How LHC tells us there is excellent potential for ILC to discover new particles

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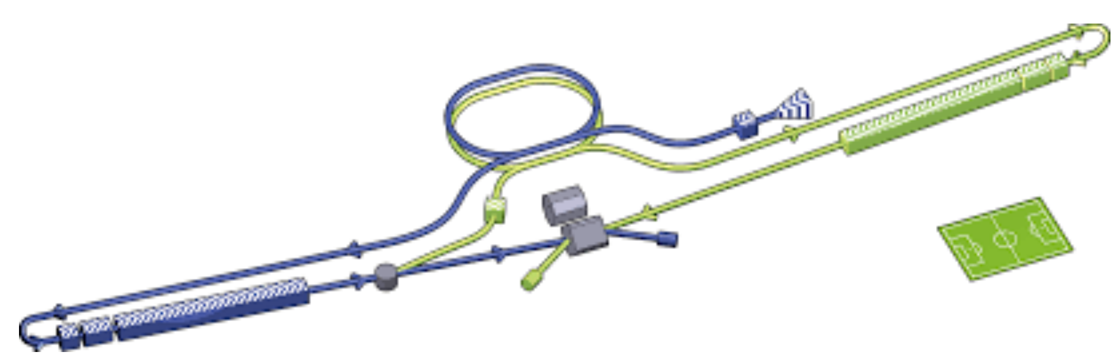
or

Why

SUSY  

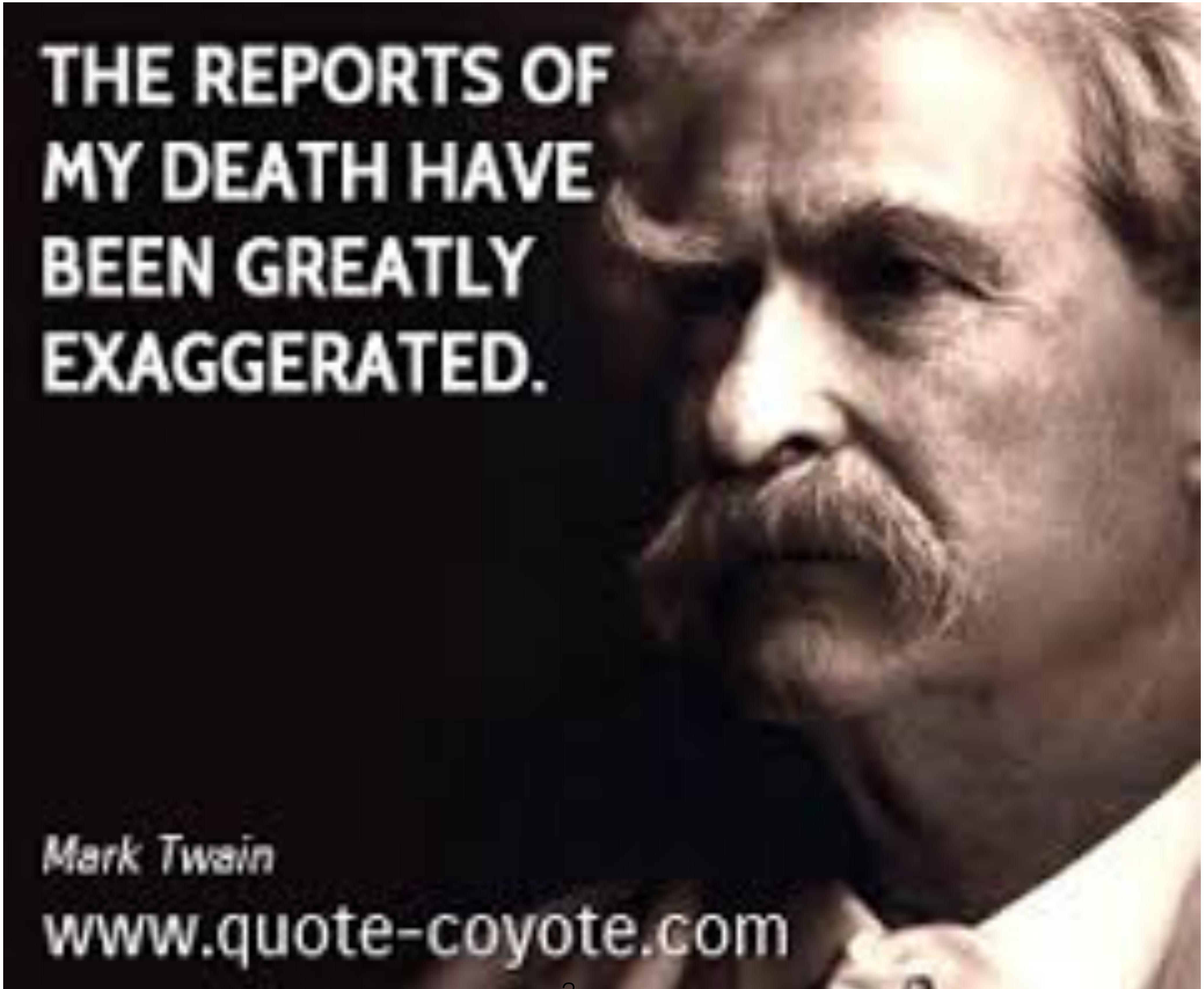
While ILC250 well-motivated
to detect new physics via virtual effects
can ILC weigh in on the biggest possibility:
the discovery of SUSY?

Or do recent LHC results, m(glno)>2 TeV, m(t1)>1 TeV
pre-empt any possibility?

[So far, the bulk of LHC searches take place within
either unnatural or simplified models]

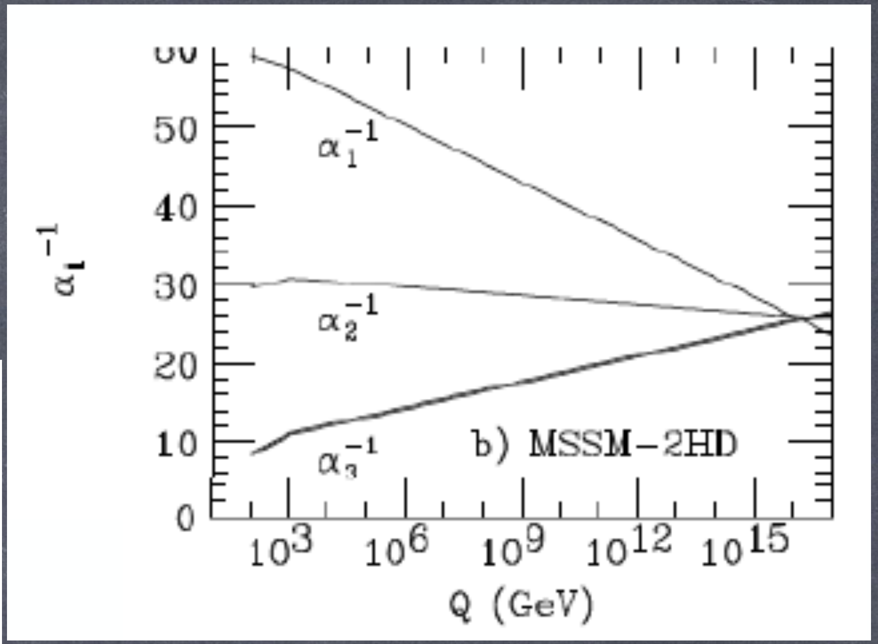
Recent episode Big Bang Theory:
Physics is dead because
LHC didn't discover SUSY:
is this true? NO!

Mark Twain, 1835-1910 (or SUSY)

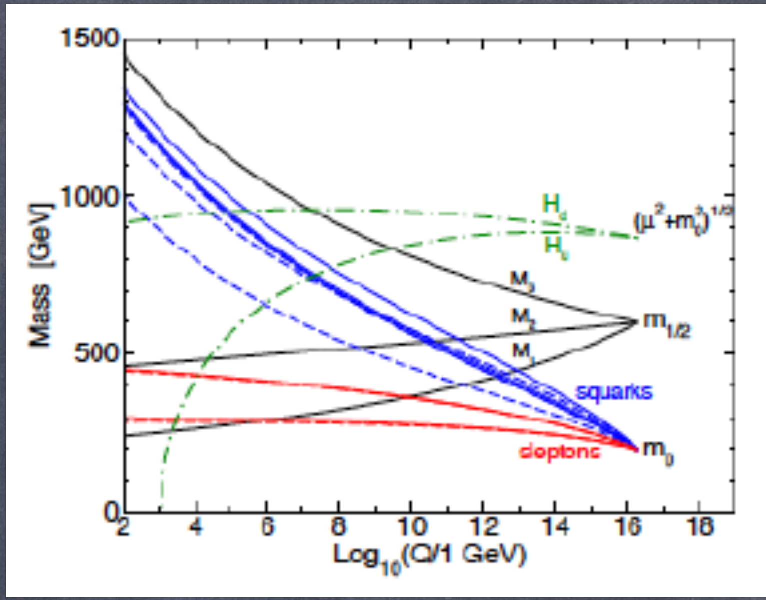


Three MSSM success stories:

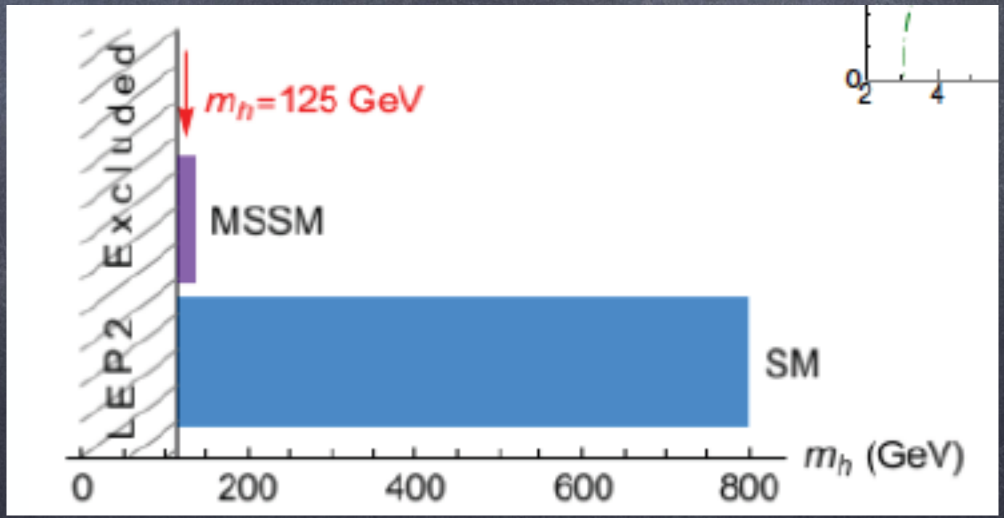
Unification of gauge couplings



m(t)~150-200 GeV required for EWSB



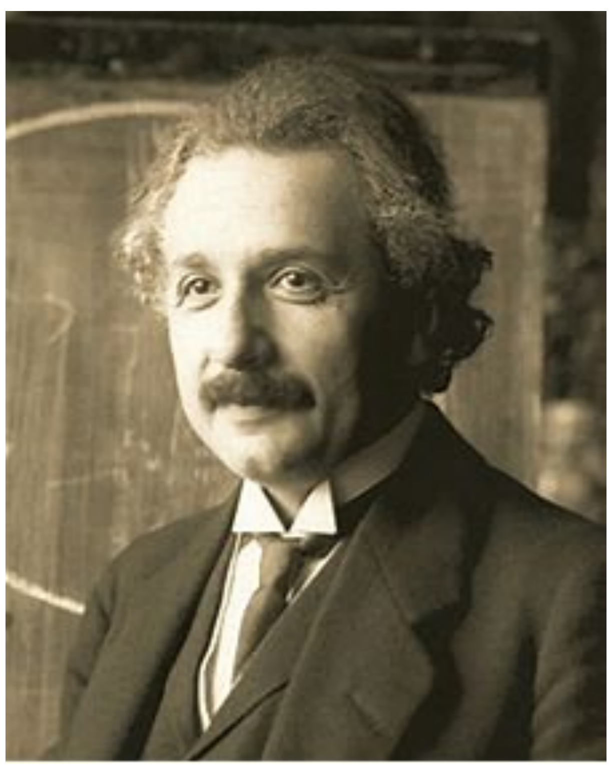
m(h) just right



But: is there now a Little Hierarchy problem, i.e.
is SUSY now unnatural in light of strong LHC sparticle mass limits?

