Axions and WIMPs from natural SUSY (and where to find 'em)

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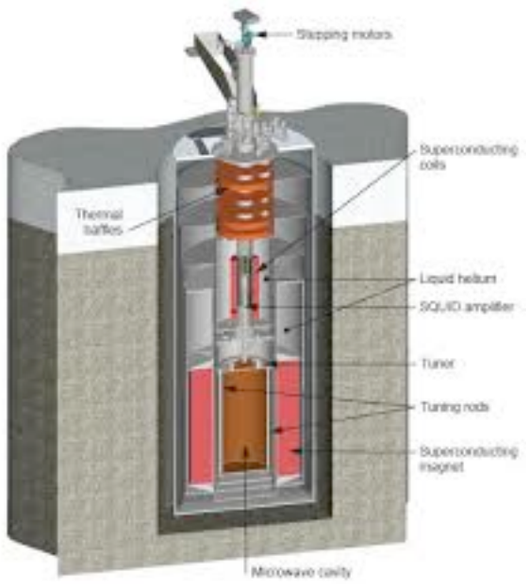
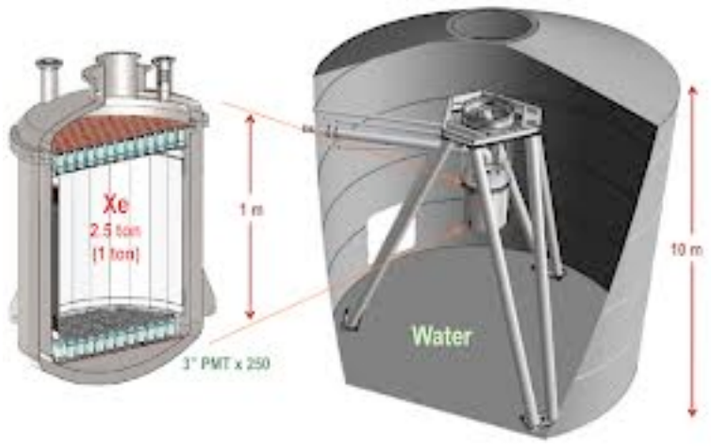




Lots of problems with SM

- 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

But where is SUSY

- LHC: m(gluino)>1.9 TeV
- LHC: m(t1)>0.85 TeV
- m(h)~125 GeV
- compare: Barbieri-Giudice naturalness: m(gluino)<350 GeV
- is SUSY unnatural? Is SUSY dead?

No

- BG naturalness computed in multi-parameter effective theories

- In more fundamental theories (e.g. SUGRA) 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: Δ_{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

then:

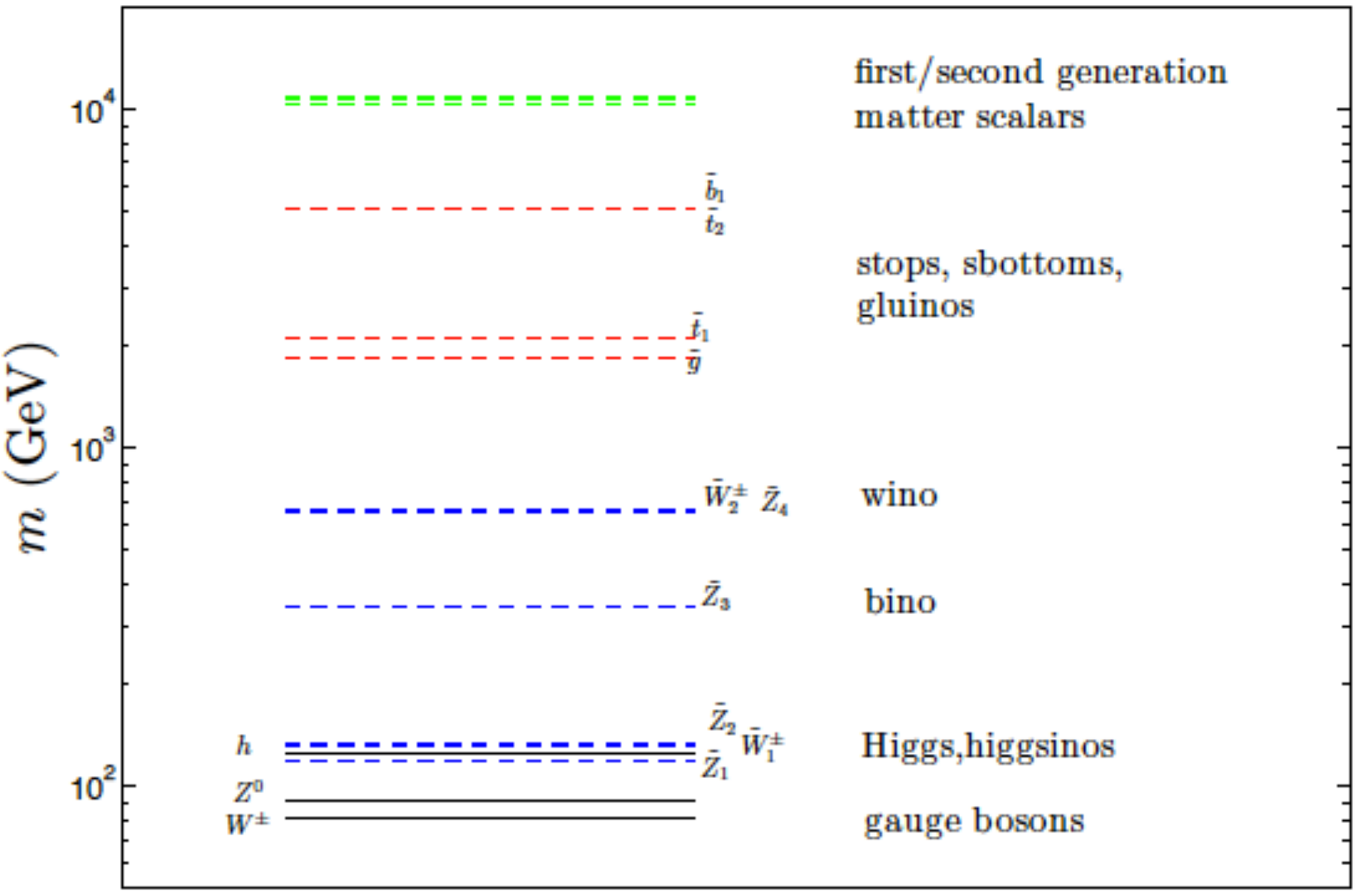
- $\mu \sim 100 - 200$ GeV
- $m_{H_u}^2$ can be driven to natural via large top Yukawa
- radiative corrections not too large

