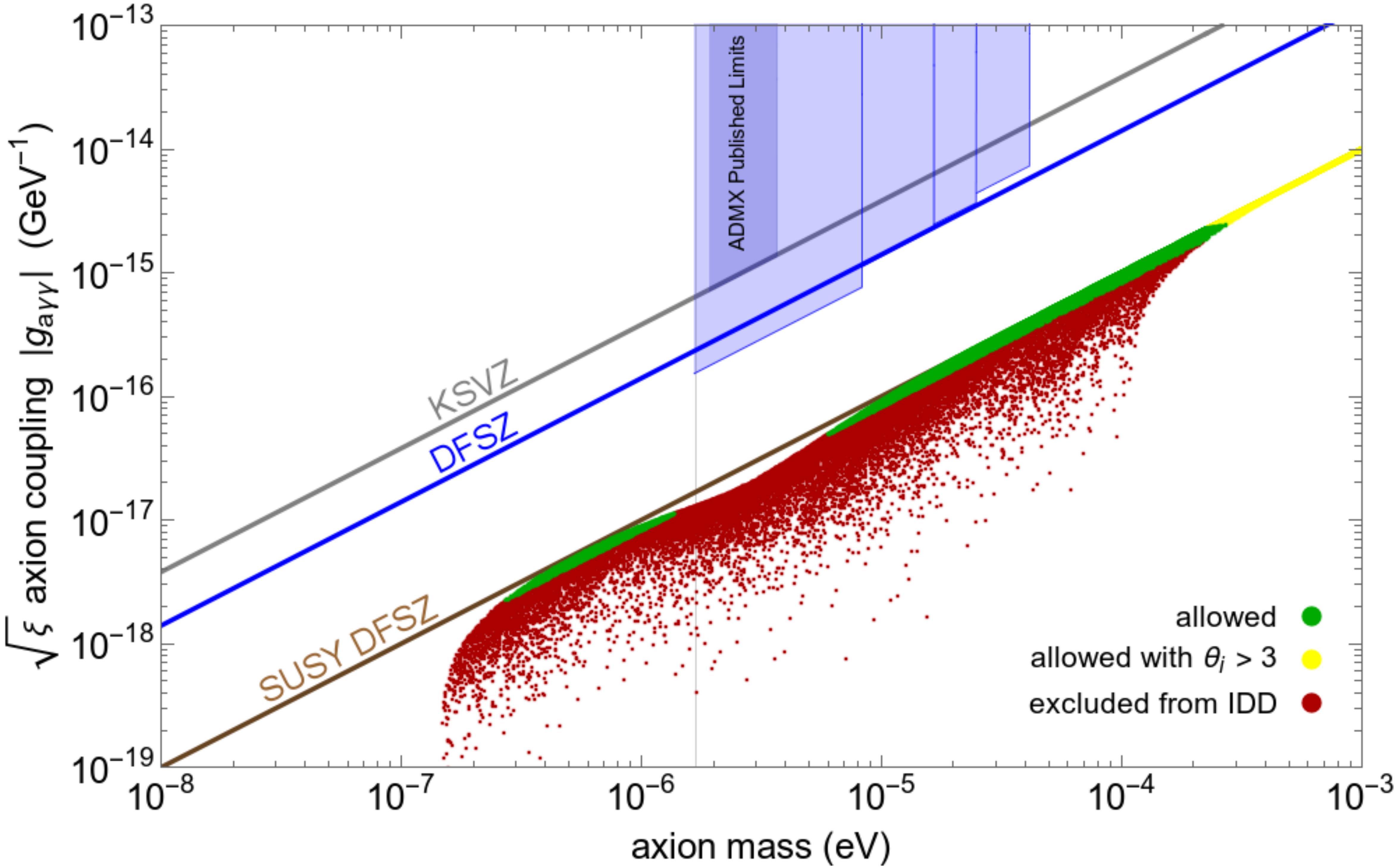
# Prospects for SD WIMP searches:



# Prospects for IDD WIMP searches:

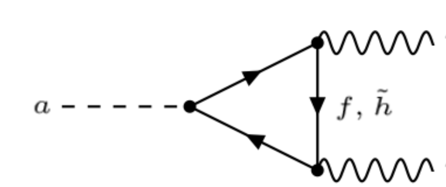



suppressed by square of diminished WIMP abundance




SUSY DFSZ axion: large range in m(a) but coupling reduced

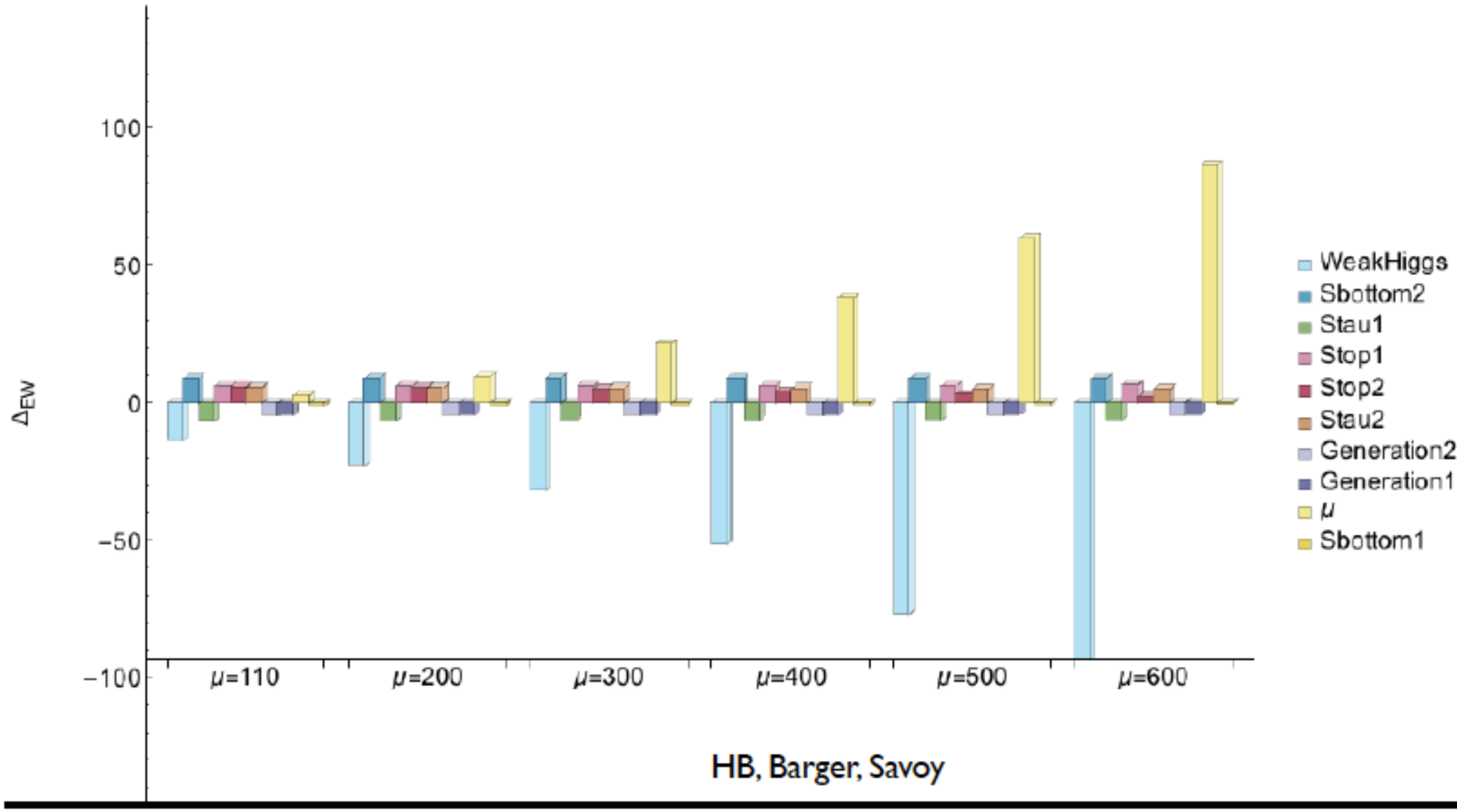
may need to probe broader and deeper!



