Supersymmetric dark matter: waxing, not waning

UCLA dark matter meeting, March 2023

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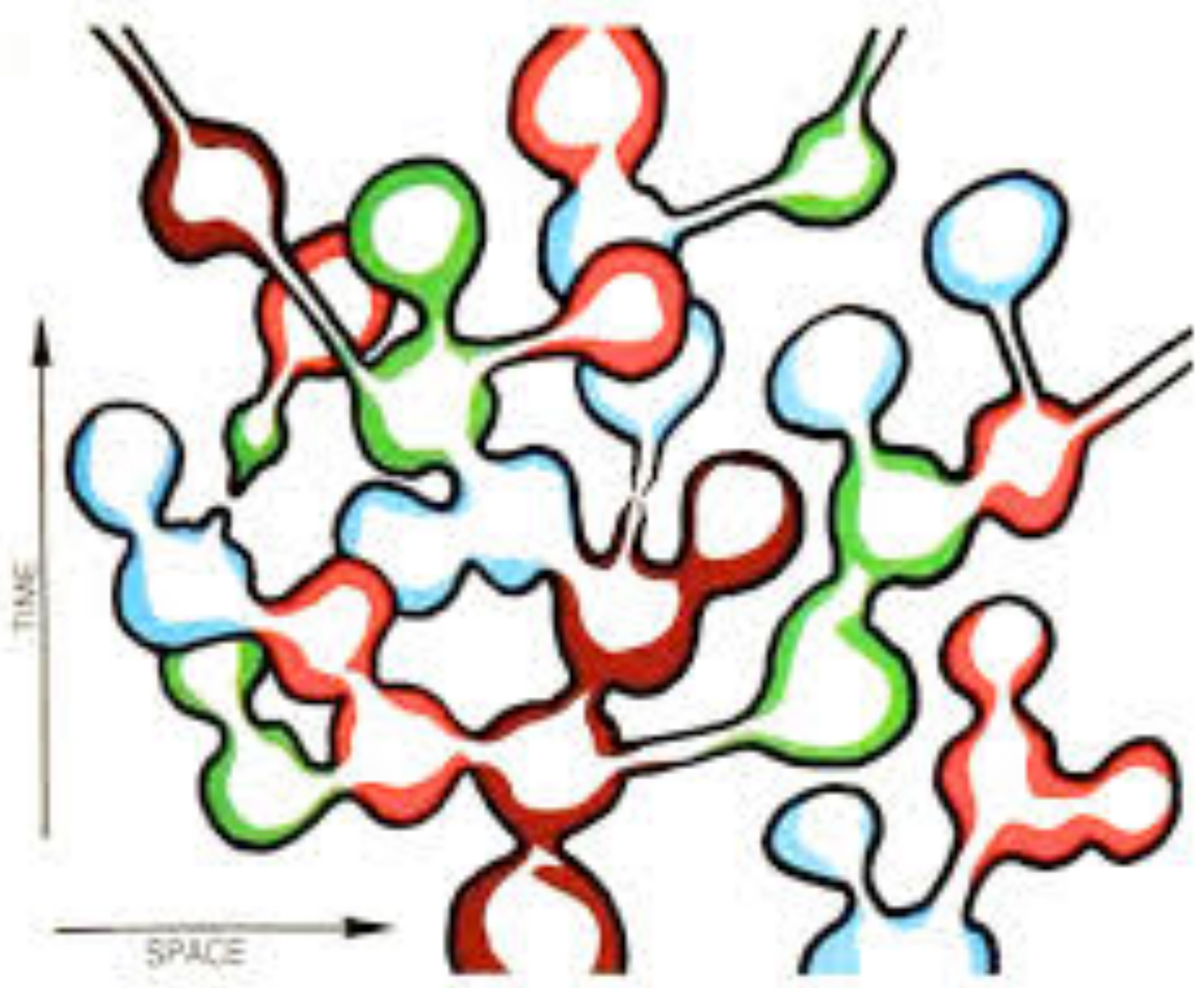

The SM is beset by several finetuning problems:

- Gauge hierarchy: how can weak scale be so much smaller than GUT/ Planck scale?
- Strong CP problem (QCD): why is QCD theta parameter so small <~10^-10
- Cosmological constant: $\rho_{vac} \sim (0.003 \text{ eV})^4 \ll m_P^4$

The SM is beset by several finetuning problems:

most plausible solutions to date

- Gauge hierarchy: how can weak scale be so much smaller than GUT/ Planck scale?