naturalness: only higgsinos need be ~100-200 GeV

higgsino is LSP

higgsino-like WIMP~100-200 GeV thermally underproduced as DM

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

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

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

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

$$f_a \ll m_{hid}$$

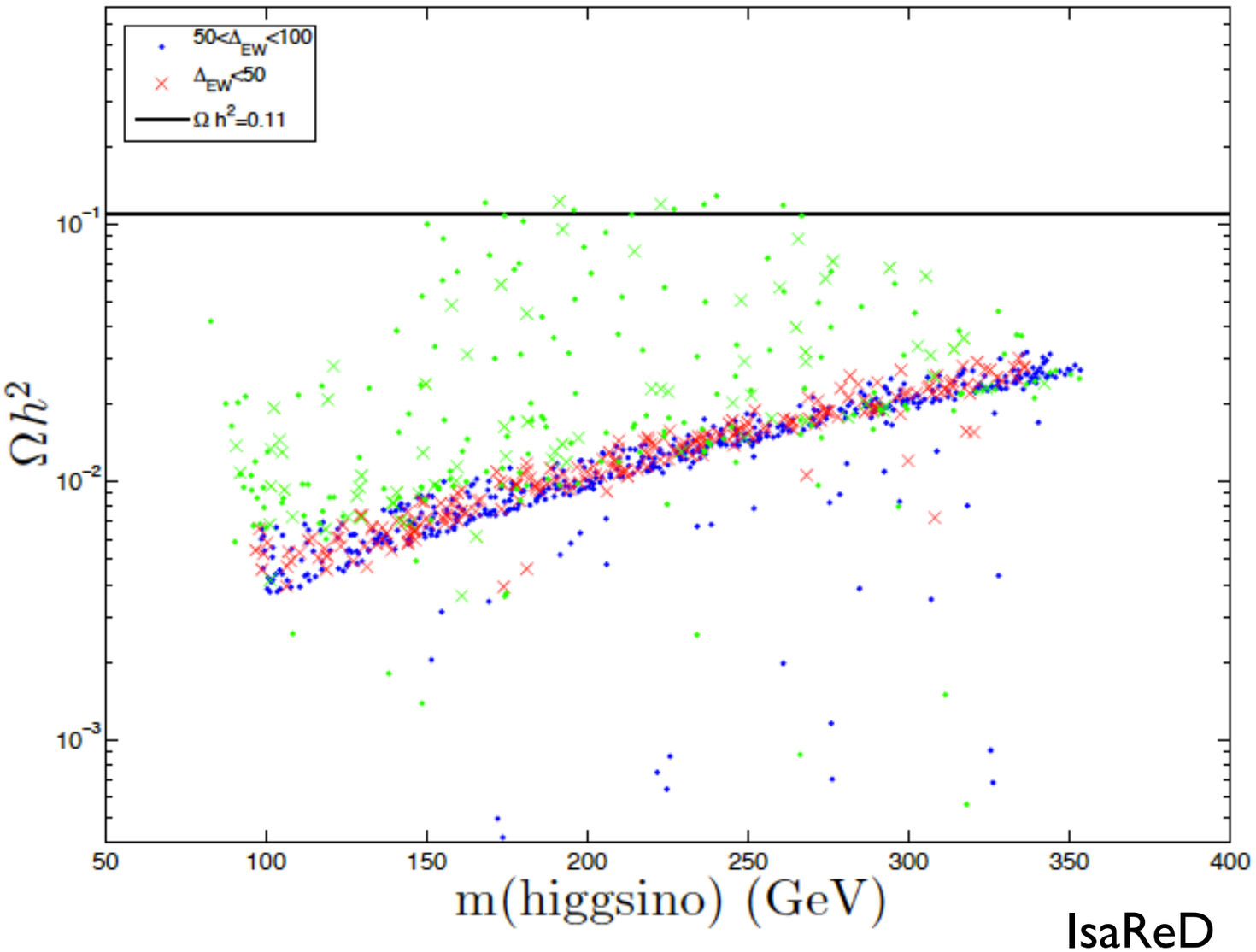
Higgs mass tells us where to look for axion!

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

bounds from naturalness (3%)	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!