# summary slide

- Solve gauge hierarchy (SUSY)
- Solve strong CP (axion)
- Solve SUSY mu problem (SUSY DFSZ axion)
- Allow/generate Little Hierarchy [mu << m(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)

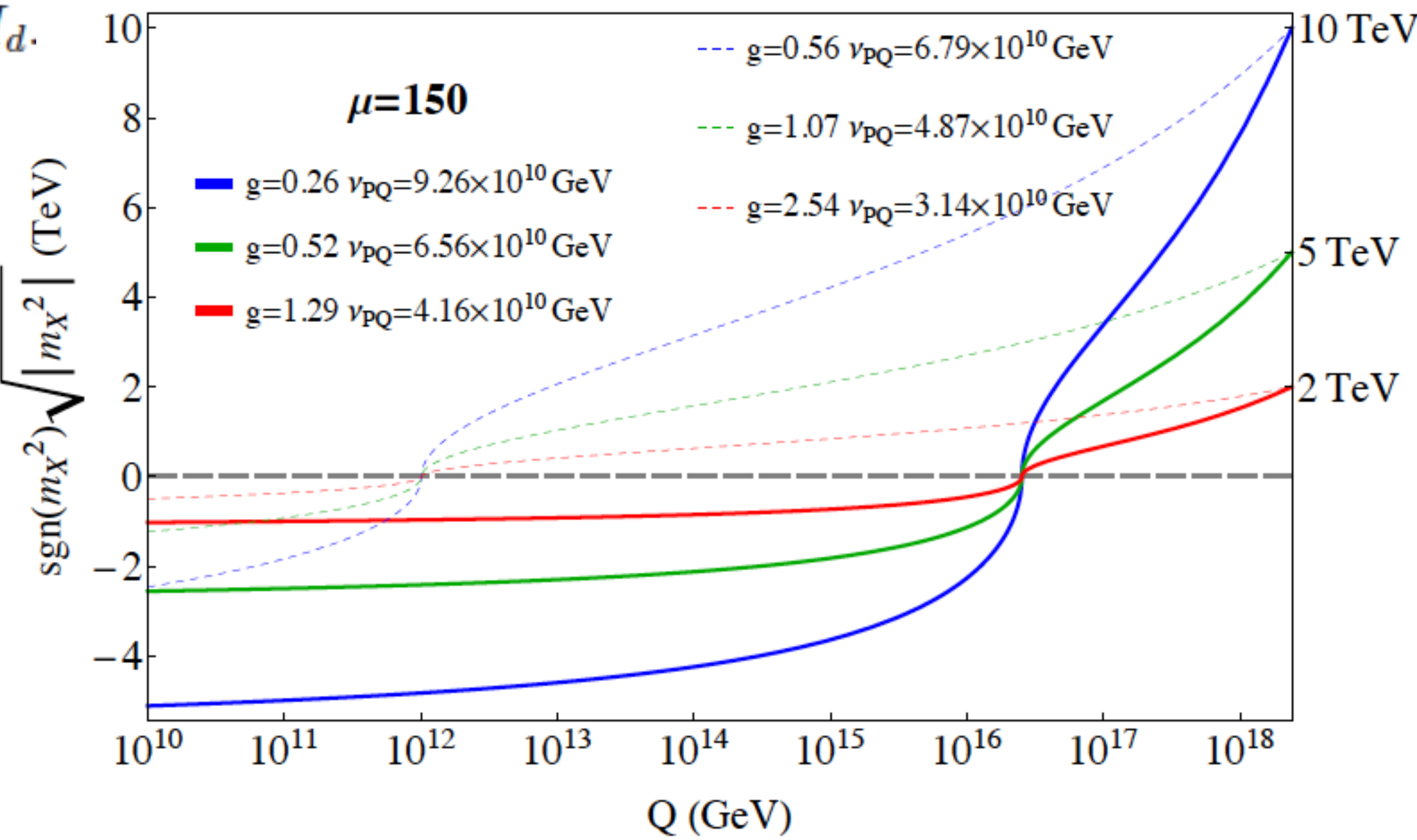