SUSY motivation: simplicity and naturalness

``The appearance of fine-tuning in a scientific theory
is like a cry of distress from nature
complaining that something needs to be better explained"
S. Weinberg



``Everything should be made as simple as possible,
but not simpler"
A. Einstein

Needed: a natural theory which contains SM: the MSSM

``...settling the ultimate fate of naturalness is perhaps the most profound theoretical question of our time''

Arkani-Hamed et al., arXiv:1511.06495

``Given the magnitude of the stakes involved, it is vital to get a clear verdict on naturalness from experiment''

This should be matched by theoretical scrutiny of what we mean by naturalness

naturalness:
all independent contributions to some observable O
should be comparable to or less than O

otherwise:
if one contribution is >>O, then some other
must be fine-tuned to large opposite-sign to maintain O
at its measured value: this is unnatural
(i.e. highly implausible; likely wrong)

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

MSSM+naturalness=> light higgsinos with mass~100-200 GeV

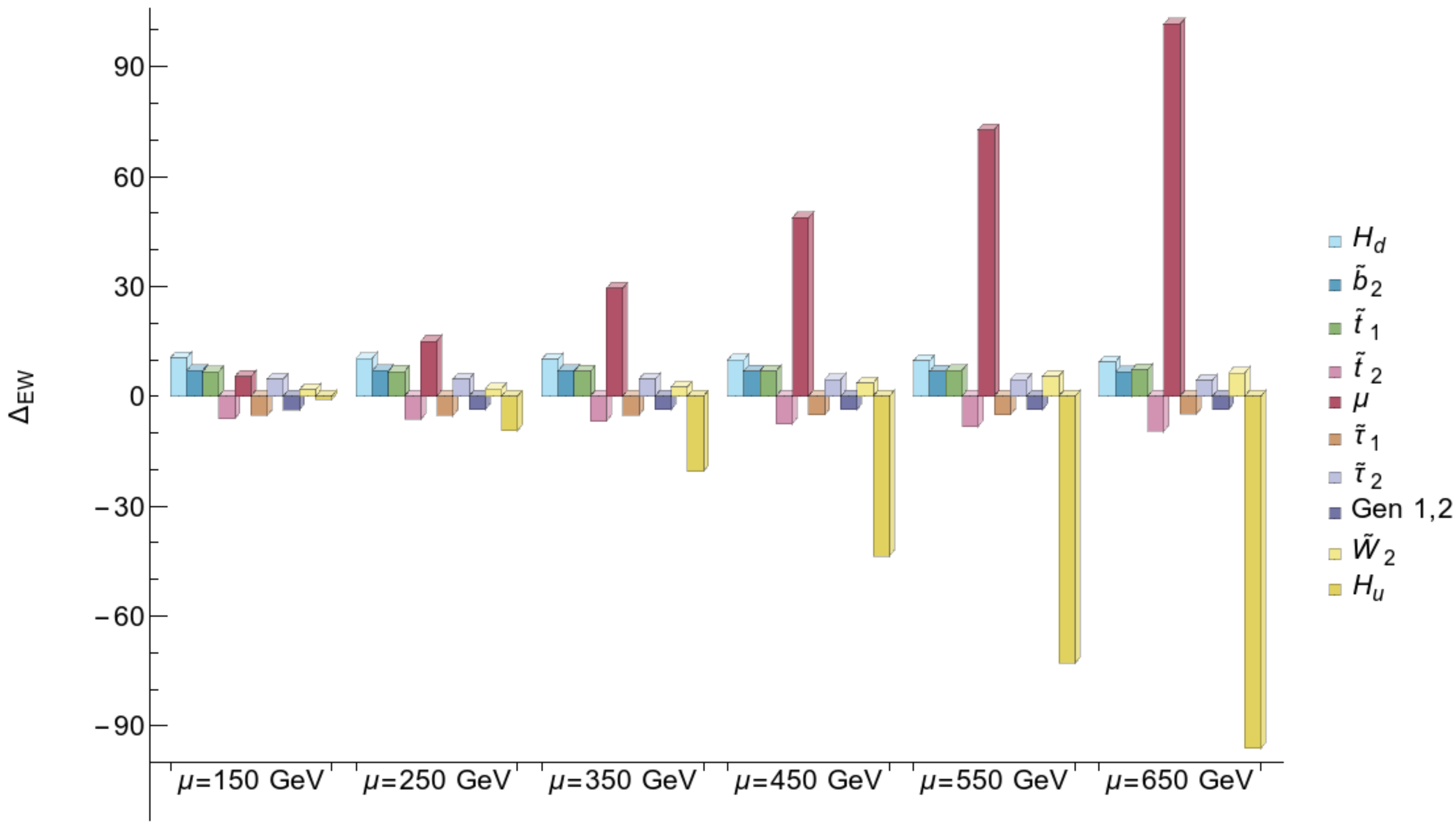
- $m_{H_u}^2$ is driven small negative (radiatively driven naturalness)
- Higgs/higgsino mass $\mu \sim 100-200$ GeV (the smaller the better)
- radiative corrections to m_Z^2 relation minimized for highly mixed TeV-scale top squarks

[m(glno)<~4-5 TeV; m(t1)<3 TeV at little cost to naturalness]

LHC has only begun to explore natural SUSY parameter space!

light higgsinos are difficult, perhaps impossible, to see at LHC

How much is too much fine-tuning?



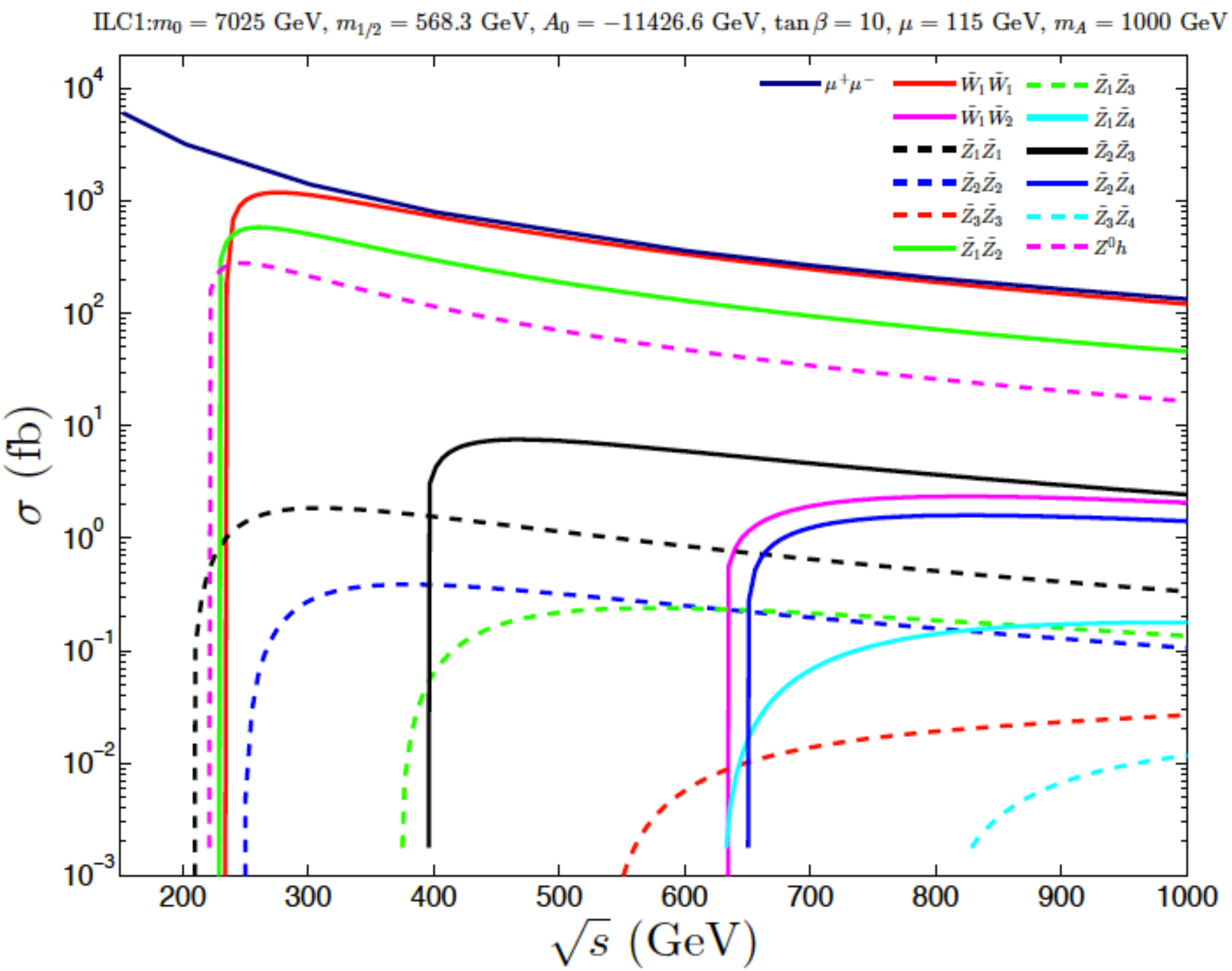
HB, Barger, Savoy

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

Nature is natural $\Rightarrow \Delta_{EW} < 20 - 30$ (take 30 as conservative)

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



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

3-15 GeV higgsino mass
gaps no problem
in clean ILC environment

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

ILC either sees light higgsinos
or natural MSSM dead

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!

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

Little Hierarchy from radiative PQ breaking? exhibited within context of MSY/CCK model

Murayama, Suzuki, Yanagida (1992);
Gherghetta, Kane (1995)

Choi, Chun, Kim (1996)

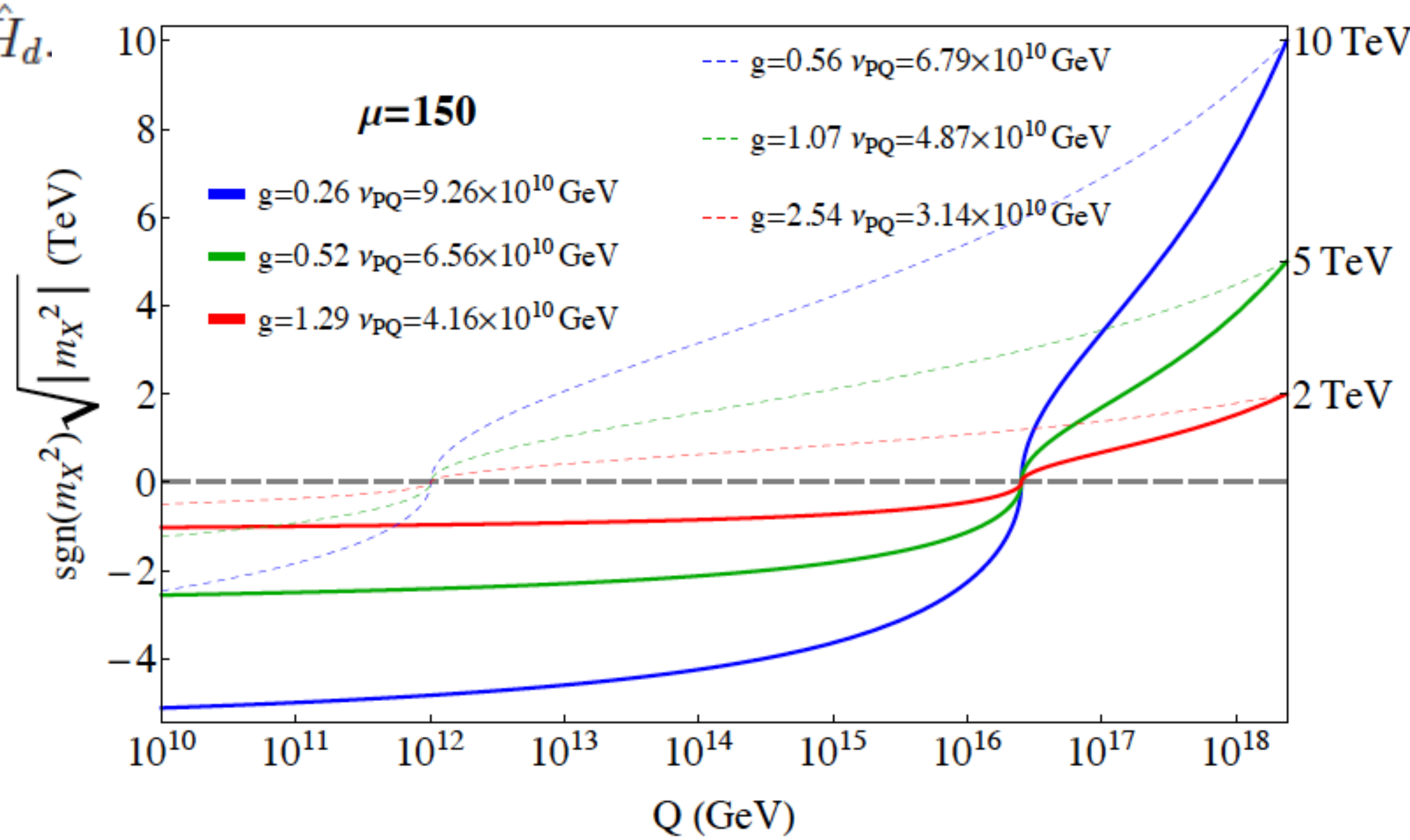
Bae, HB, Serce, PRD91 (2015) 015003

augment MSSM with PQ charges/fields:

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

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

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



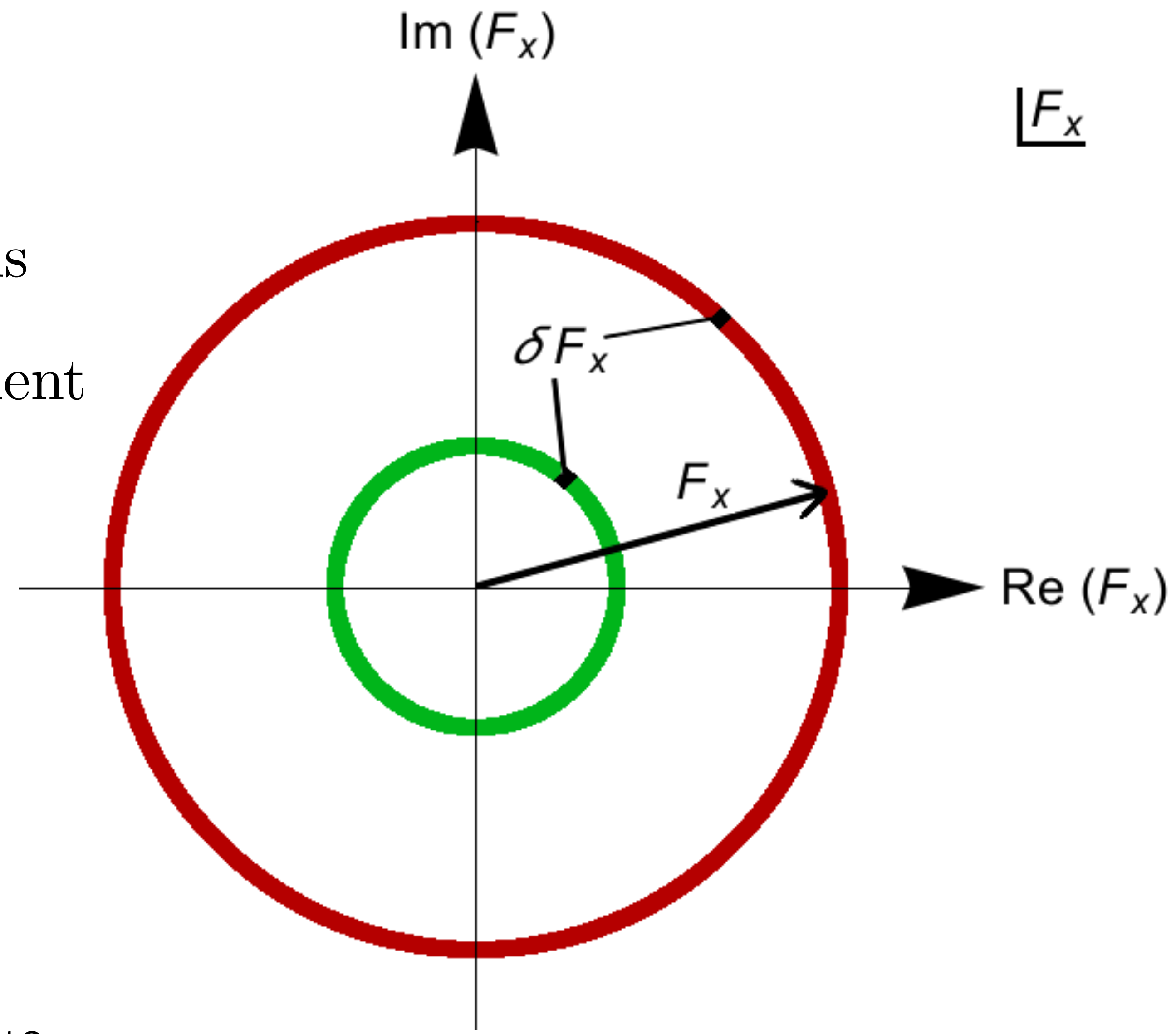
Intermediate scale SUSY breaking generates as well both PQ and Majorana nu scales!

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

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

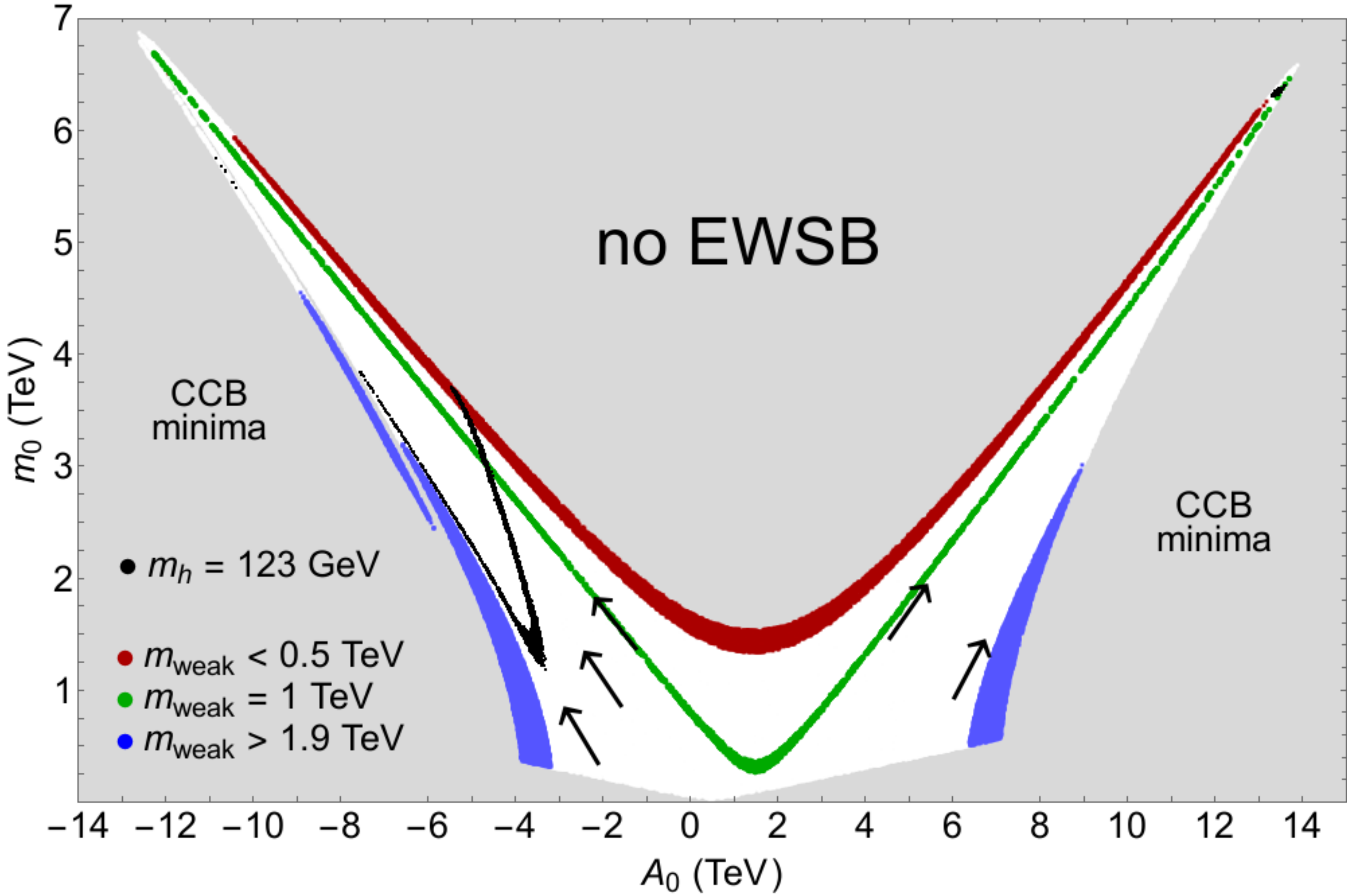
string theory landscape?

- 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



Agrawal, Barr, Donoghue and Seckel

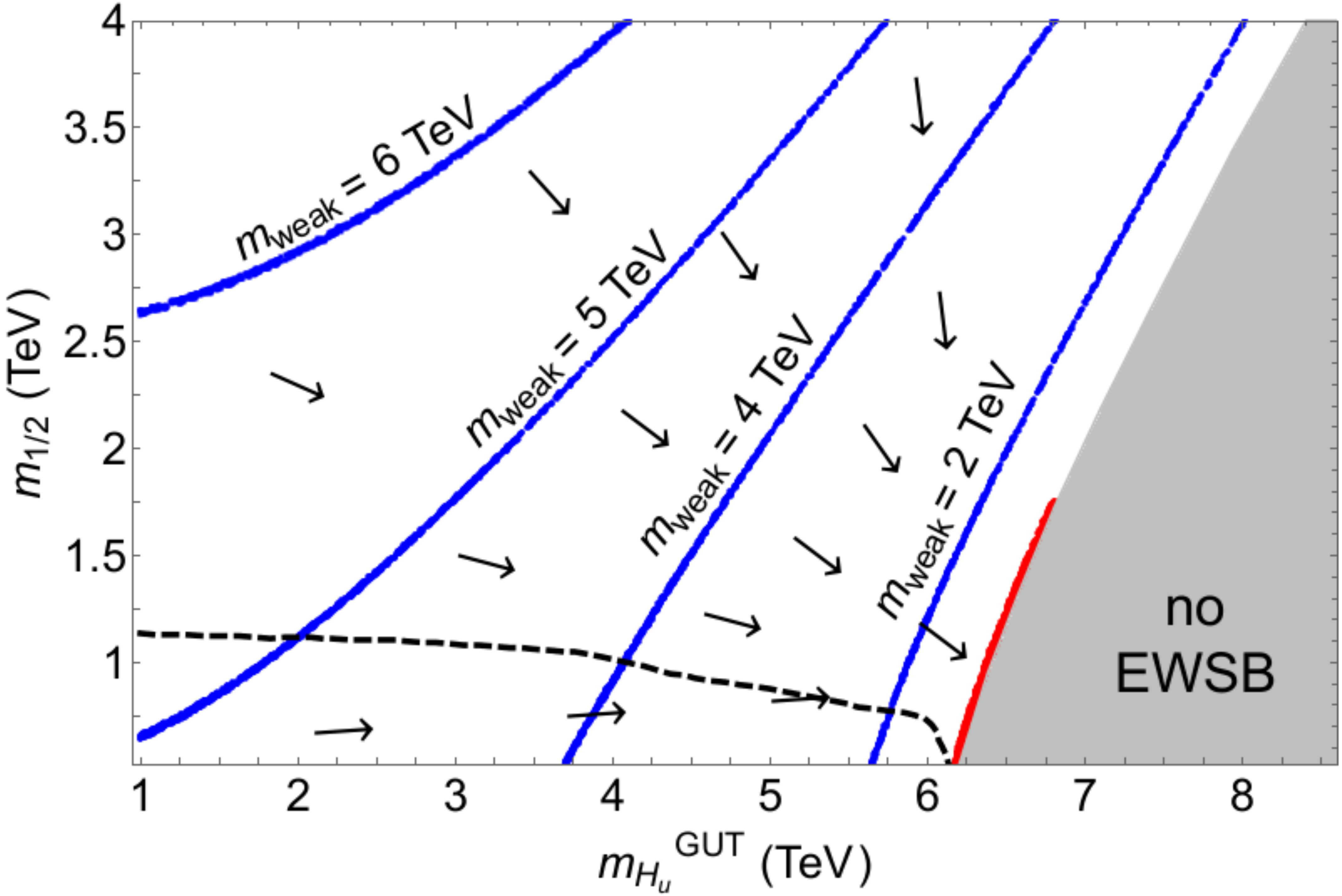
Anthropic selection of $m_{weak} \sim 100\ GeV$:
If m_W too large, then weak interactions $\sim (1/m_W^4)$ too weak
weak decays, fusion reactions suppressed
elements not as we know them