Mainly higgsino-like WIMPs thermally underproduce DM



IsaReD

green: excluded;
red/blue:allowed

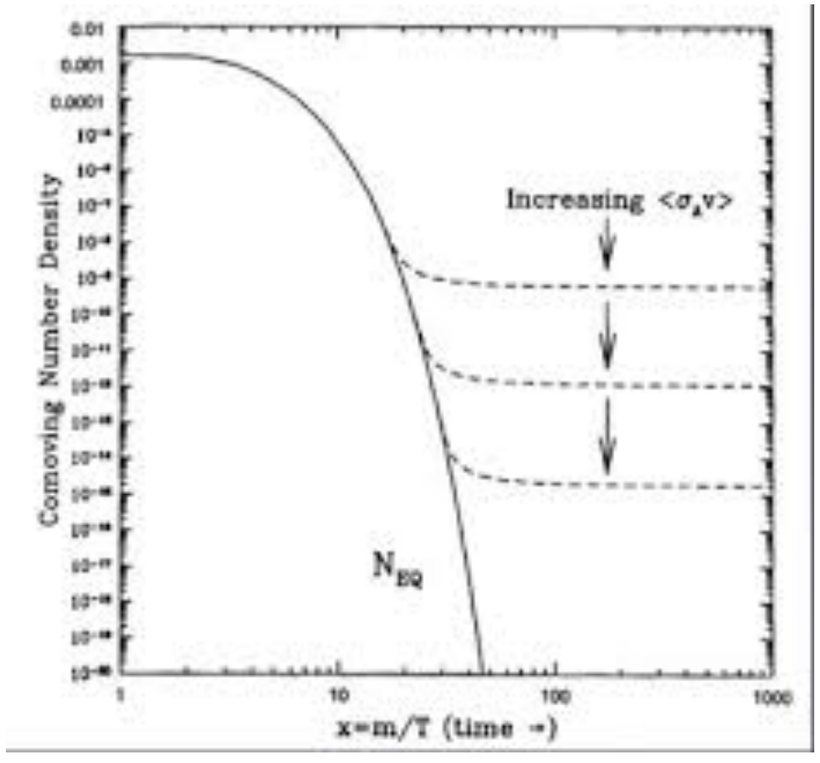
HB, Barger, Mickelson

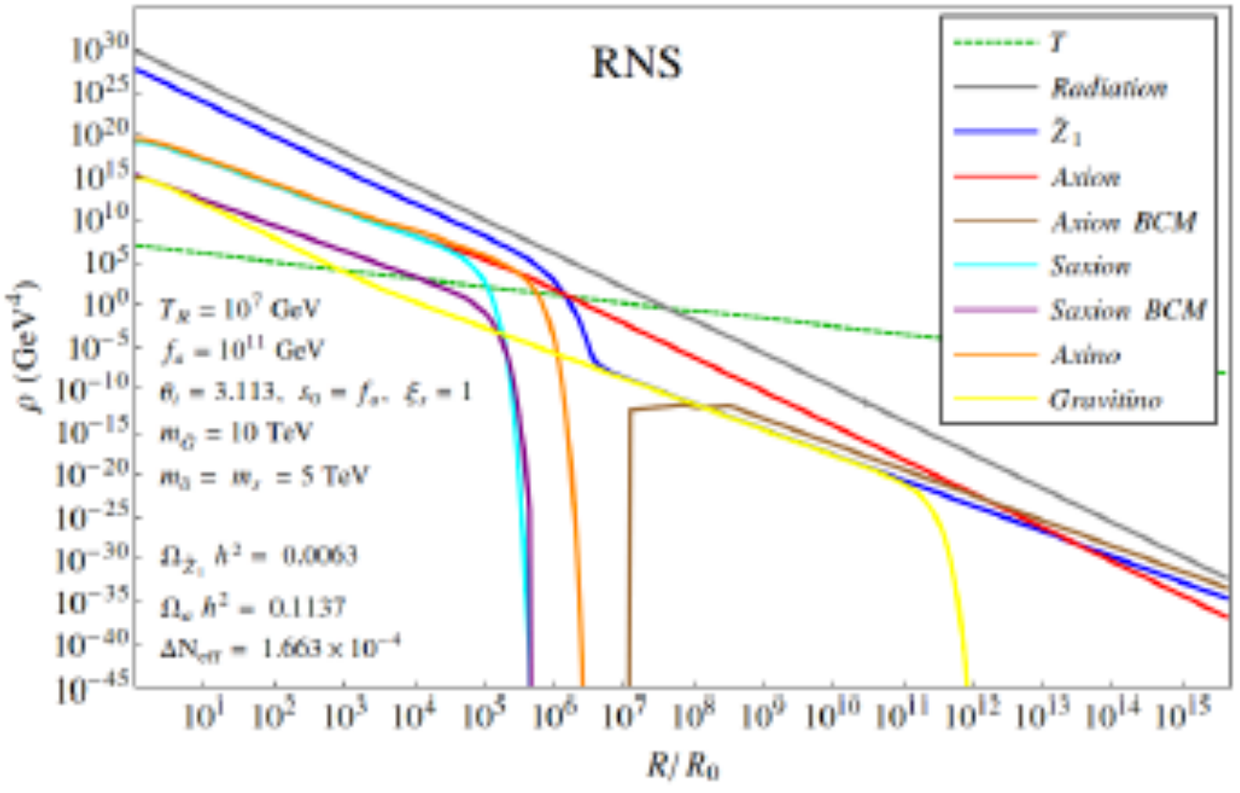
Factor of 10-15 too low

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

usual picture => mixed axion/WIMP

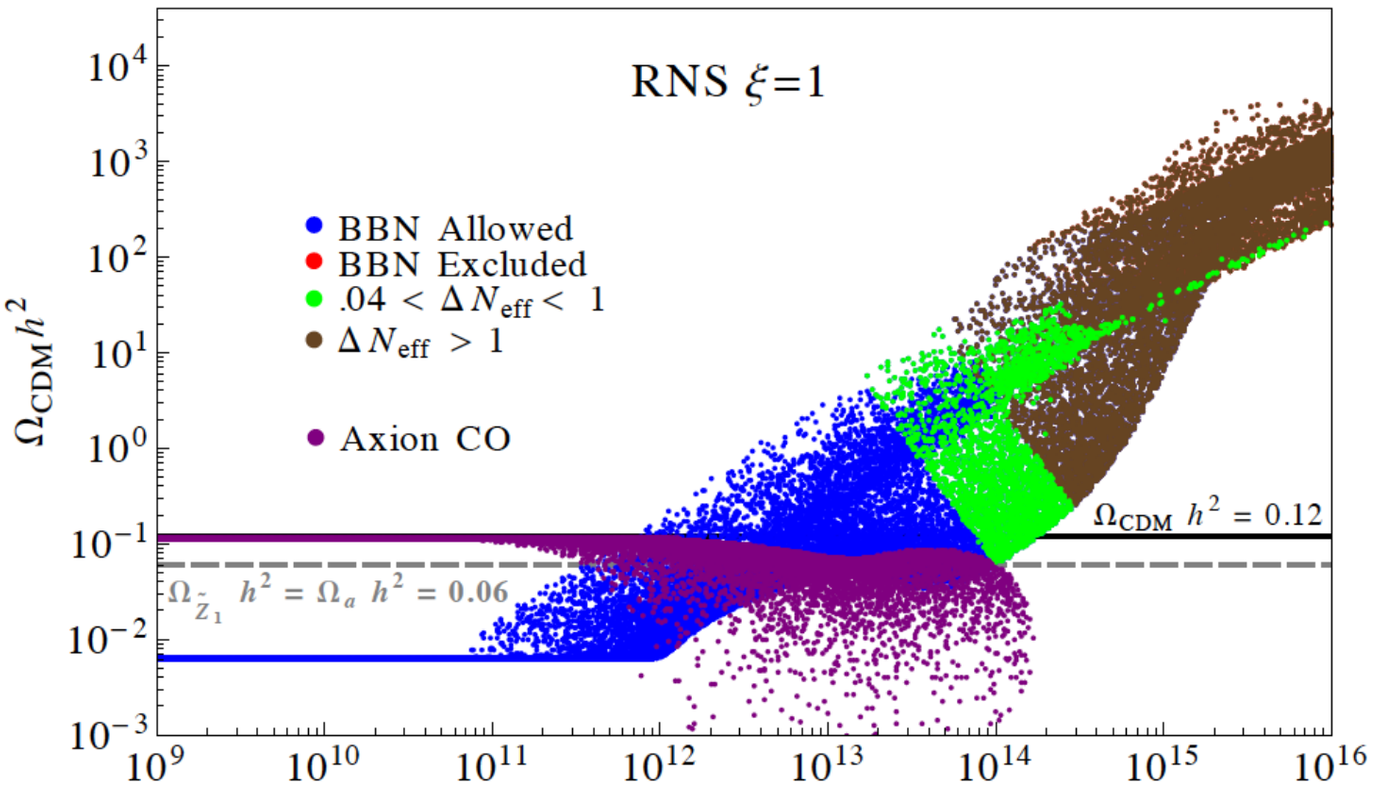




KJ Bae, HB, Lessa, Serce

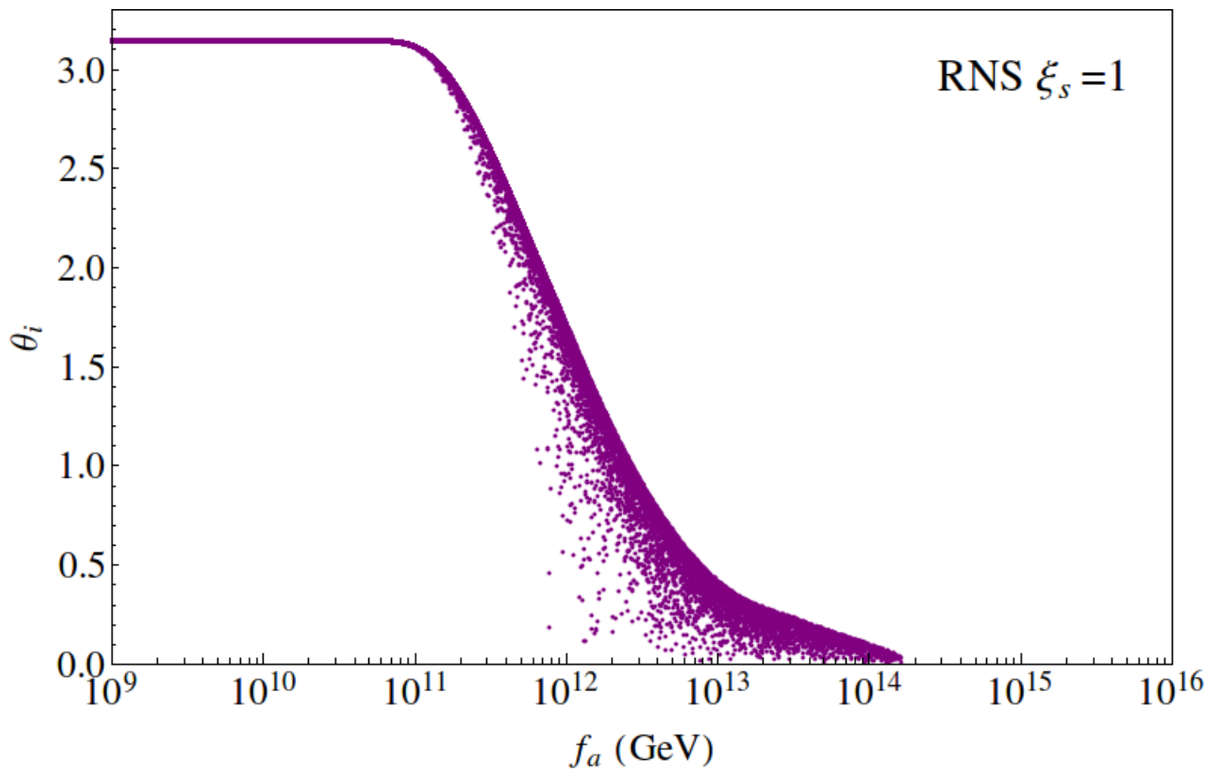
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