Bae, HB, Serce, PRD91 (2015) 015003

# augment MSSM with PQ charges/fields:

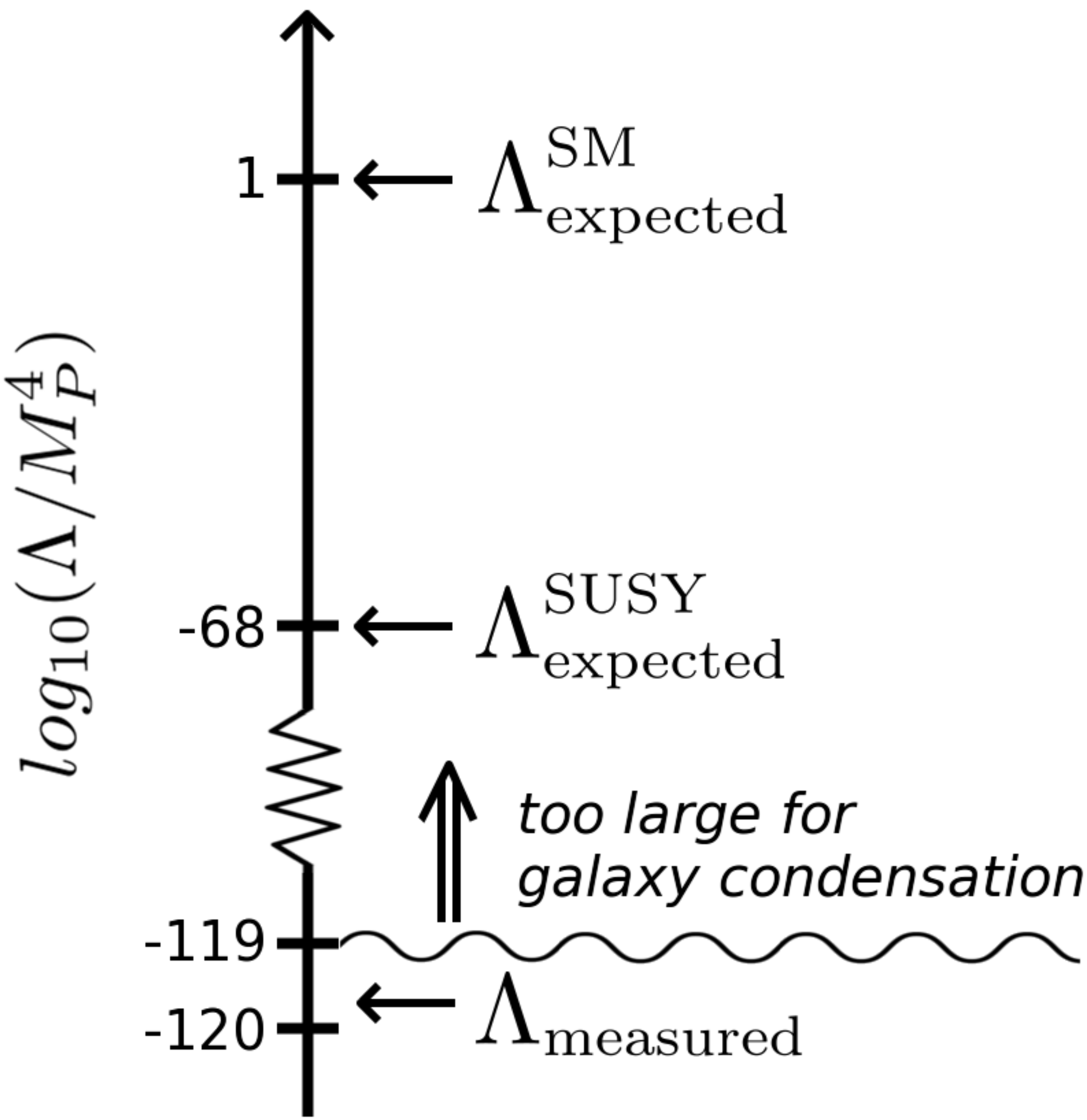
$$\hat{f}' = \frac{1}{2}h_{ij}\hat{X}\hat{N}_i^c\hat{N}_j^c + \frac{f}{M_P}\hat{X}^3\hat{Y} + \frac{g}{M_P}\hat{X}\hat{Y}\hat{H}_u\hat{H}_d.$$