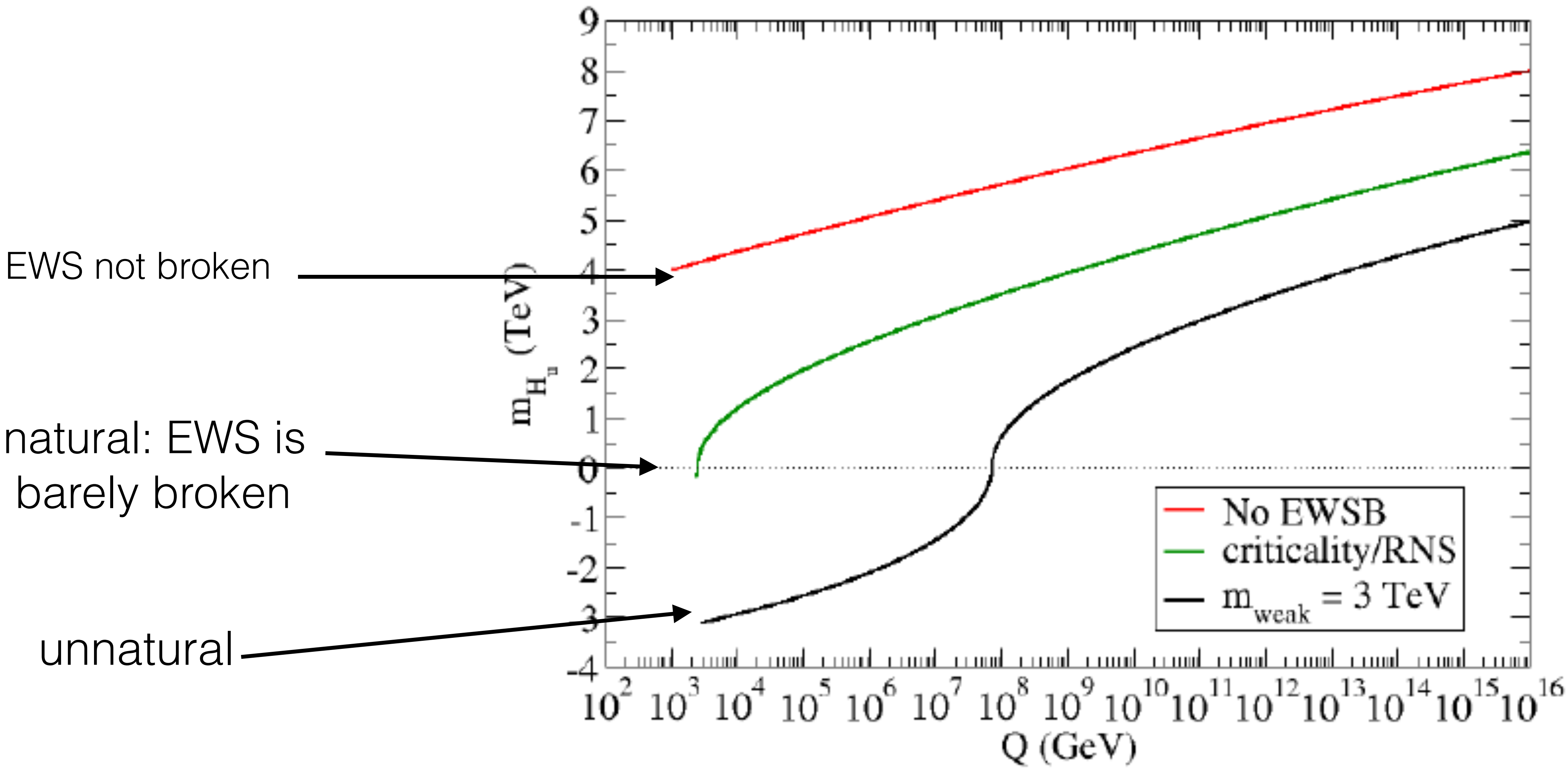
statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

Giudice, Rattazzi, 2006

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



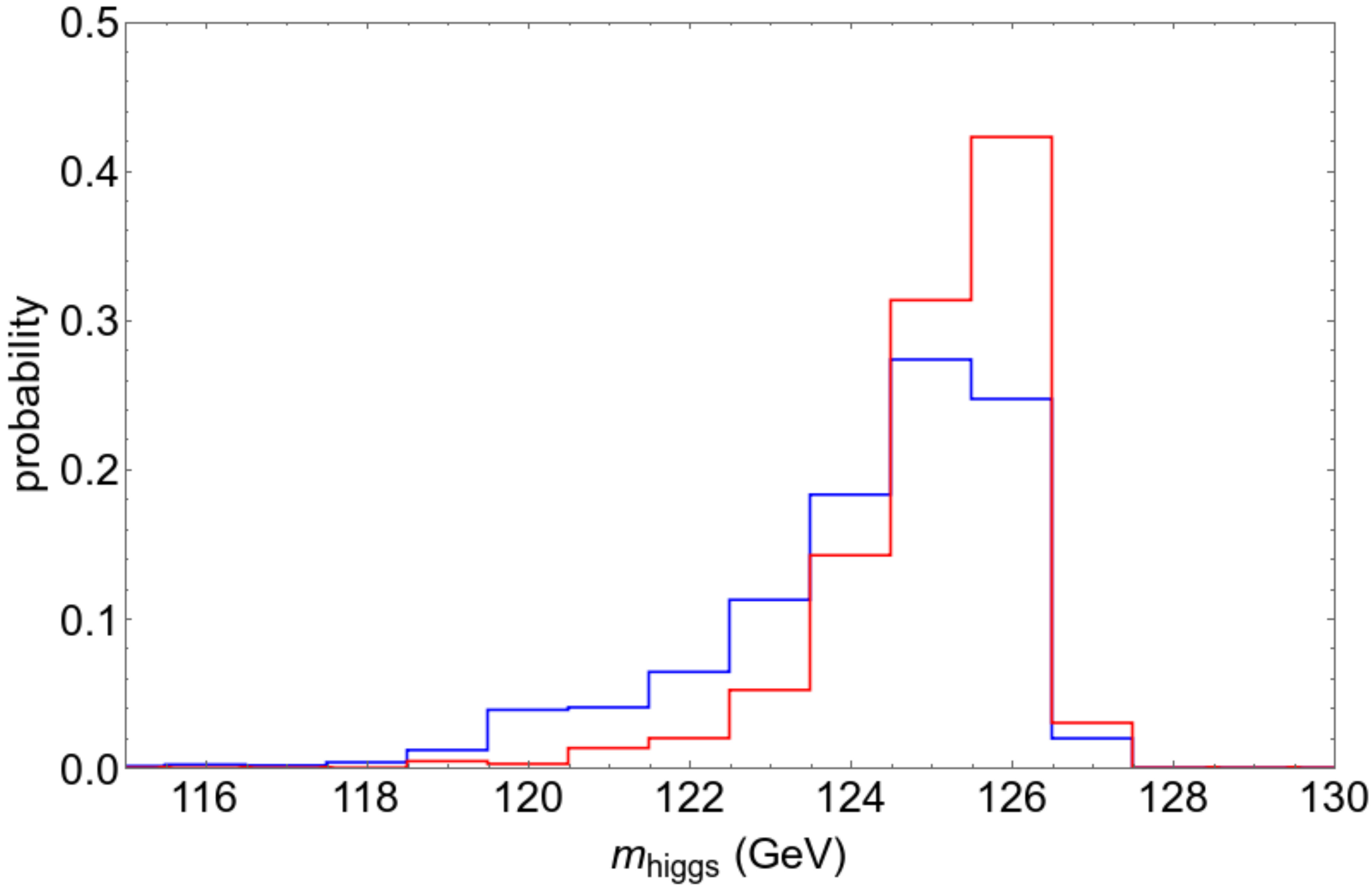
statistical/anthropic draw toward FP-like region radiative corrections drive $m^2_{H_u}$ from unnatural GUT scale values to naturalness at weak scale: radiatively-driven naturalness



Evolution of the soft SUSY breaking mass squared term $sign(m^2_{H_u})\sqrt{|m^2_{H_u}|}$ vs. Q

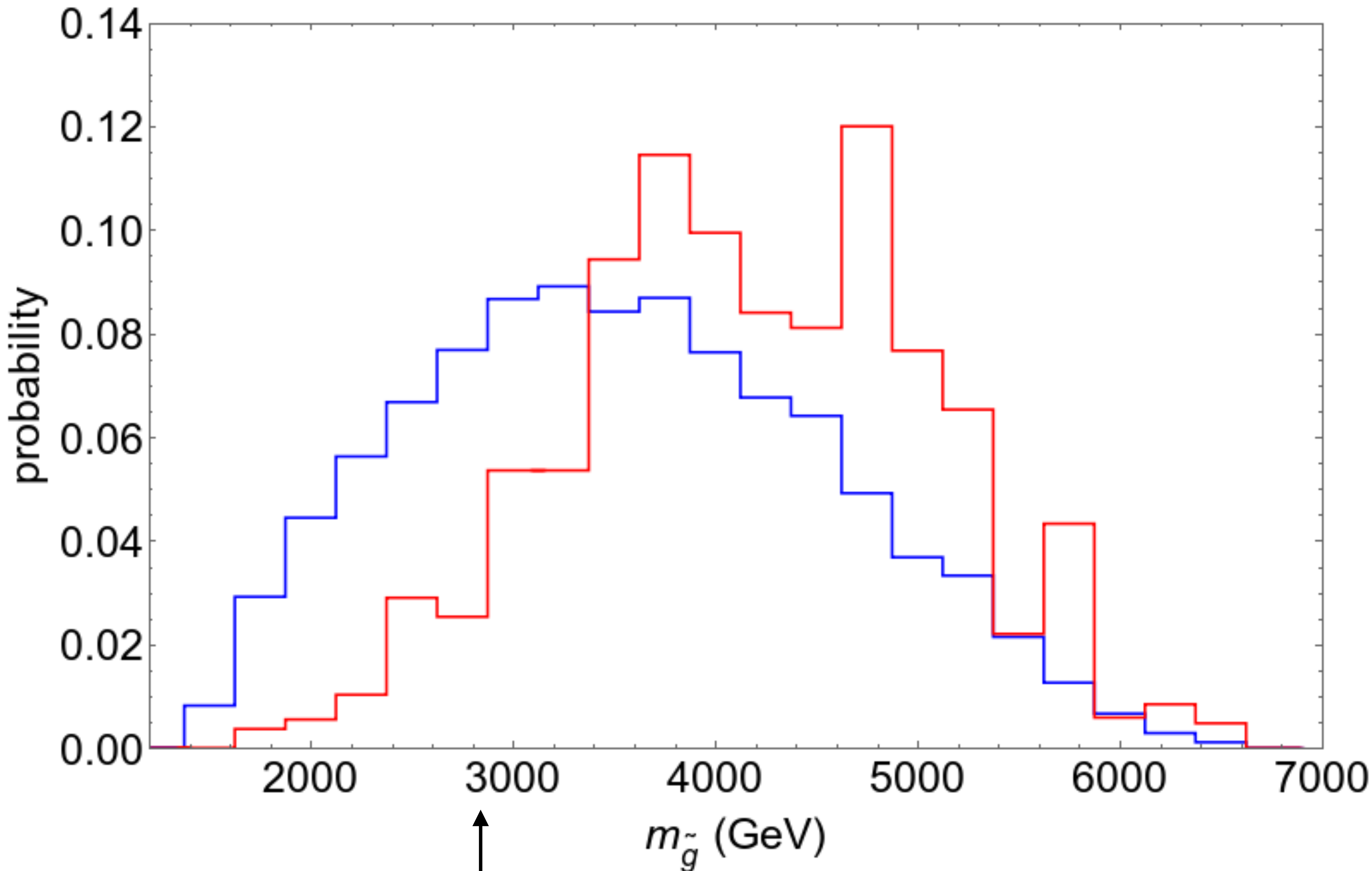
Simple landscape prediction for m(h):
blue: n=1
red: n=2