axion abundance

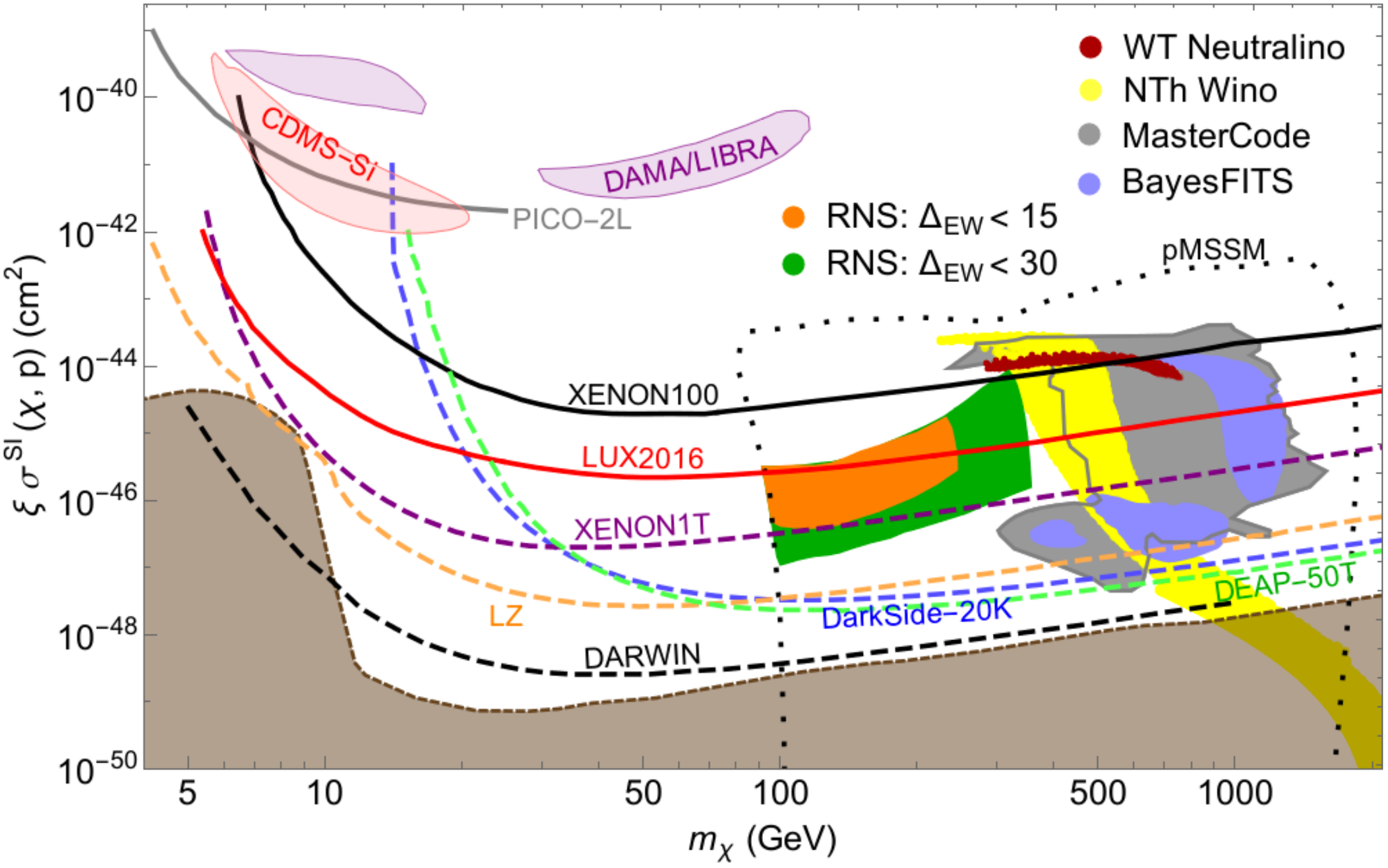


mainly axion CDM

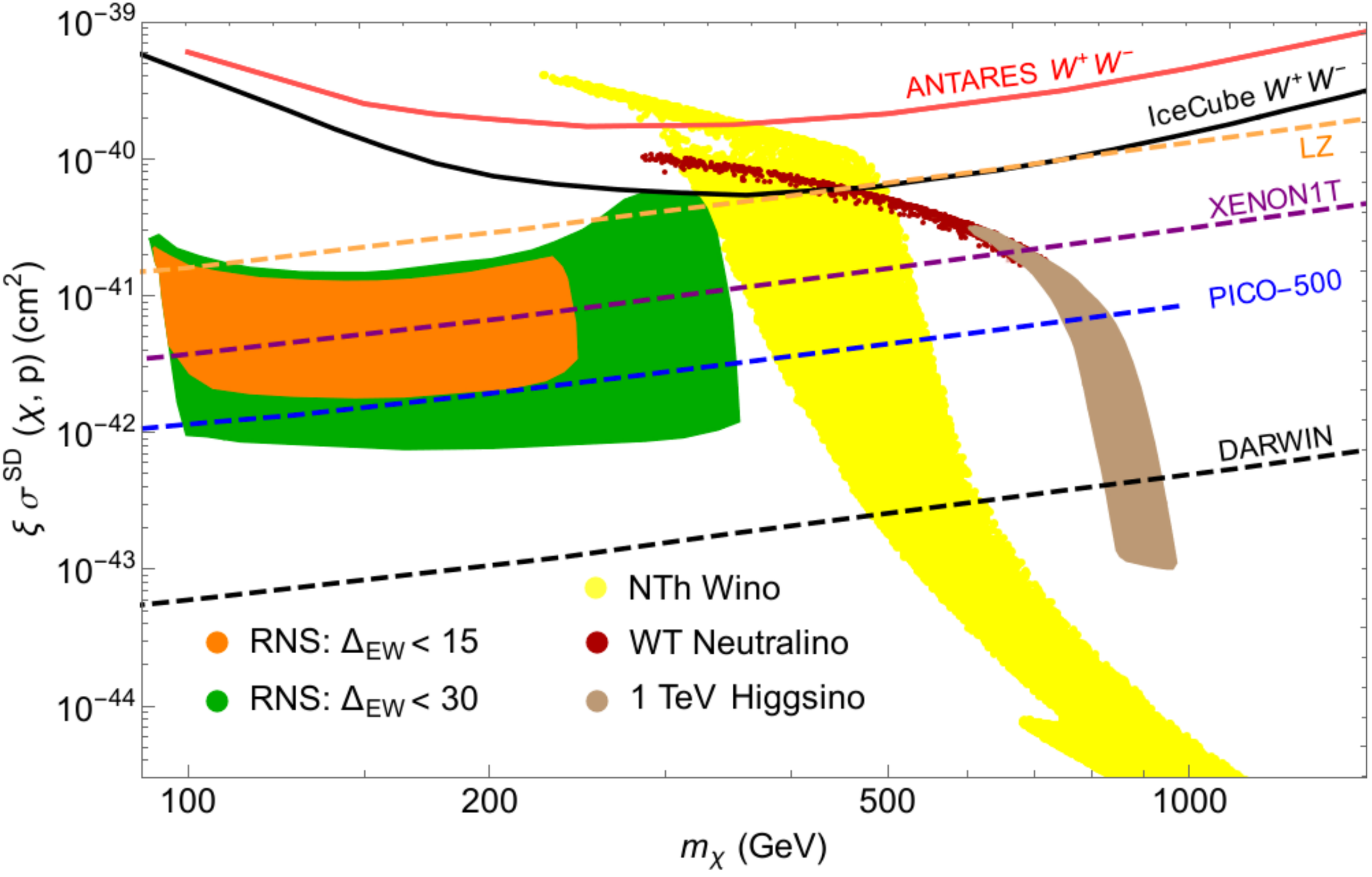
for fa<~10^12 GeV;