$$M_{N_i^c} = v_X\, h_i|_{Q=v_X}$$

$$\mu = g\frac{v_X v_Y}{M_P}\,.$$



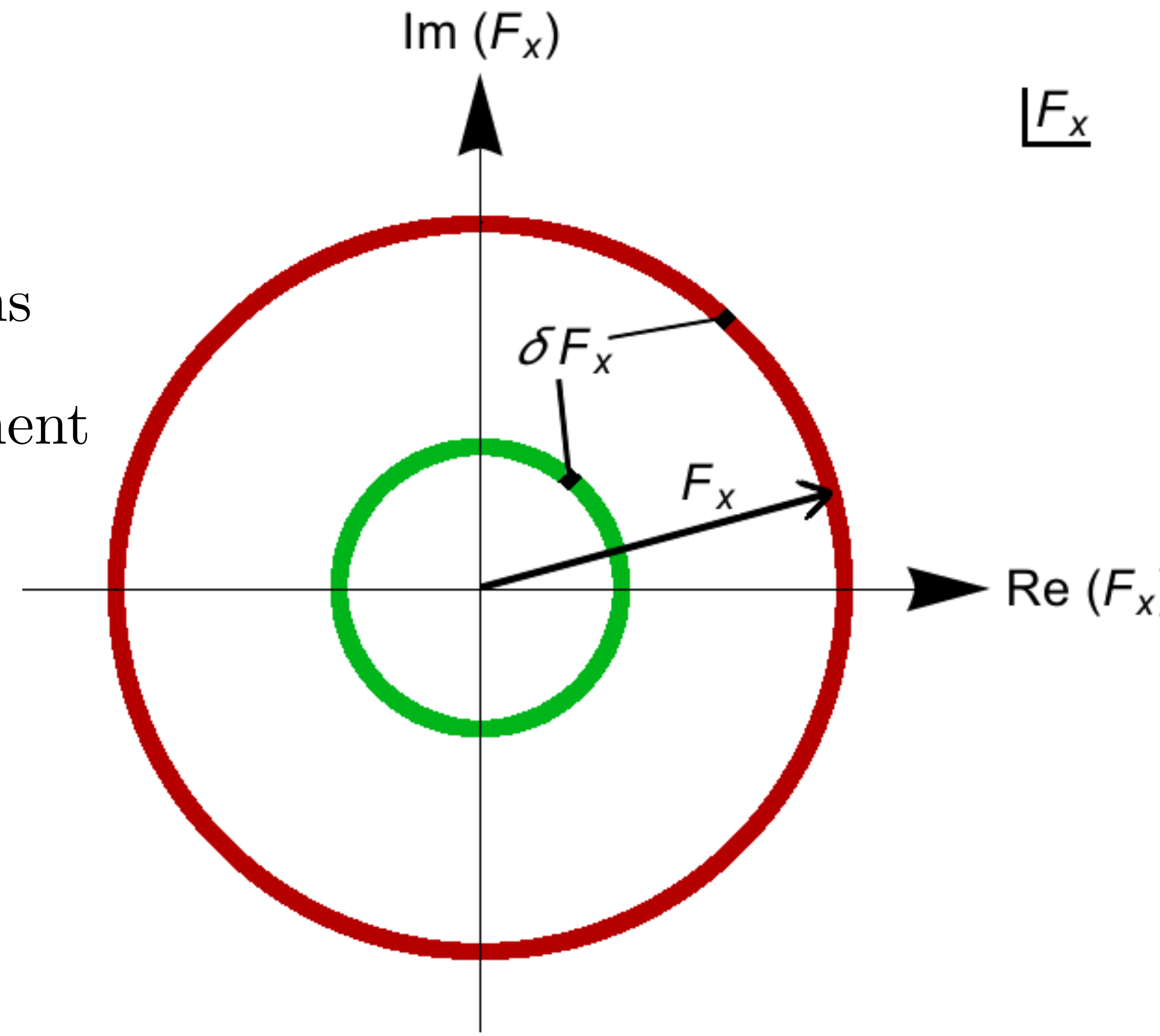

Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!


$log_{10}(\Lambda/M_P^4)$
1
$\Lambda^{\rm SM}_{\rm expected}$
-68
$\Lambda^{\rm SUSY}_{\rm expected}$
too large for
galaxy condensation
-119
-120
$\Lambda_{\rm measured}$