SUSY

- Strong CP problem (QCD): why is QCD theta parameter so small <~10^-10

axion

- Cosmological constant: $\rho_{vac} \sim (0.003 \text{ eV})^4 \ll m_P^4$

anthropic vacua selection from multiverse/string vacua

SUSY solves Big Hierarchy: but LHC => Little Hierarchy

- It is (mistakenly) believed that weak scale SUSY is no longer natural due to strong LHC constraints on sparticle masses (m(glno)>2.2 TeV) and the rather large value of m(h)~125 GeV
- 1. BG naturalness measure overestimates finetuning by factors of 10-500 due to adopting various soft terms as independent when in realistic SUGRA models these are in fact *dependent*: soft terms computed as multiples of gravitino mass m_3/2
- 2. Higgs mass finetuning measure breaks soft terms into *dependent* contributions which each vary as they are tuned: violates finetuning rule, leading again to overestimates by orders of magnitude
- 3. EW finetuning measure: mandatory and model independent

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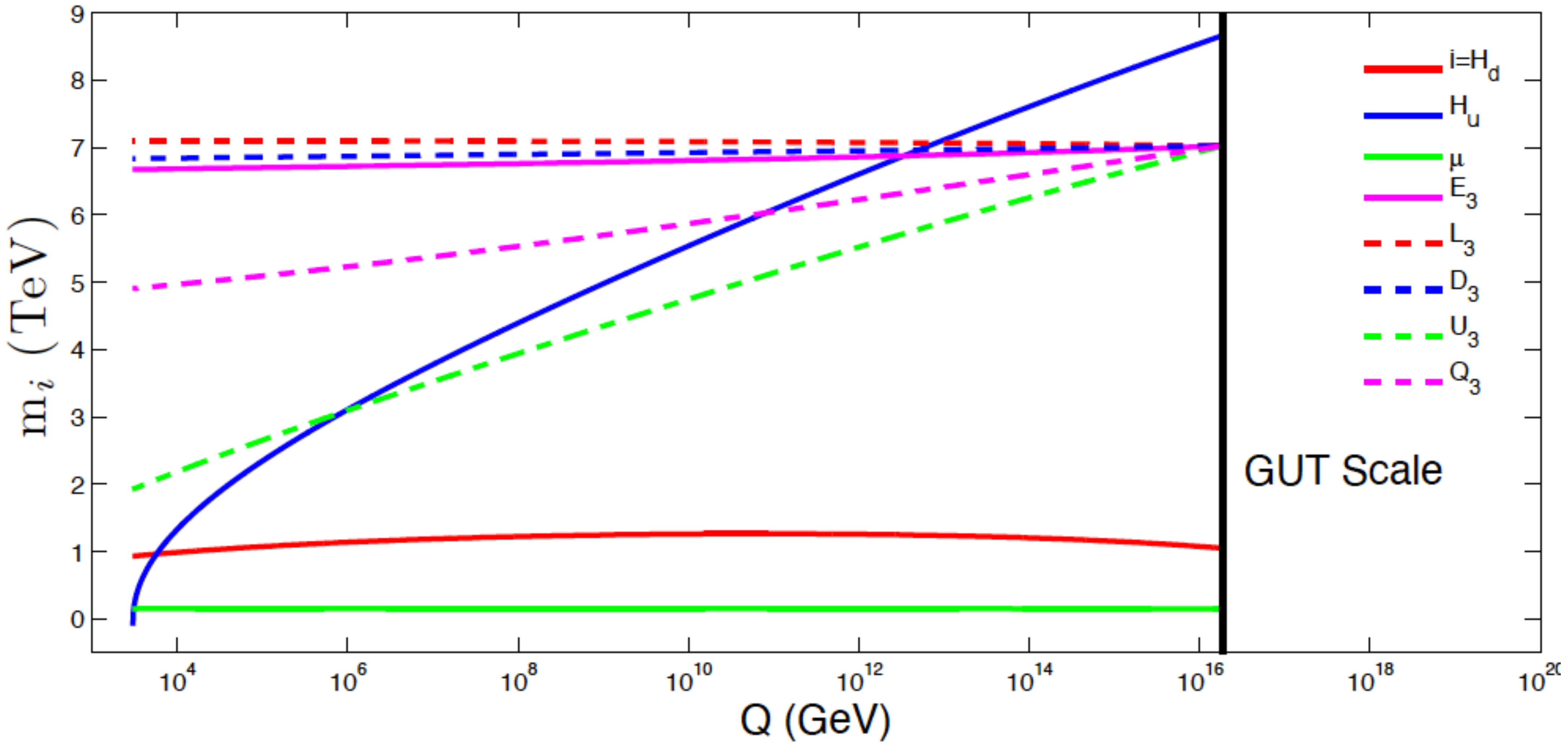
How conventional measures overestimate electroweak fine-tuning in supersymmetric theory