for higher fa, then get increasing wimp abundance

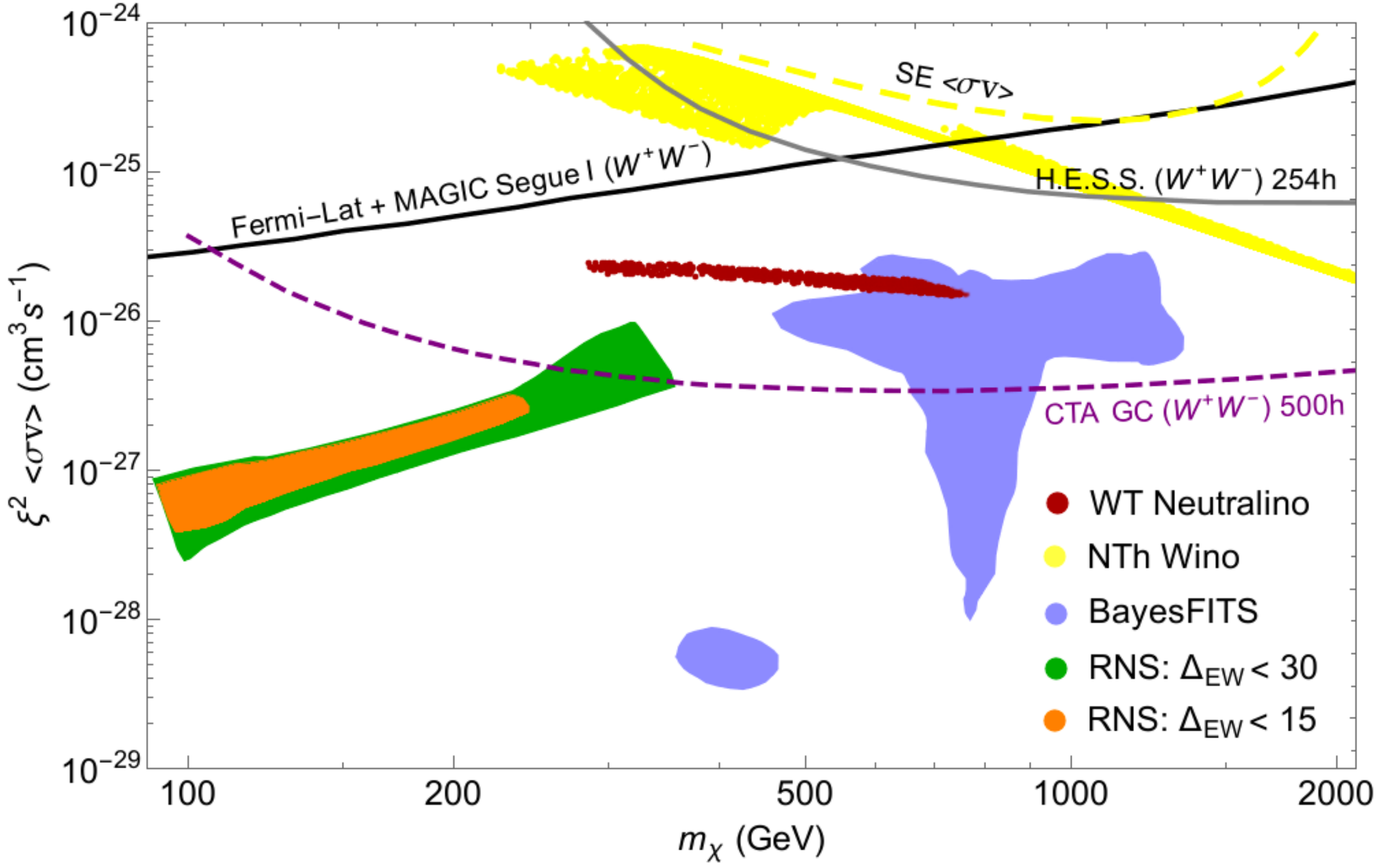
Bae, HB,Lessa,Serce



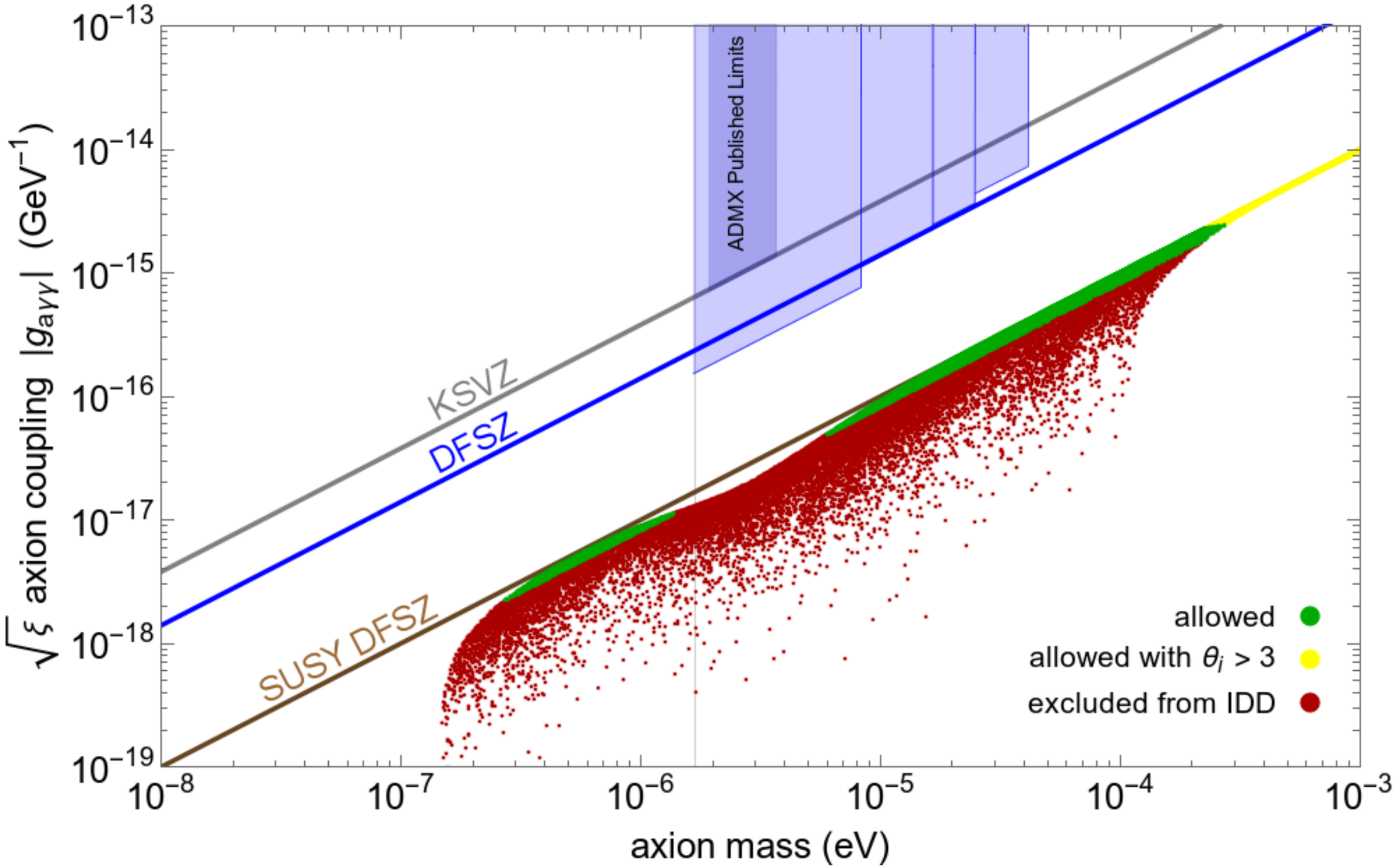
may need n-ton scale noble liquid detector because may be fewer target WIMPs if most DM=axions