$$P(m_{SUSY}) \sim m_{SUSY}^n$$



HB, Barger, Serce, Sinha, to appear

Simple landscape prediction for m(gluino)
blue: n=1
red: n=2

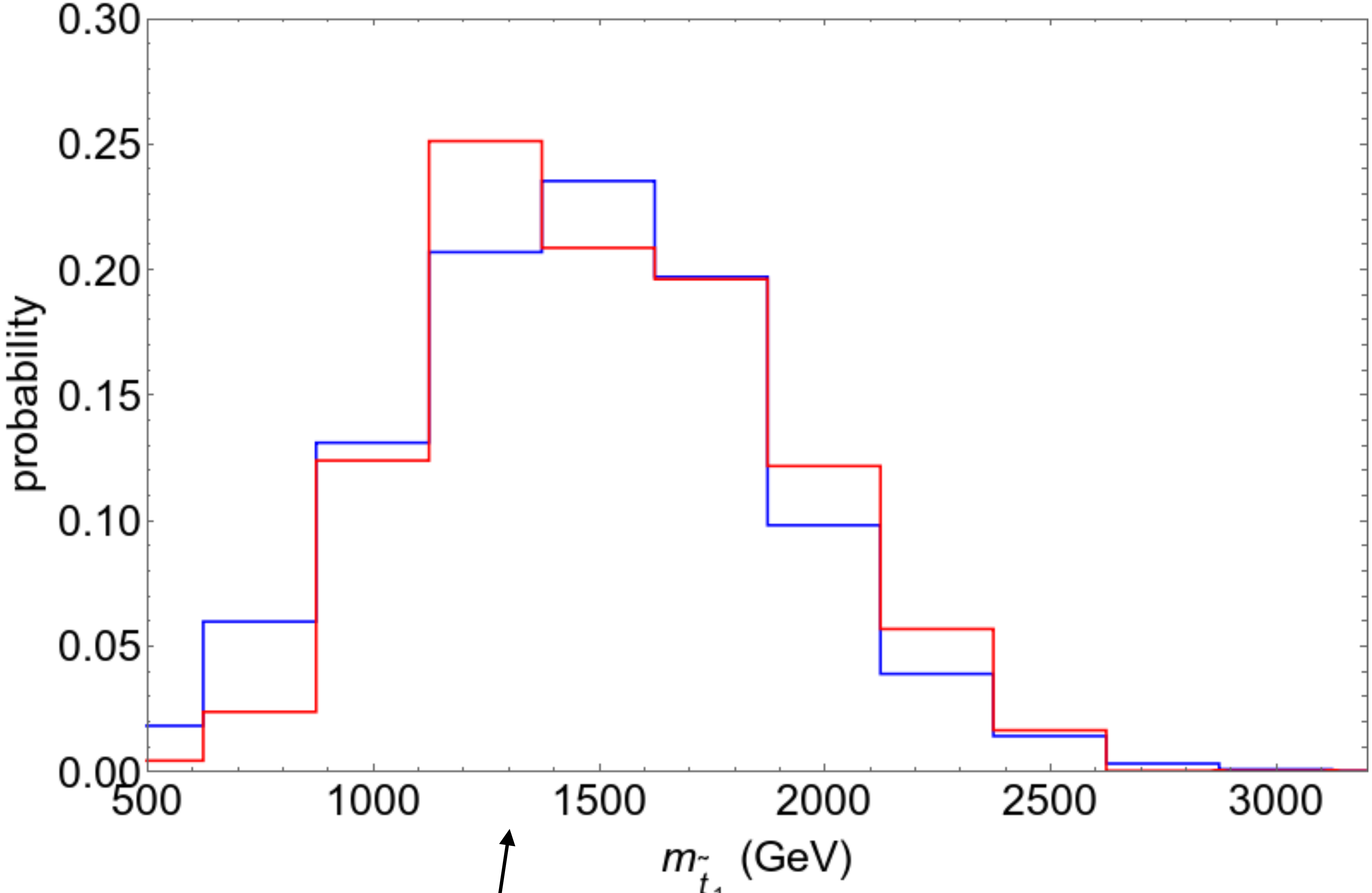


HL-LHC reach is to m(glno)~2.8 TeV

Simple landscape prediction for m(t1)

blue: n=1

red: n=2



HL-LHC reach is to m(t1)~1.2-1.4 TeV

Mirage mediation: comparable moduli- & anomaly-mediation

Choi, Falkowski, Nilles, Olechowski, Pokorski

Generalized mirage mediation model:

HB, Barger, Serce, Tata: arXiv:1610.06205

$$M_a = \left(\alpha + b_a g_a^2\right) m_{3/2}/16\pi^2, \tag{10}$$
$$A_\tau = \left(-a_3\alpha + \gamma_{L_3} + \gamma_{H_d} + \gamma_{E_3}\right) m_{3/2}/16\pi^2, \tag{11}$$
$$A_b = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_d} + \gamma_{D_3}\right) m_{3/2}/16\pi^2, \tag{12}$$
$$A_t = \left(-a_3\alpha + \gamma_{Q_3} + \gamma_{H_u} + \gamma_{U_3}\right) m_{3/2}/16\pi^2, \tag{13}$$
$$m_i^2(1,2) = \left(c_m\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right)\left(m_{3/2}/16\pi^2\right)^2, \tag{14}$$
$$m_j^2(3) = \left(c_{m3}\alpha^2 + 4\alpha\xi_j - \dot{\gamma}_j\right)\left(m_{3/2}/16\pi^2\right)^2, \tag{15}$$
$$m_{H_u}^2 = \left(c_{H_u}\alpha^2 + 4\alpha\xi_{H_u} - \dot{\gamma}_{H_u}\right)\left(m_{3/2}/16\pi^2\right)^2, \tag{16}$$
$$m_{H_d}^2 = \left(c_{H_d}\alpha^2 + 4\alpha\xi_{H_d} - \dot{\gamma}_{H_d}\right)\left(m_{3/2}/16\pi^2\right)^2, \tag{17}$$

elevate a_3, c_m, c_{m3}, c_{H_u}, c_{H_d} from discrete to continuous: soft terms depend on location of fields in compactified manifold!

p-space:

$$\alpha,\ m_{3/2},\ c_m,\ c_{m3},\ a_3,\ c_{H_u},\ c_{H_d},\ \tan\beta \quad (GMM)$$

$$\alpha,\ m_{3/2},\ c_m,\ c_{m3},\ a_3,\ \tan\beta, \mu,\ m_A \quad (GMM'). \qquad <=$$

allows for natural mirage mediation

Allows to generate mini-landscape spectra: heterotic string compactified on Z6-II orbifold

Lebedev, Nilles, Raby, Ramos-Sanches, Ratz, Vaudrevange

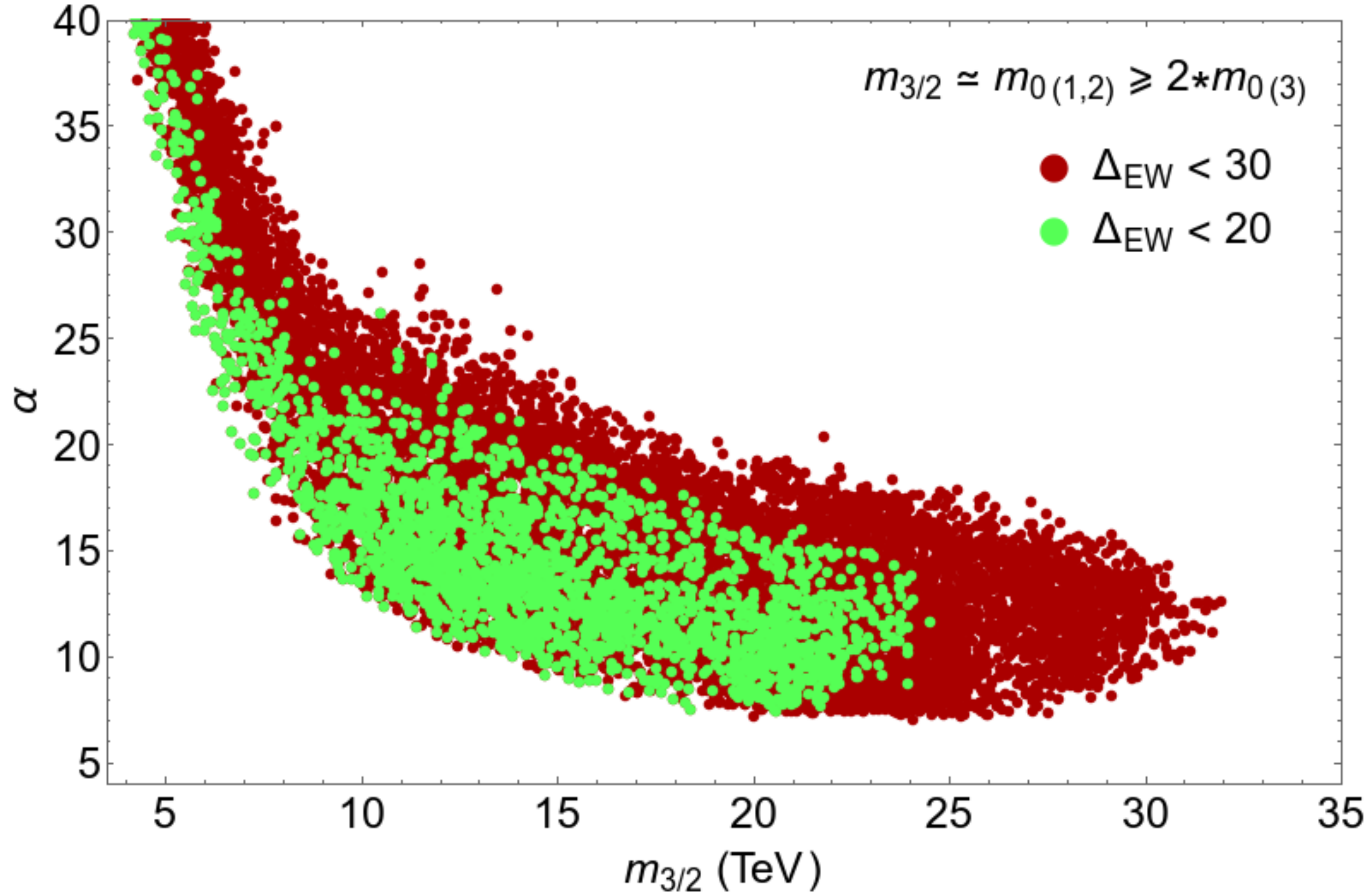
but with radiatively-driven naturalness

HB, Barger, Savoy, Serce, Tata, arXiv:1705.01578

- Look for fertile patch of landscape giving MSSM
- 1,2 gen lives on orbifold fixed points/tori: in 16 of SO(10)
- 3rd gen, Higgs, gauge live more in bulk: split multiplets
- m(1,2)~m(3/2)~10-30 TeV
- m(3)~m(H)~A's~m(inos)~1-3 TeV
- soft terms that of mirage mediation
- programmed Isajet 7.86