Howard Baer,[1,*] Vernon Barger,[2,†] and Dan Mickelson[1,‡] practical naturalness: all *independent* contributions to an observable should be comparable to or less than the observable

[This is the way naturalness has been successfully applied by e.g. Gaillard and Lee to predict the value of m(charm) shortly before it was discovered]

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



1. mu~m(Z)~100-300 GeV: LSP is higgsino-like!

2. m(Hu)~m(Z)~100-300 GeV can be radiatively driven to small (natural) values

3. top squarks loop suppressed: range up to 3 TeV

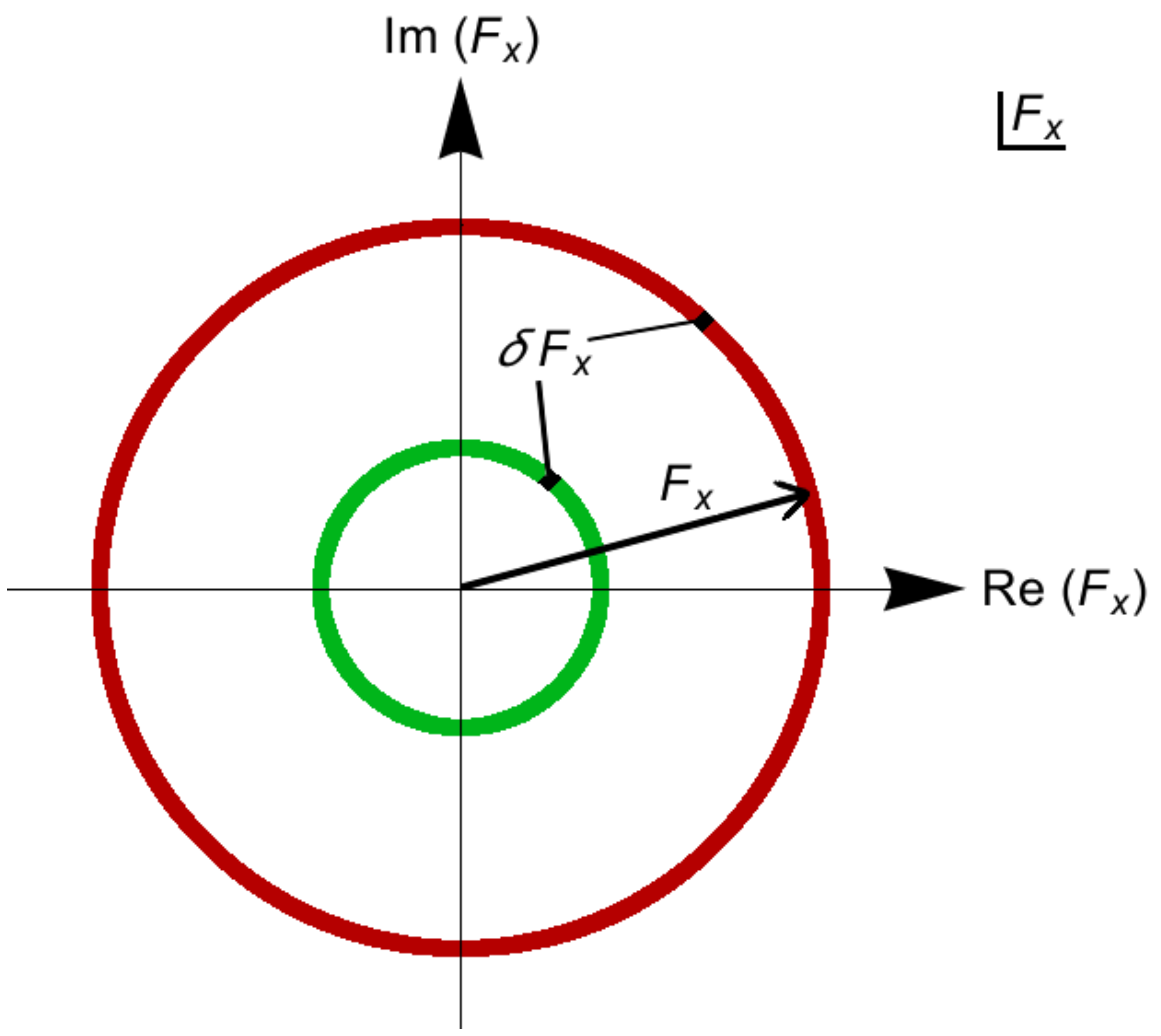
4. gluinos enter at 2-loops: can range up to 6 TeV