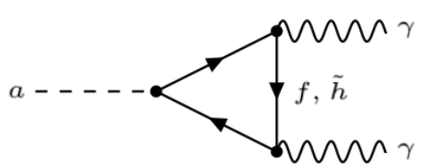
spin-dependent WIMP detection



IDD- rate goes like square of depleted abundance



SUSY DFSZ axion: large range in m(a) but coupling reduced may need to probe broader and deeper!



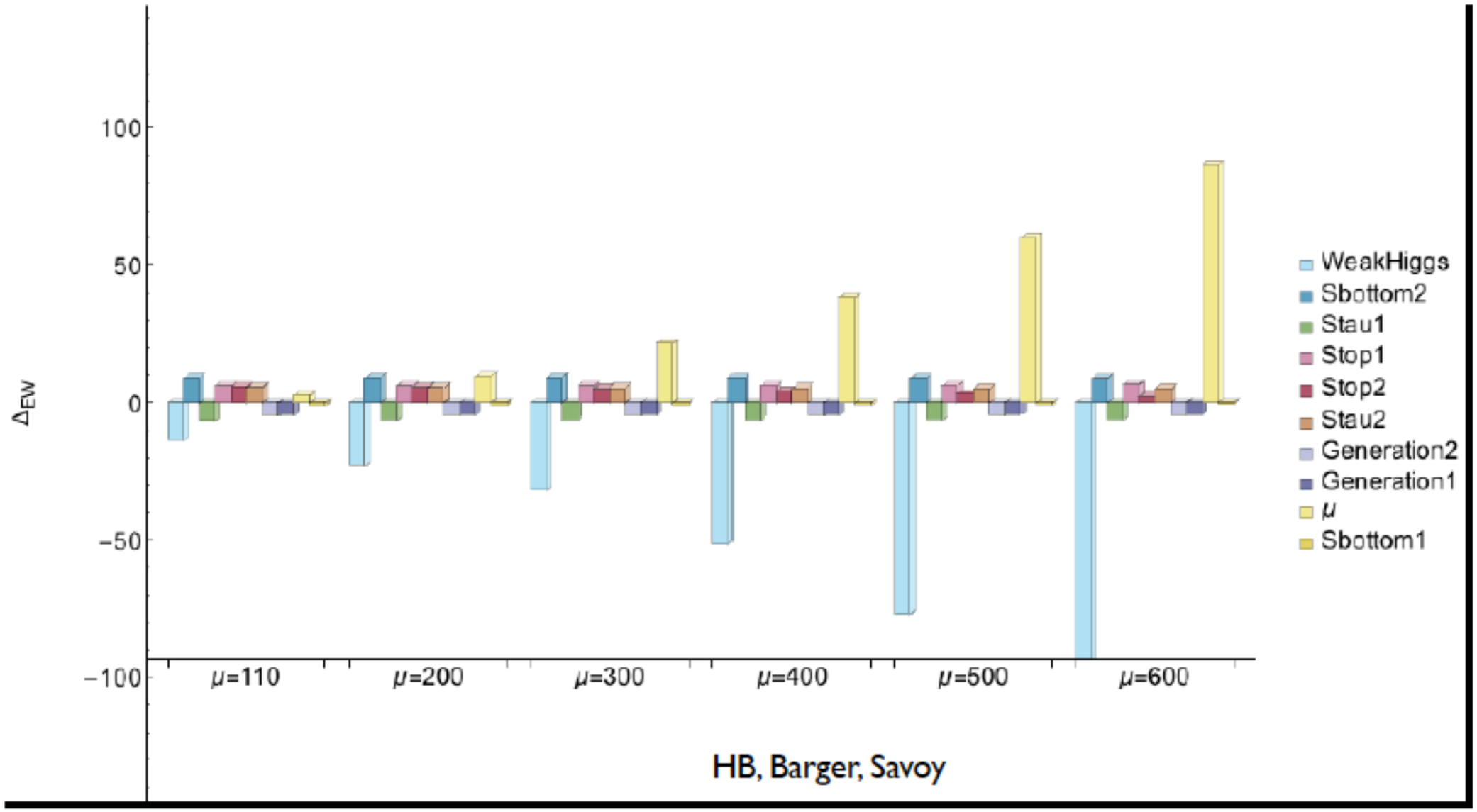
summary slide

- 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
- Higgsino should be probed by 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
- Cost? see my experimental colleagues...