To generate mini-landscape, take:

$$c_m = 16\pi^2/\alpha)^2 \text{ so that } m_0(1,2) \simeq m_{3/2}$$

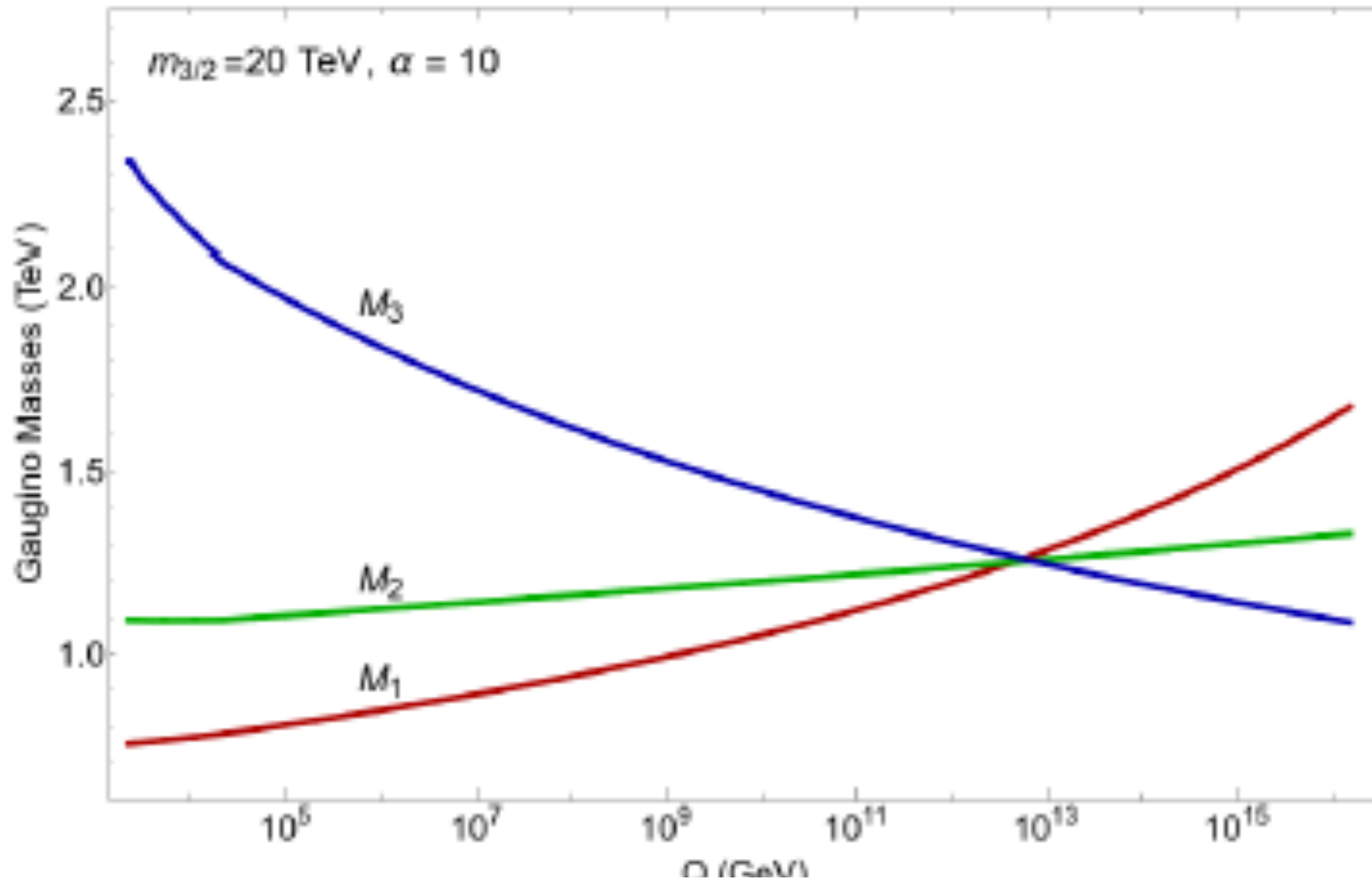


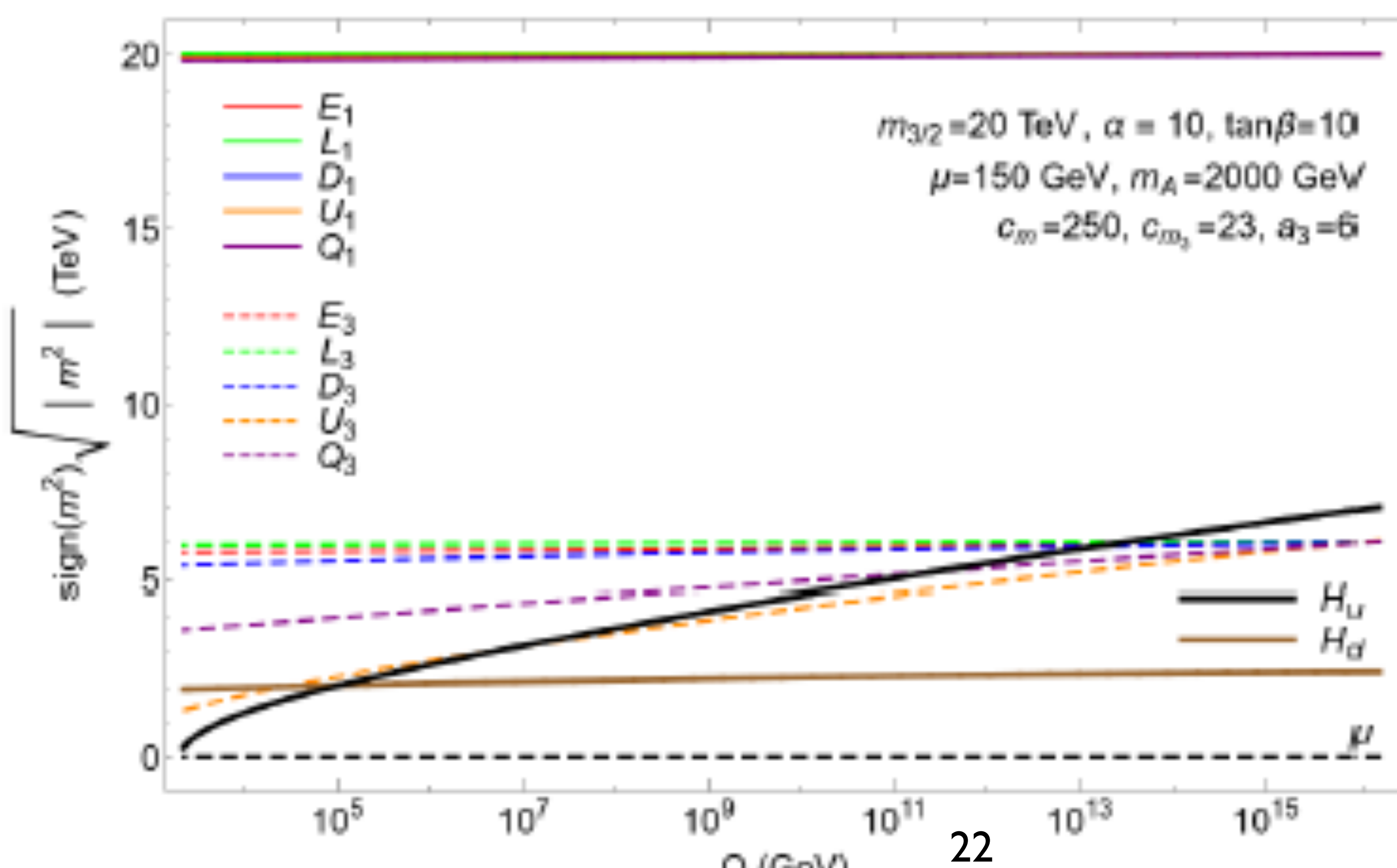
Then get upper bound $m_{3/2} < 25 - 30$ TeV and $\alpha > 7$ else too large $m_0(1,2)$ drives 3rd generation tachyonic

Martin, Vaughn, 2-loop RGEs

Increased upper bound on m(gluino)<6 TeV

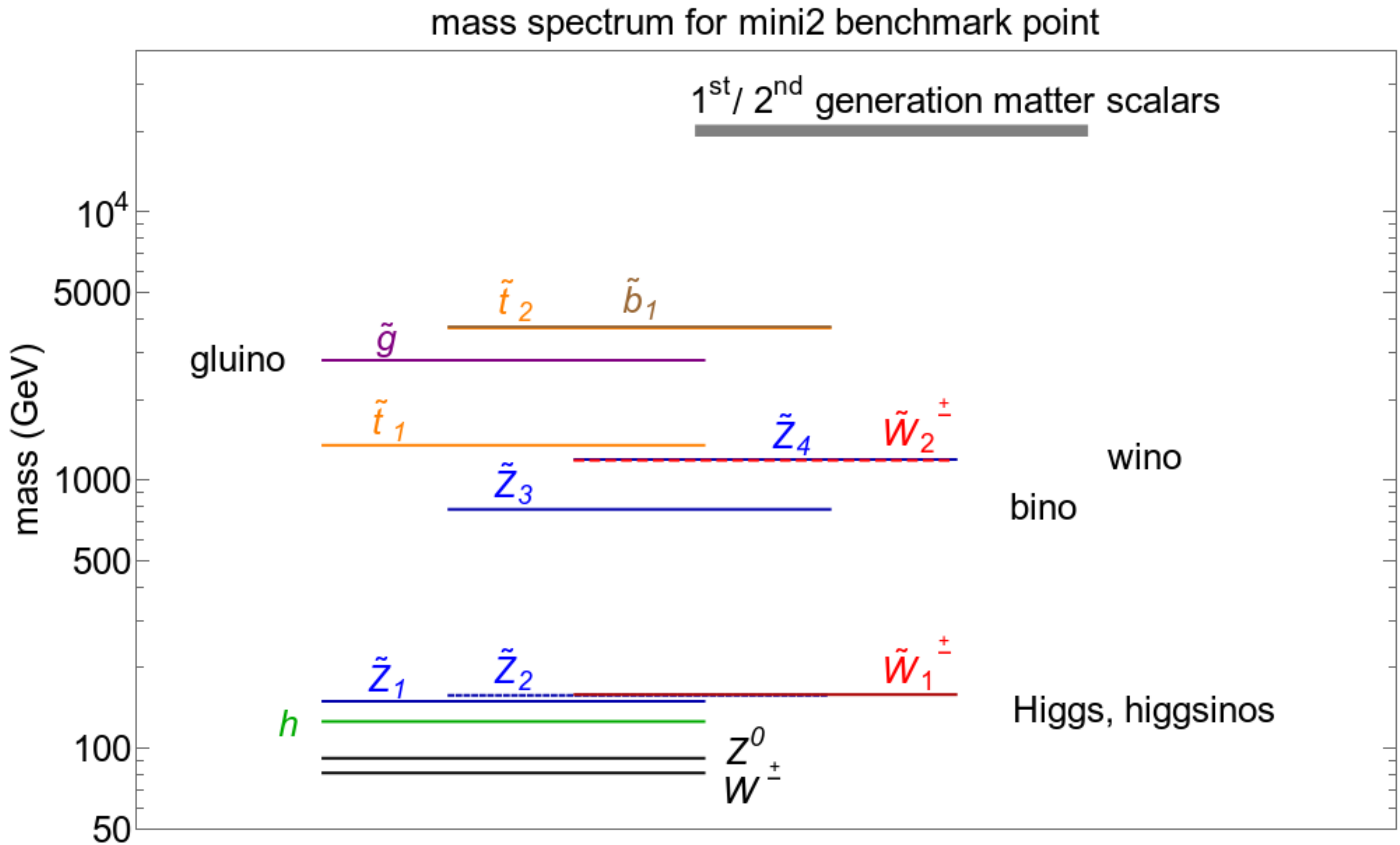
Alpha bound => mirage unif scale >10^11 GeV
(not too much compression of inos)