SUSY with radiatively-driven naturalness is natural!

review: see arXiv:2002.03013

vacua selection in multiverse

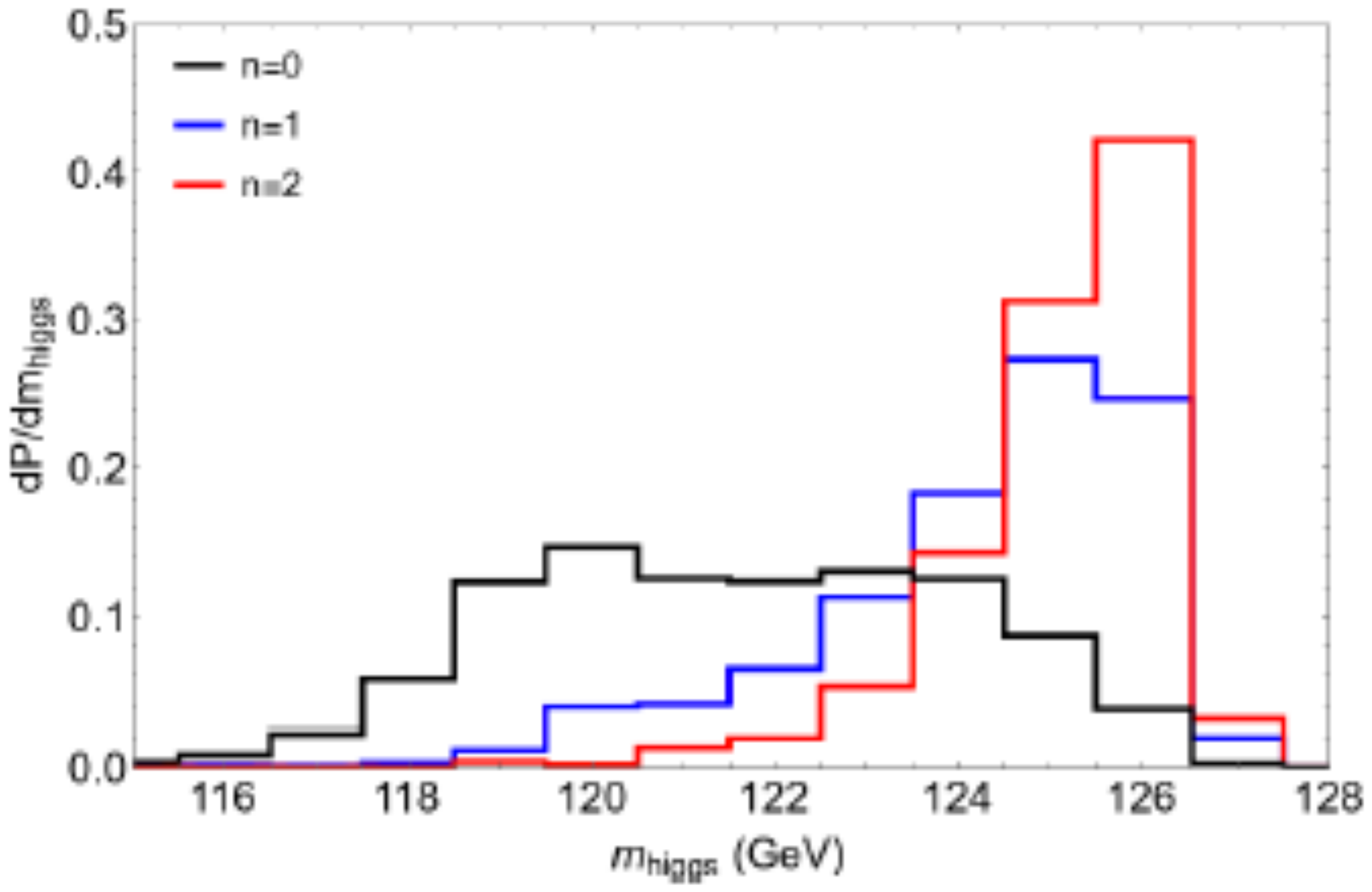
- anthropic selection of tiny CC at present perhaps most plausible solution to CC problem (Weinberg)
- realized in 3rd string revolution (Bousso & Polchinski, flux compactifications)
- may provide mechanism for origin of weak scale due to SUSY breaking
- statistical predictions from string vacua?
- power law draw to large soft terms (Douglas, Susskind)
- tempered by anthropic requirement of pocket universe m(weak) within factor of few of our measured value: ABDS window-atomic principle!