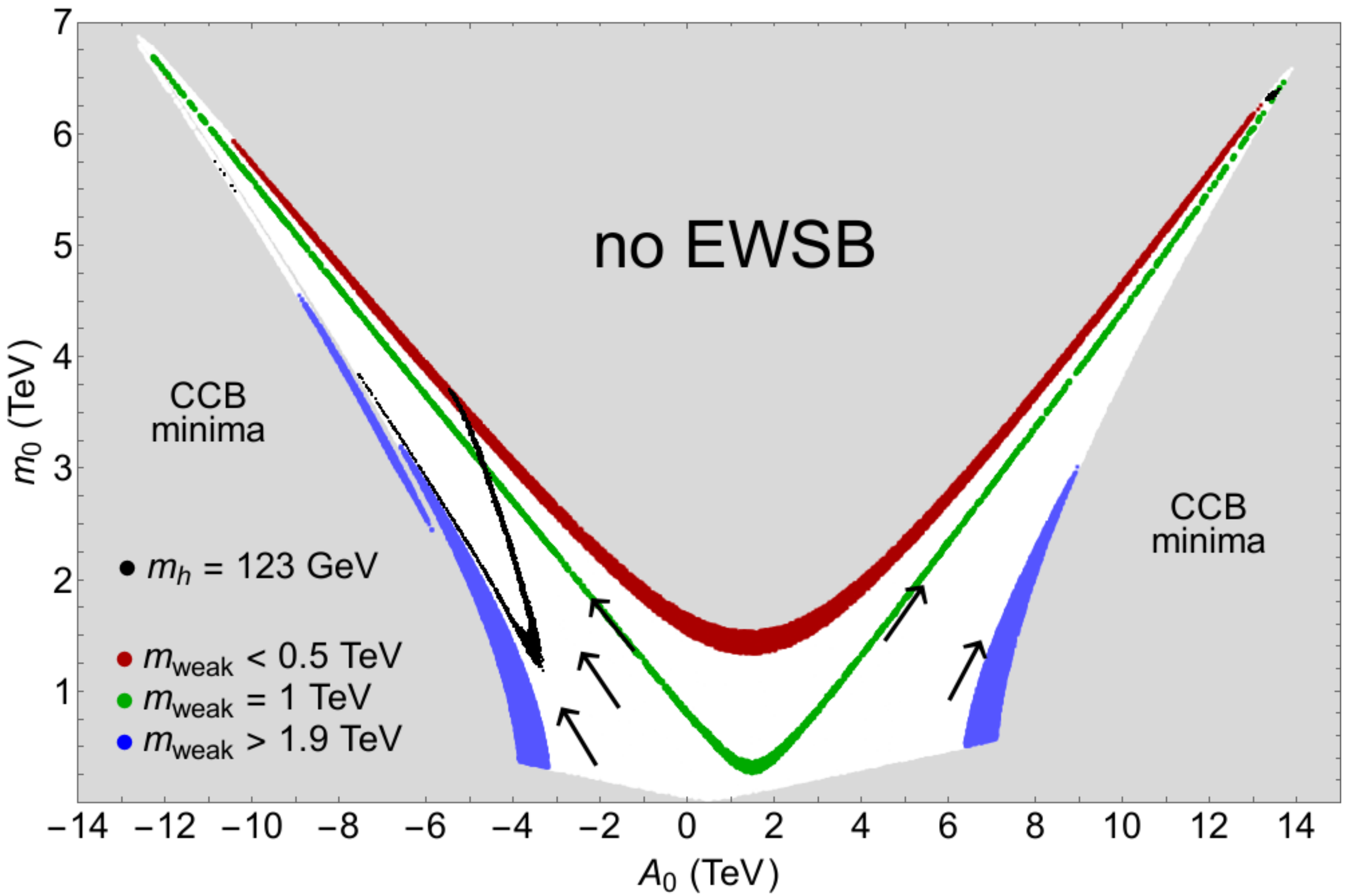
# Why do soft terms take on values needed for natural (barely-broken) EWSB?

string theory landscape?

- assume model like MSY/CCK where $\mu \sim 100$ GeV
- then $m(weak)^2 \sim |m^2_{H_u}|$
- 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