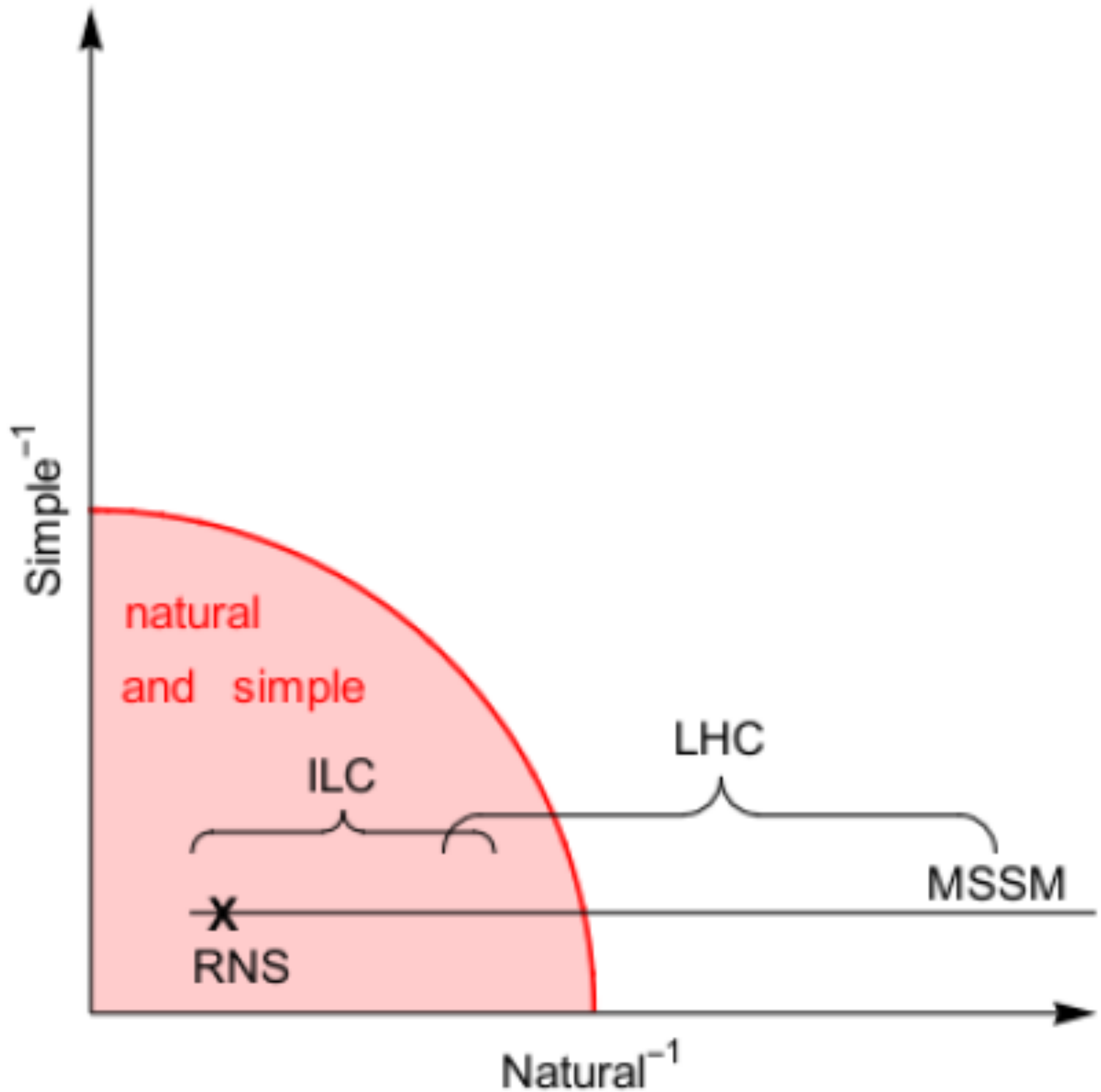


$$\Delta_{EW} = 17.6$$

$$m_h \simeq 125 \text{ GeV}$$



SUSY may not be accessible to HL-LHC;
must have ILC to discover required light higgsinos


Simple^{-1}
natural
and simple
ILC
LHC
MSSM
RNS
Natural^{-1}

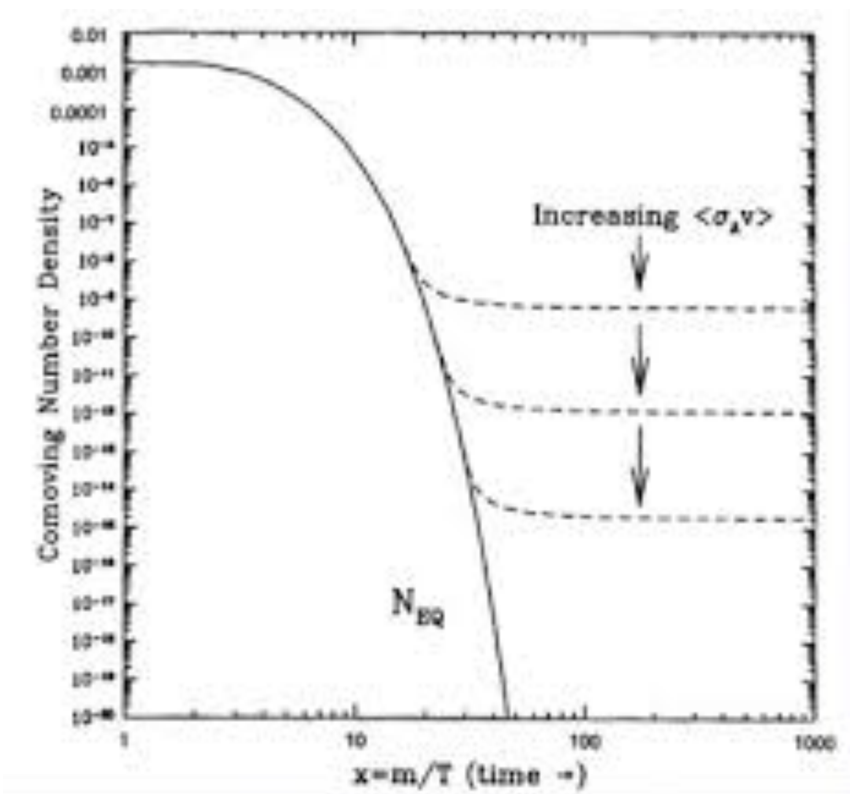
Conclusions

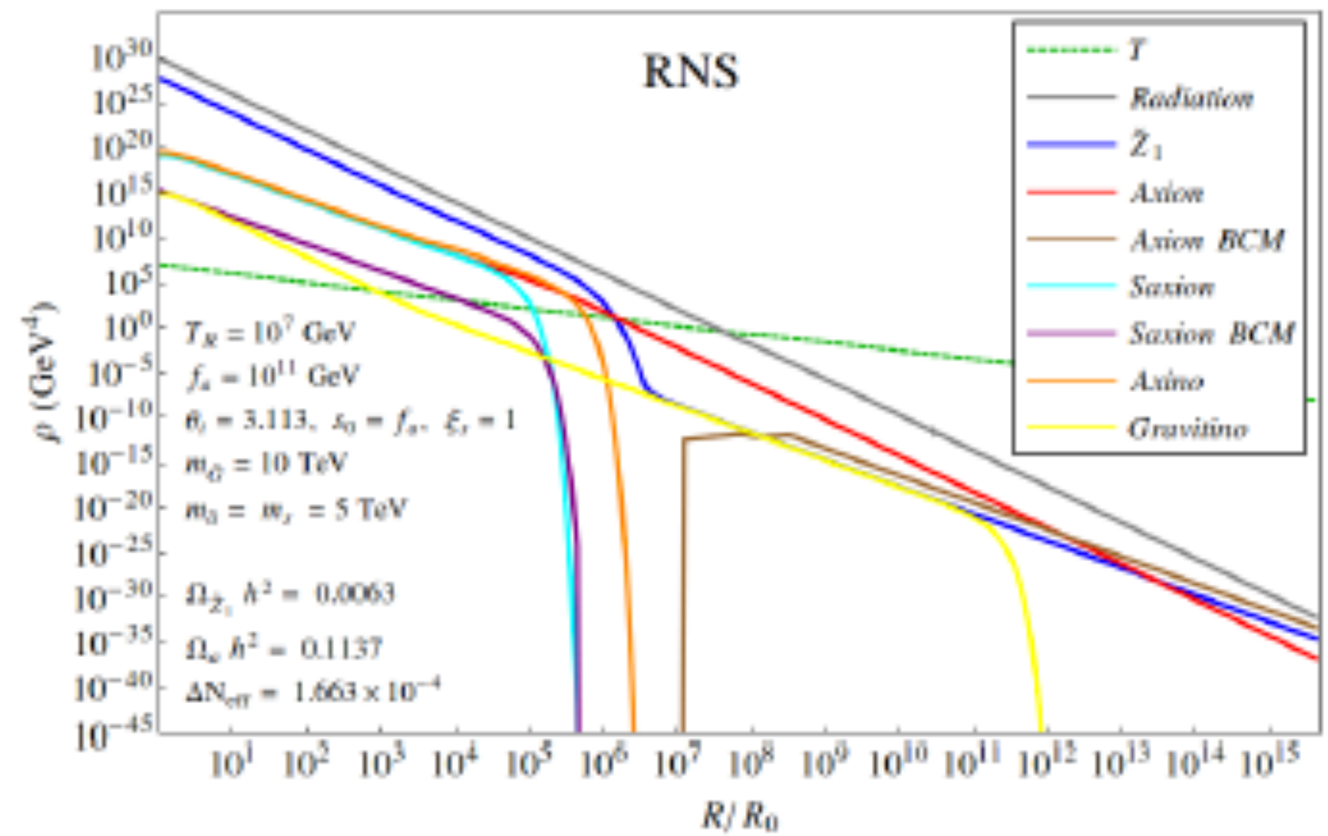
- ILC250 has strong motivation for discovering new physics via virtual effects
- But case for direct production of superparticles (higgsinos) at ILC highly motivated by naturalness: this is most plausible rendition of SUSY and in dire need of ILC!
- small mu related to PQ mechanism: unification of intermediate scales: SUSYbreaking, PQ, Majorana
- string landscape favors large soft terms/barely broken EWS: get mh right but favor high sparticle masses except mu~100-200 GeV
- UV completion for MSSM within heterotic string compactified on Z6-II orbifold: mini-landscape picture with localized SUSY GUTs and natural with light higgsinos
- imprint of higgsino mass splitting tells whether gaugino masses unify or else mirage unification!
- (dark matter: in this case, likely axion-higgsino-like WIMP admixture)

What happens to SUSY WIMP dark matter?

- higgsino-like WIMPs thermally underproduced
- 3 not four light pions => QCD theta vacuum
- EDM(neutron) => axions: no fine-tuning in QCD sector
- SUSY context: axion superfield, axinos and saxions
- DM= axion+higgsino-like WIMP admixture
- DFSZ SUSY axion: solves mu problem with mu<< m_3/2!
- ultimately detect both WIMP and axion?