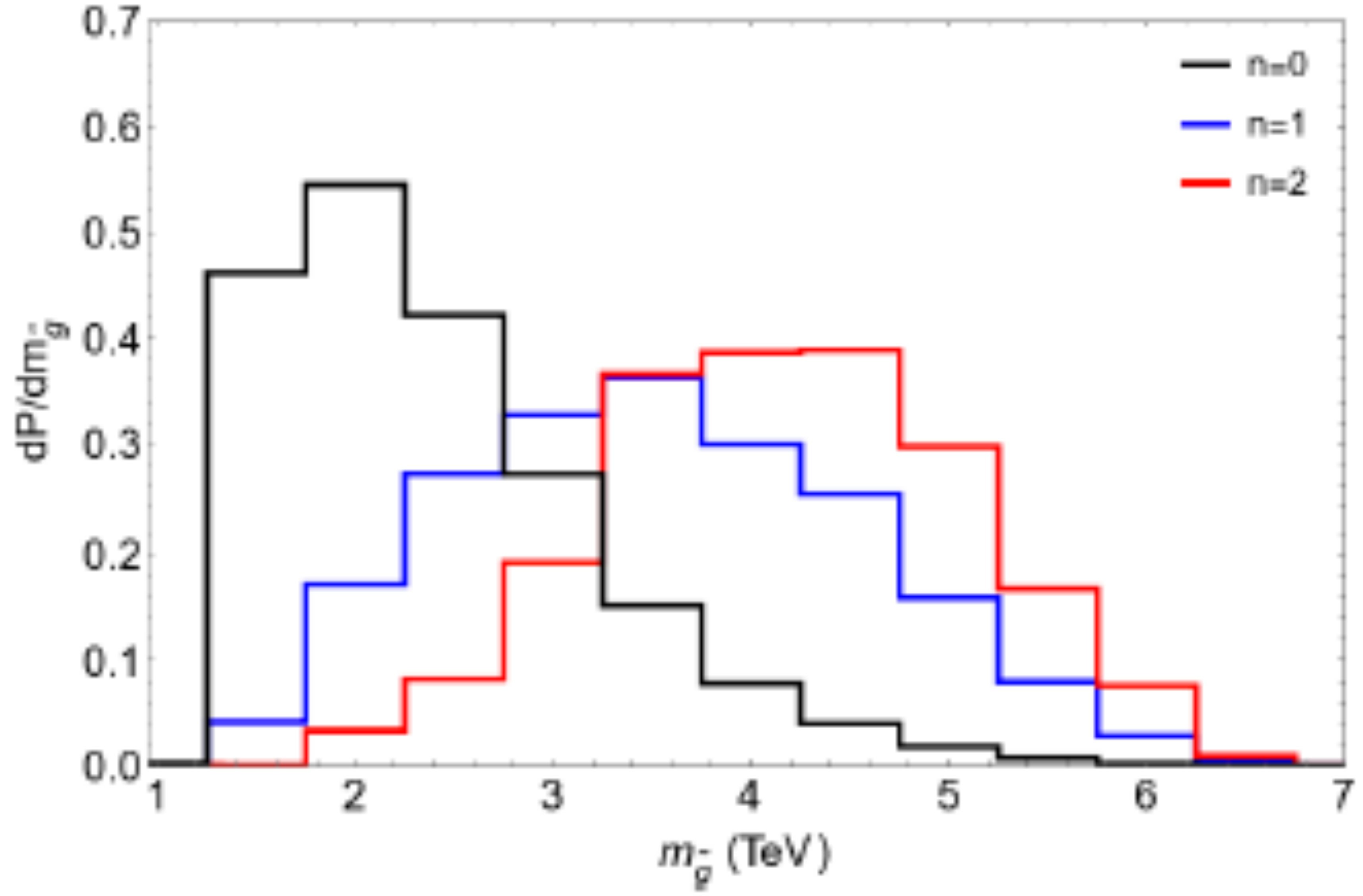


multiverse selection of SUSY breaking complex-valued F-term

SUSY from the multiverse

- 10^500 string vacua: each -> different 4-d laws of physics
- power-law draw of landscape to large soft terms (Douglas, Susskind)
- derived value for pocket-universe weak scale must lie ~(2-5)m(weak)~100 GeV: ABDS window/atomic principle
- => m(h)~125 GeV
- => sparticles beyond LHC bounds
- decoupling/quasi-degeneracy sol'n to SUSY flavor problem
- HB, Barger, Serce, Sinha, arXiv: 1712.01399