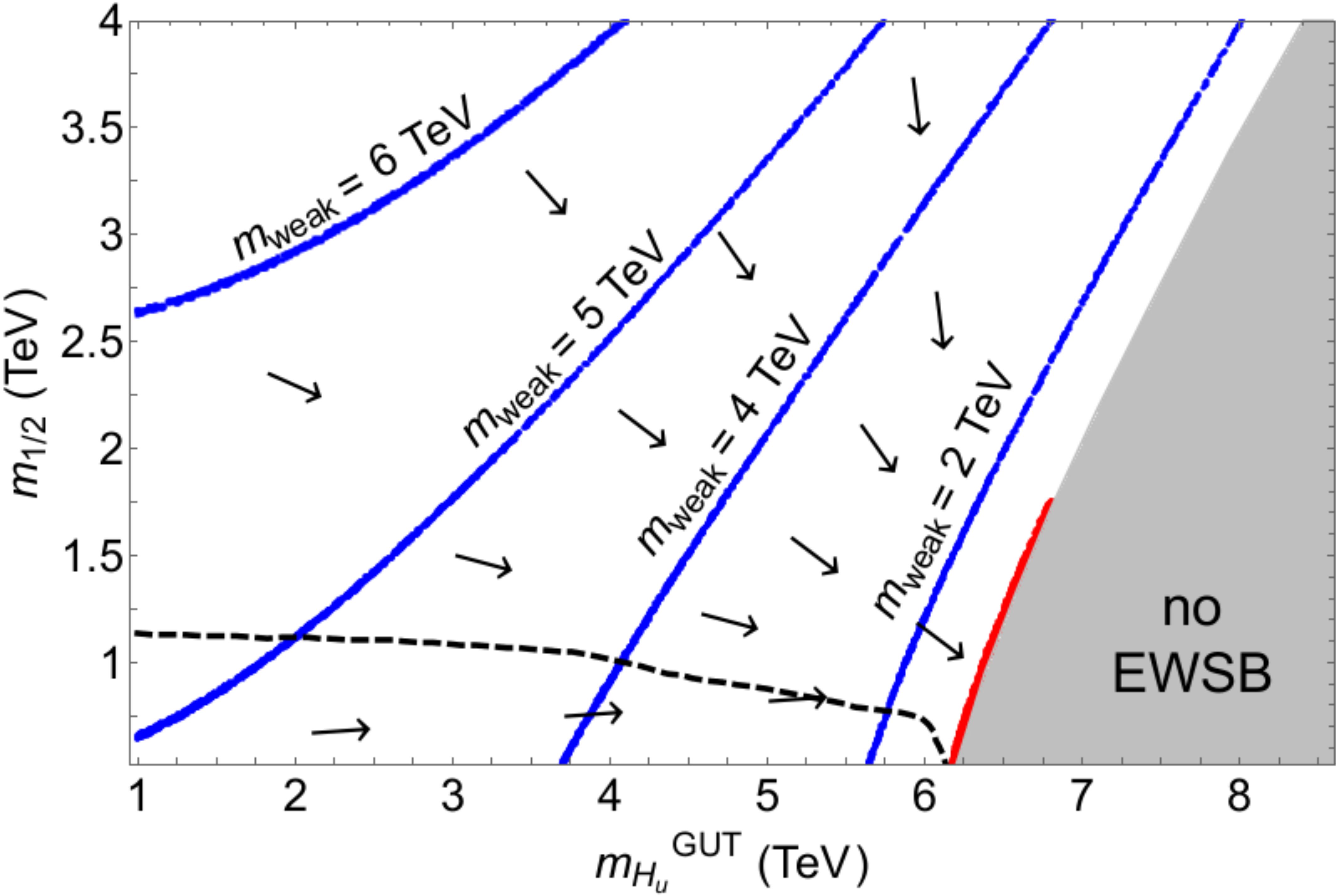

*Anthropic selection of* $m_{weak} \sim 100\ GeV$:
If $m_W$ too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them




statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

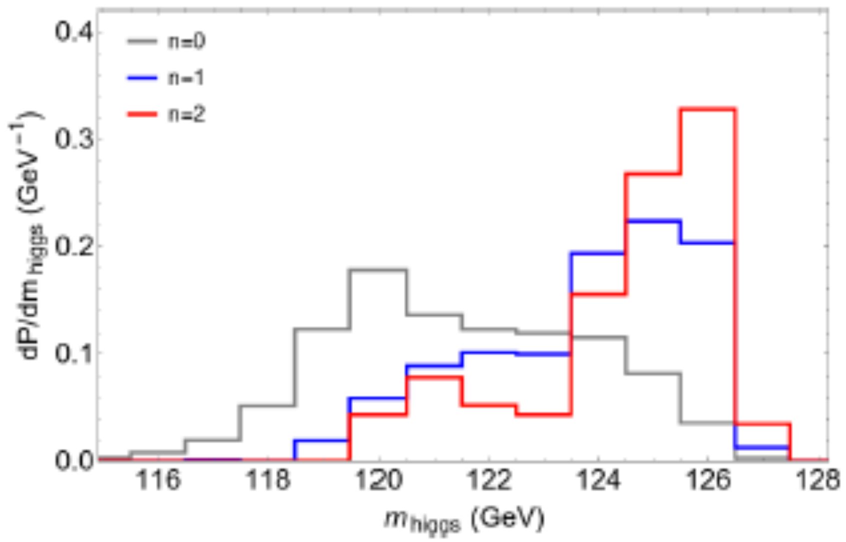
Giudice, Rattazzi, 2006

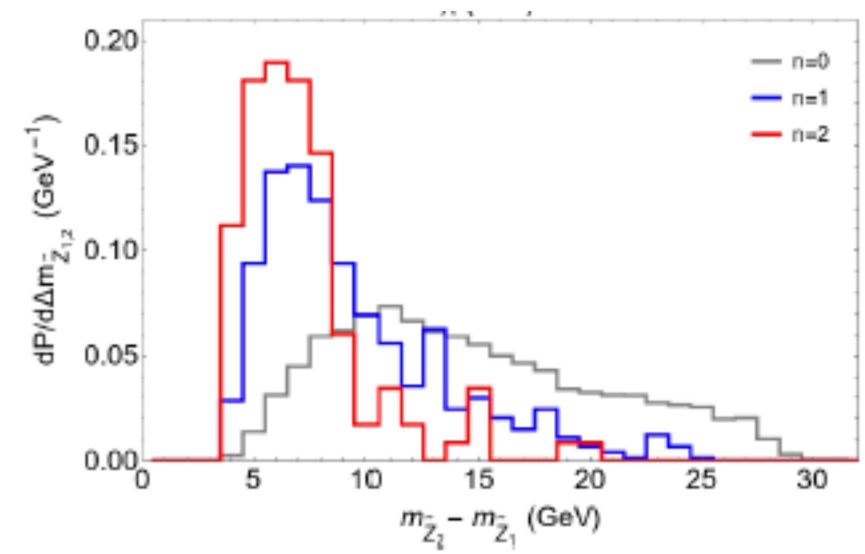
HB, Barger, Savoy, Serce, PLB758 (2016) 113

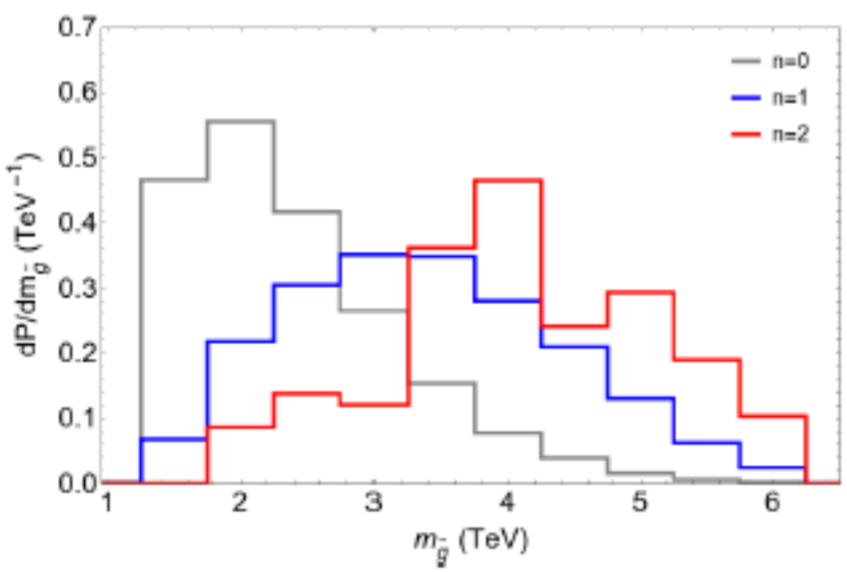


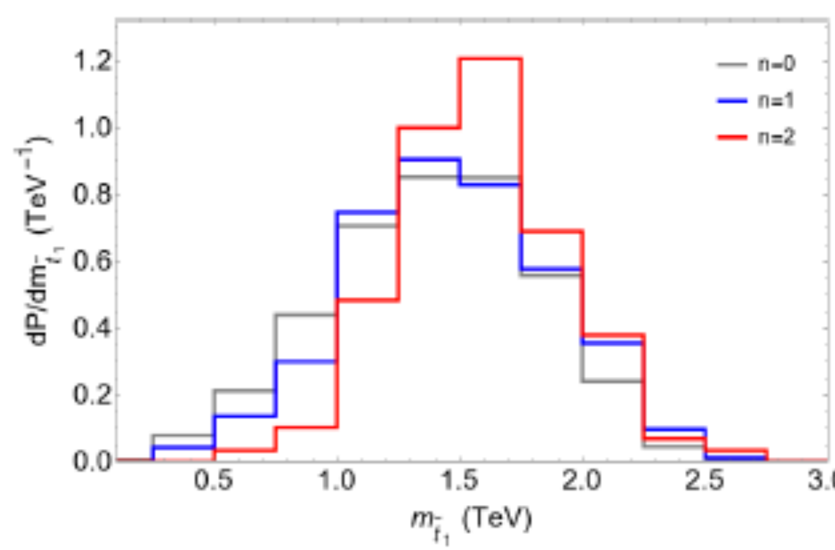

statistical/anthropic draw toward FP-like region

# 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~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-LHC33 TeV may be required
- ILC500 is ideal for light higgsinos