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
- ILC 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)

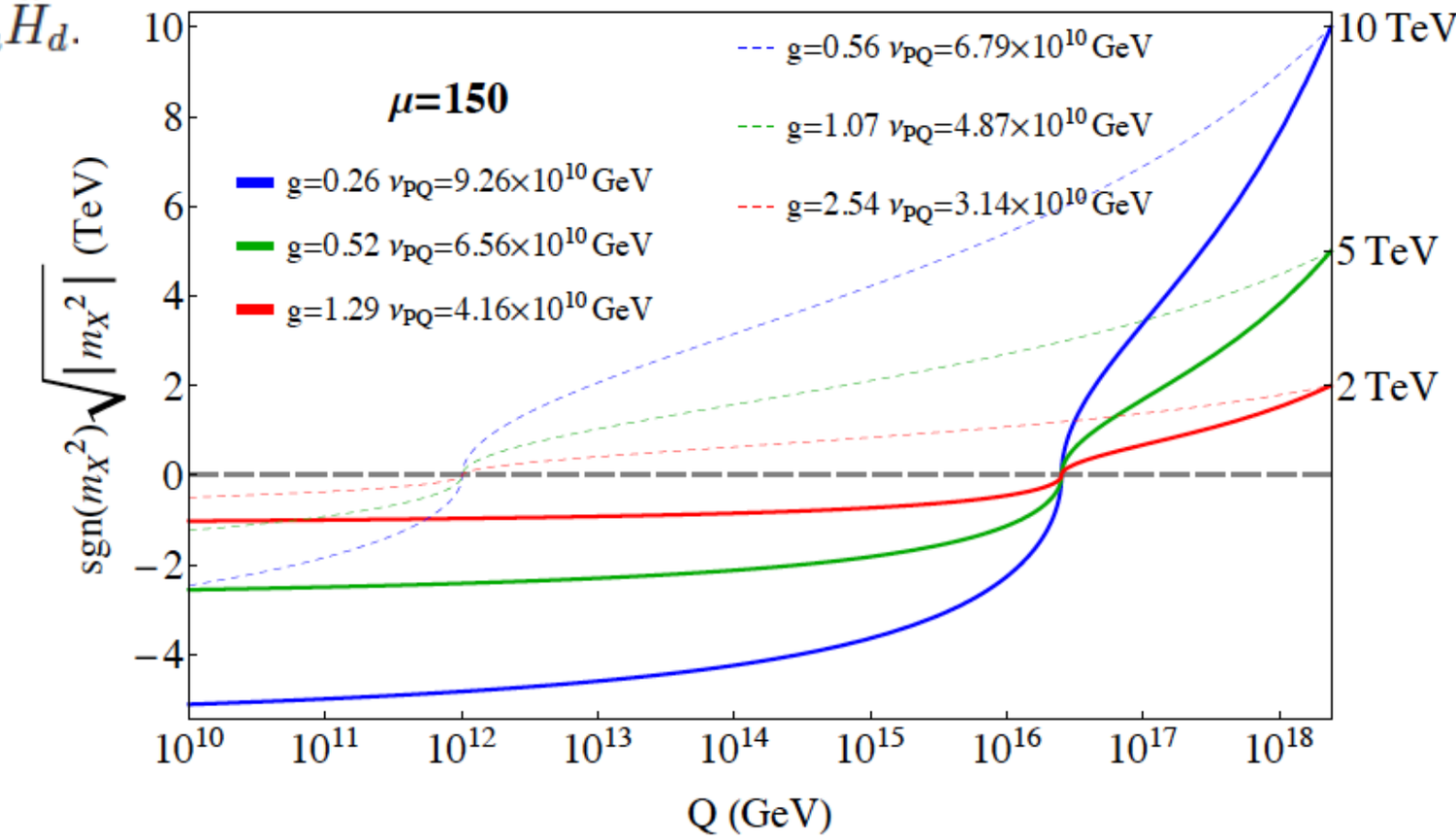
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