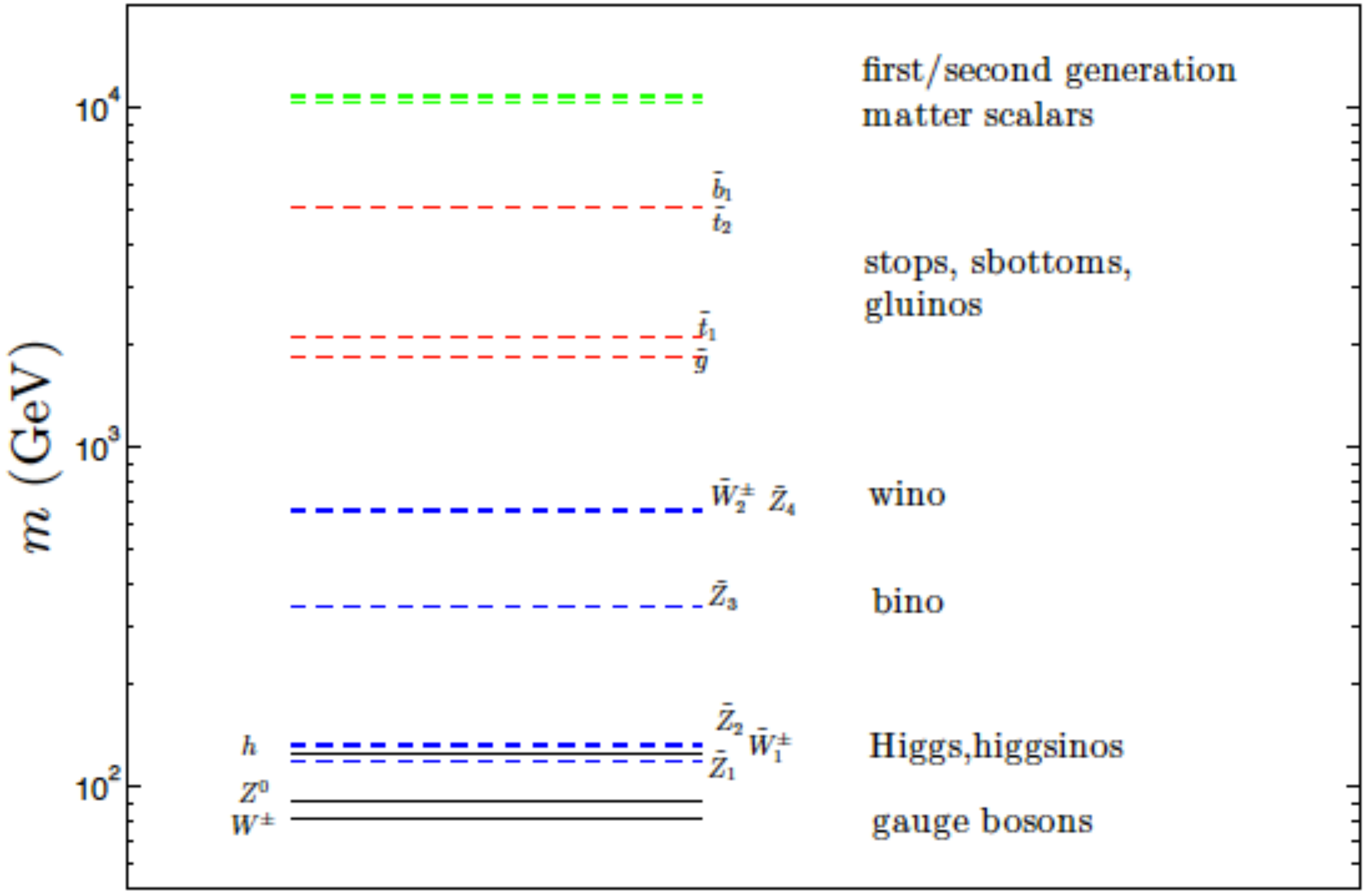




The string landscape provides a mechanism for SUSY with low Delta(EW)