usual picture => mixed axion/WIMP

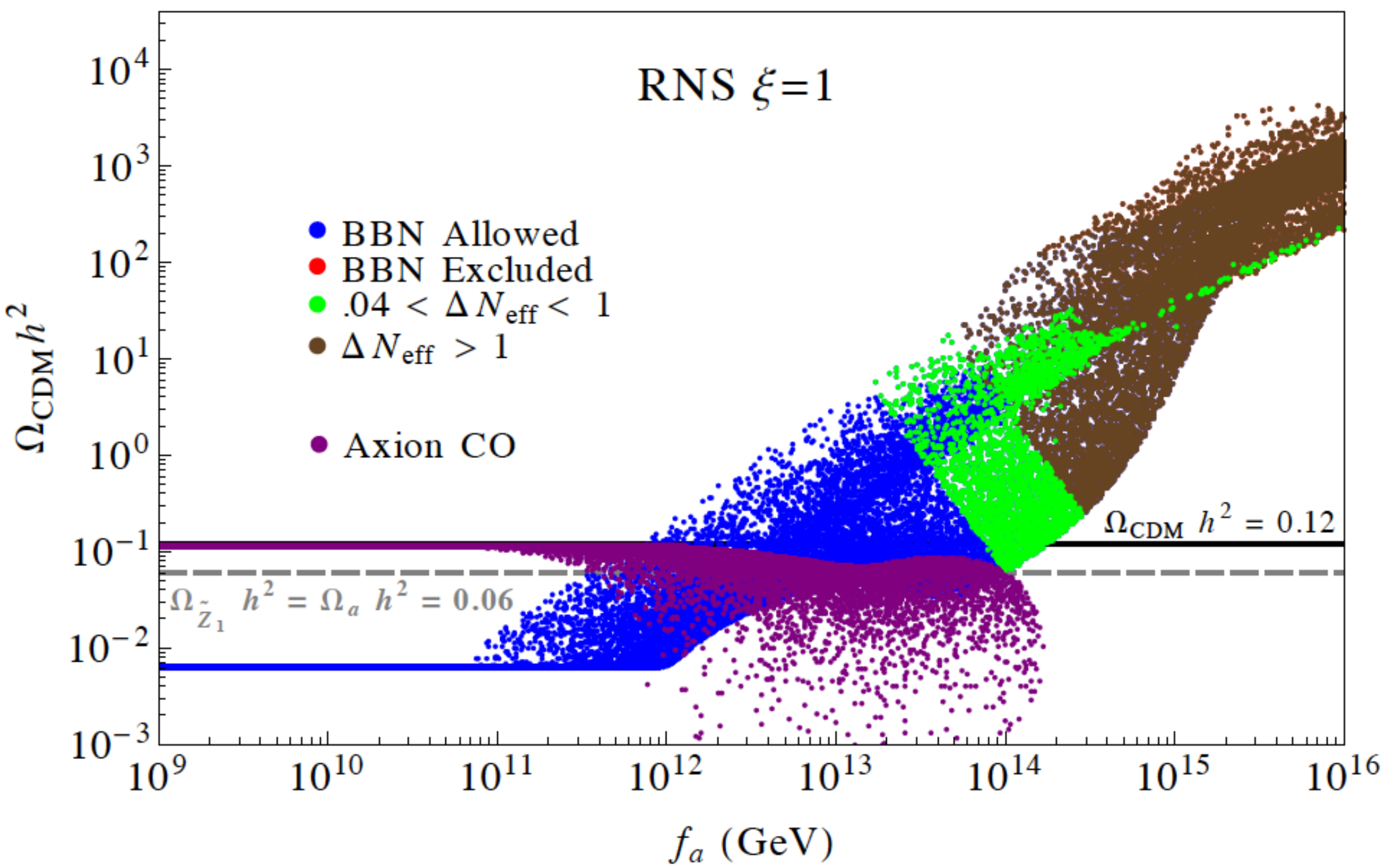




KJ Bae, HB, Lessa, Serce

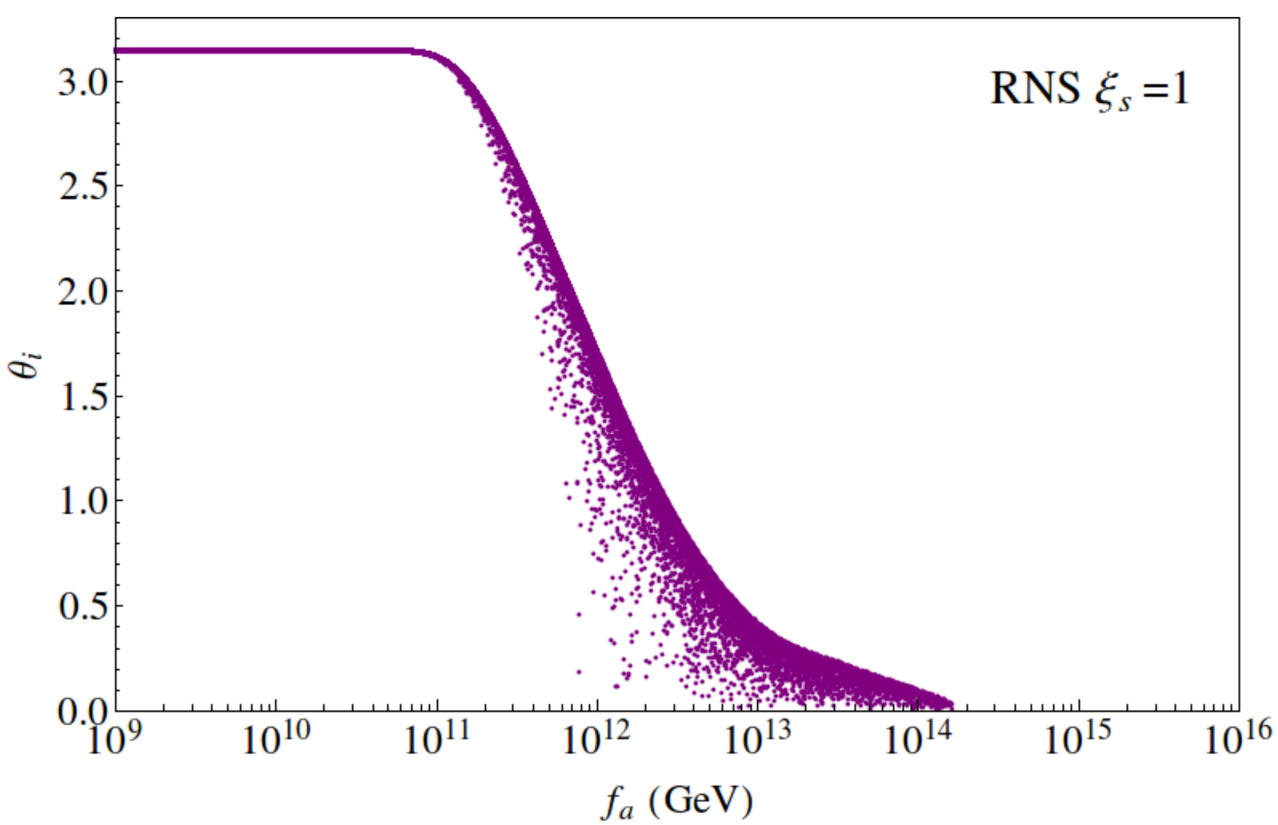
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

axion abundance



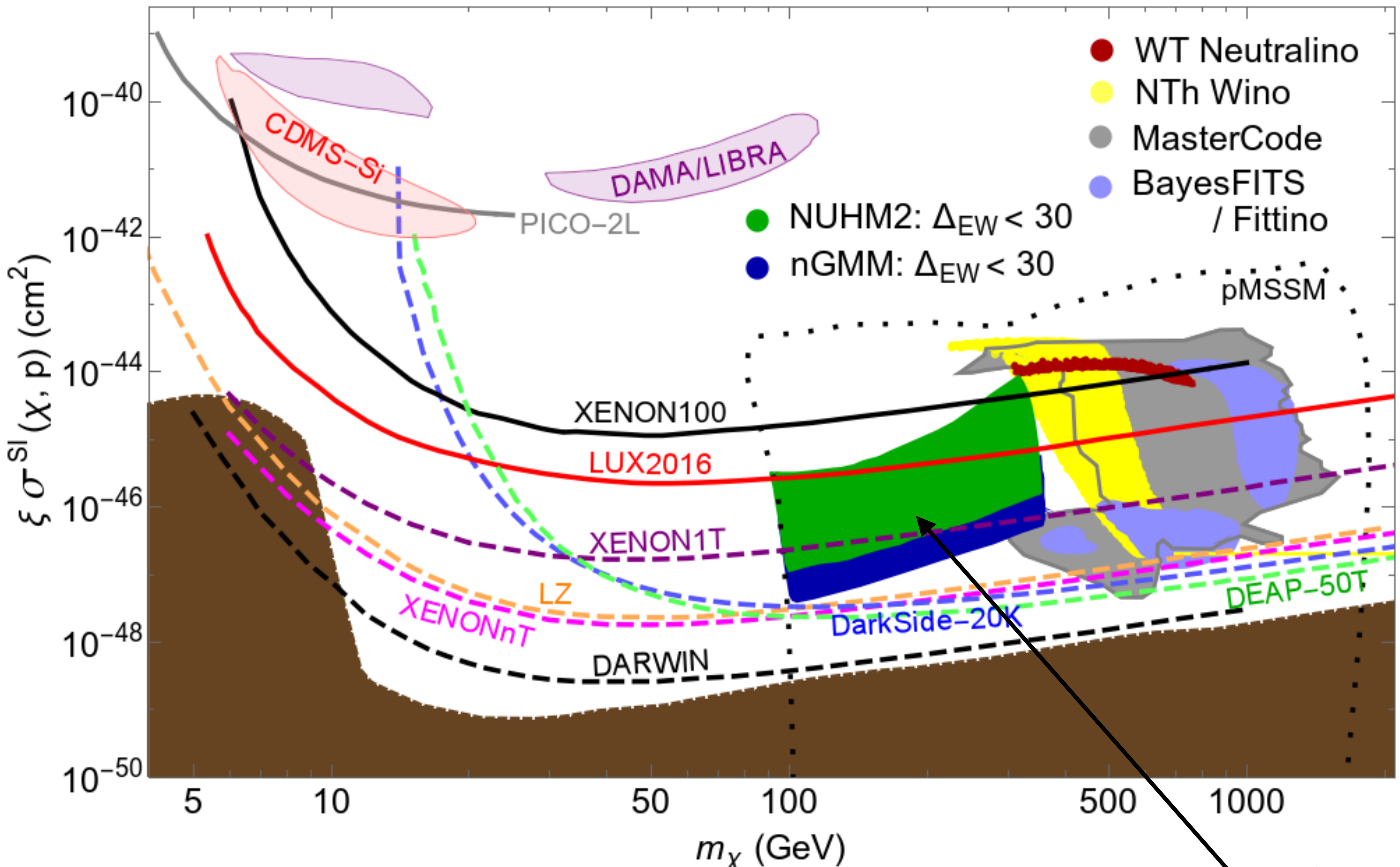
mainly axion CDM

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 $\xi \equiv \Omega_\chi^{TP} h^2/0.12$



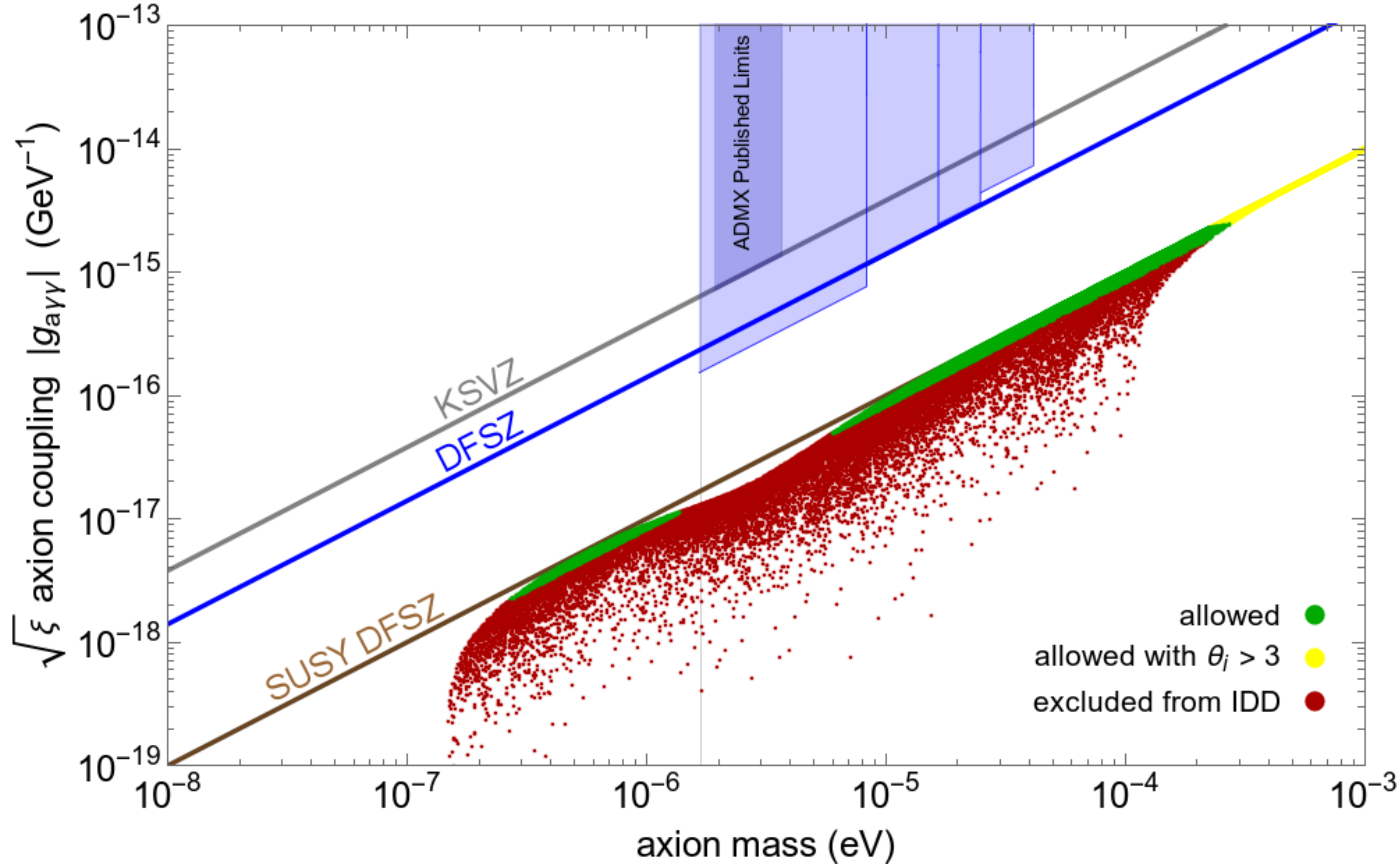
Bae, HB, Barger,Savoy,Serce

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

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

Xe-1-ton now operating!

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



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

may need to probe broader and deeper!