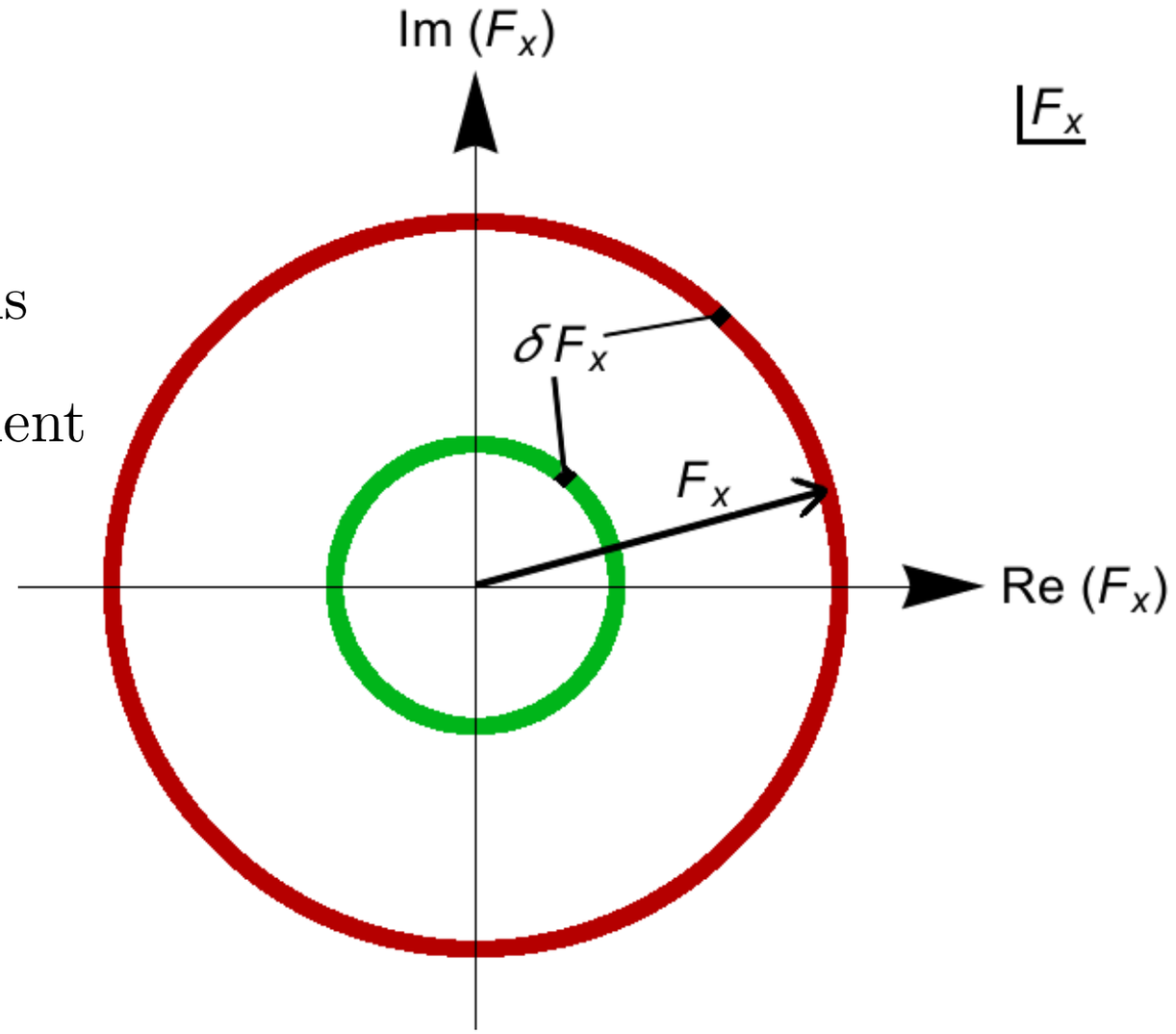
$$\mu = g\frac{v_X v_Y}{M_P}\ .$$



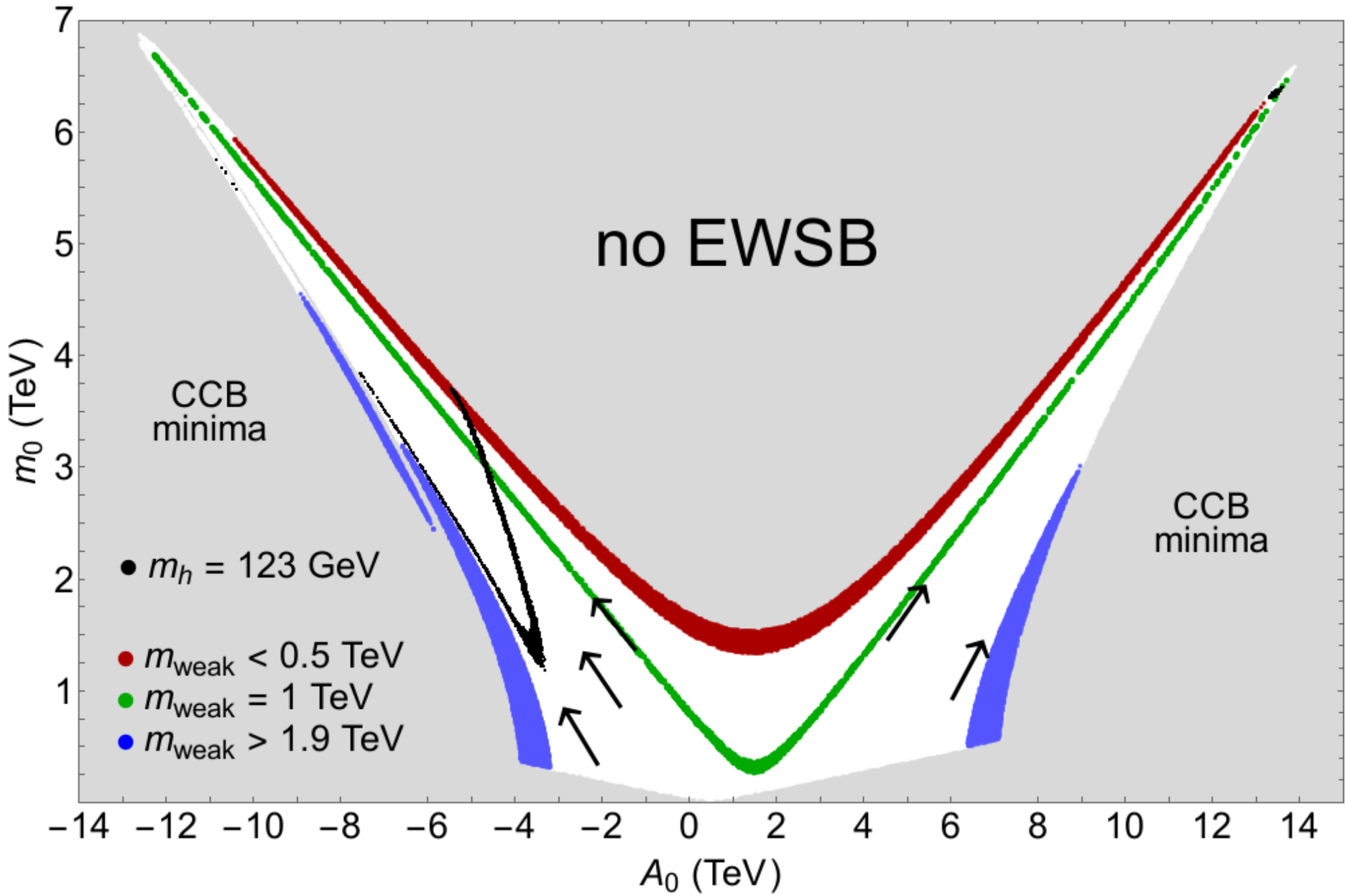
Large $m_{3/2}$ generates small $\mu \sim 100 - 200$ GeV!

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



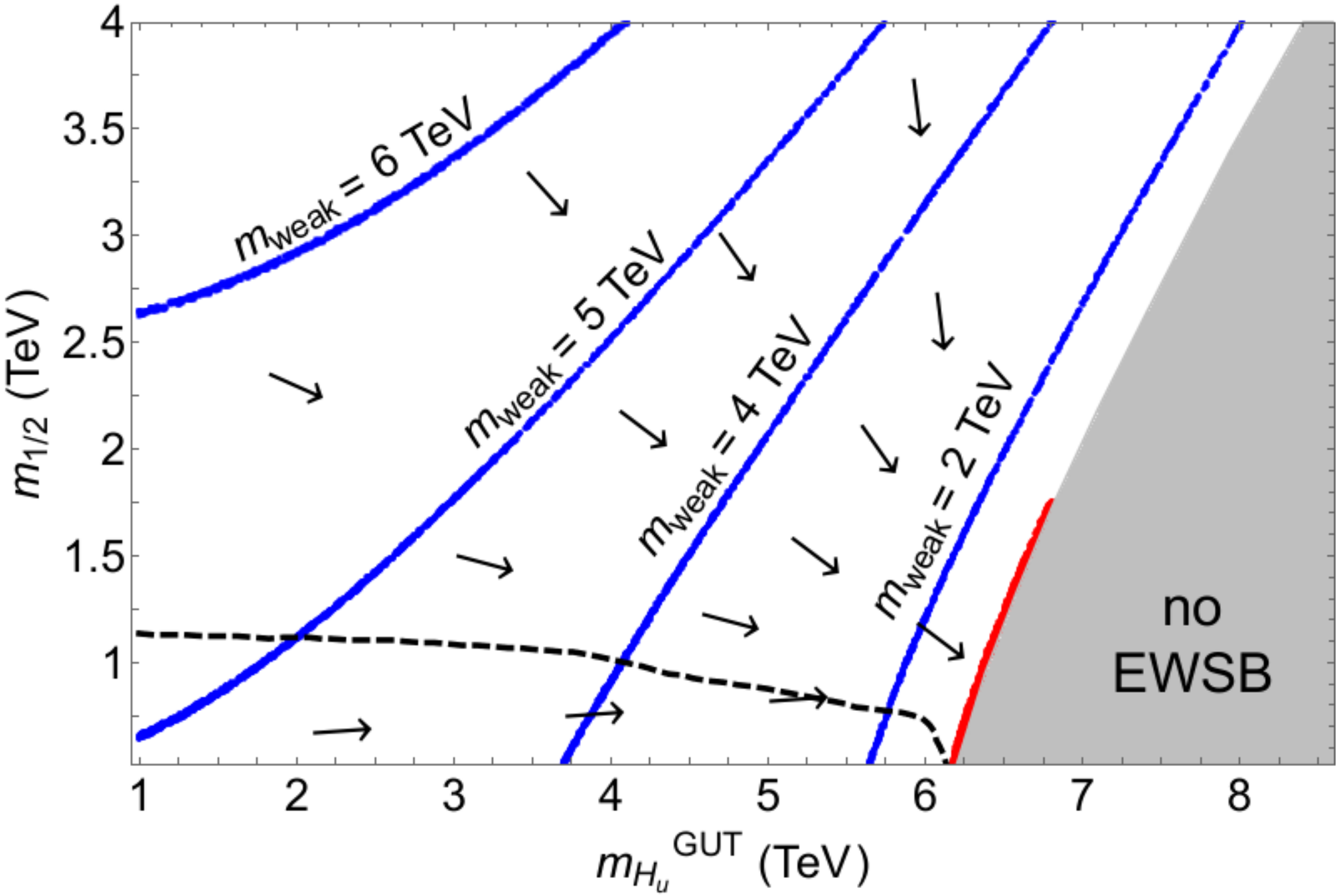
Anthropic selection of $m_{weak} \sim 100$ *GeV*:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them



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