HB, Barger, Martinez, Salam
arXiv:2202.07046

Typical spectrum for low Δ_{EW} models

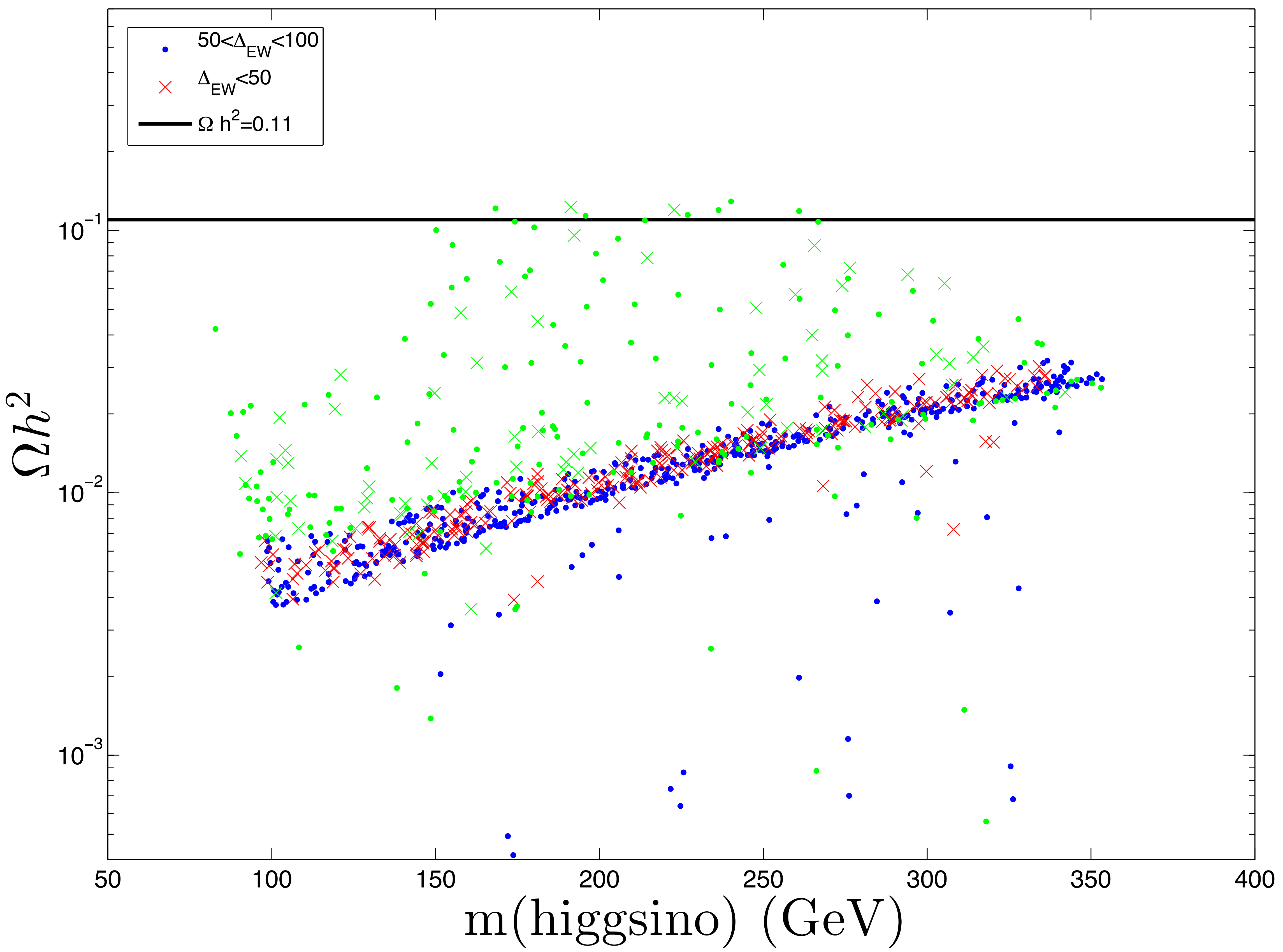


There is a Little Hierarchy, but it is no problem

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

higgsinos likely the lightest superparticles!

But ‘natural’ higgsino-like WIMPs thermally underproduced



But no problem: need PQ solution to strong CP also: SUSY axions!

PQ axions need SUSY

- PQ: need new scale f_a~10^11 GeV; but don't want m(h)-> newly introduced high scale
- global PQ inconsistent with quantum gravity: no global symmetries! But PQ can emerge as accidental, approximate global symmetry from more fundamental discrete R-symmetries (intrinsically SUSY) which arise from string compactifications: similar to B and L conservation arising accidentally from SM gauge symmetries
- why f_a~10^11 GeV? link to SUSY breaking scale sqrt{F_x}~10^11 GeV
- axion quality problem: higher dim op's can destroy thetabar<10^-10: but e.g. discrete R-symmetries can sufficiently suppress these terms
- axion quality: stringy instantons can destroy but not for MSSM as LE-EFT (McAllister et al., PQ axiverse)

and SUSY needs axion

- SUSY mu problem: superpotential mu term is SUSY conserving, not SUSY breaking: then expect mu~m(Planck) unless forbidden by e.g. PQ symmetry (Kim-Nilles solution to SUSY mu problem in SUSY DFSZ axion model [DFSZ fits well with MSSM as both require two Higgs doublets])
- naturalness => SUSY LSP is light higgsino: thermally underproduced by typically factor of 10
- marriage of SUSY with PQ axion => multicomponent DM: DFSZ axion plus higgsino-like WIMP admixture
- R-parity, B/L conservation, PQ can all emerge from discrete R-symmetry
- related work: see Harigaya, Yanagida et al.

Gravity safe, electroweak natural axionic solution to strong CP and SUSY μ problems

HB, Barger, Sengupta, arXiv:1810.03713

1. Global symmetries fundamentally incompatible with gravity completion
2. Expect global symmetry to emerge as accidental (approximate) symmetry from some more fundamental gravity-safe (e.g. gauge or R-) symmetry.
3. Discrete R-symmetries:

intrinically supersymmetric and expected to emerge from string compactification

A model which works: Z(24) R symmetry

(see also Lee et al.), arXiv:1102.3595

$$W \ni f_u Q H_u U^c + f_d Q H_d D^c + f_\ell L H_d E^c + f_\nu L H_u N^c + M_N N^c N^c/2 + \lambda_\mu X^2 H_u H_d/m_P + f X^3 Y/m_P + \lambda_3 X^p Y^q/m_P^{p+q-3}$$

- Lowest dimension PQ breaking operator contributing to scalar PQ potential $\sim 1/m_P^8$: enough suppression so that PQ is gravity-safe
- Also forbids/suppresses RPV/p-decay operators
- $\mu \sim \lambda_\mu f_a^2/m_P$

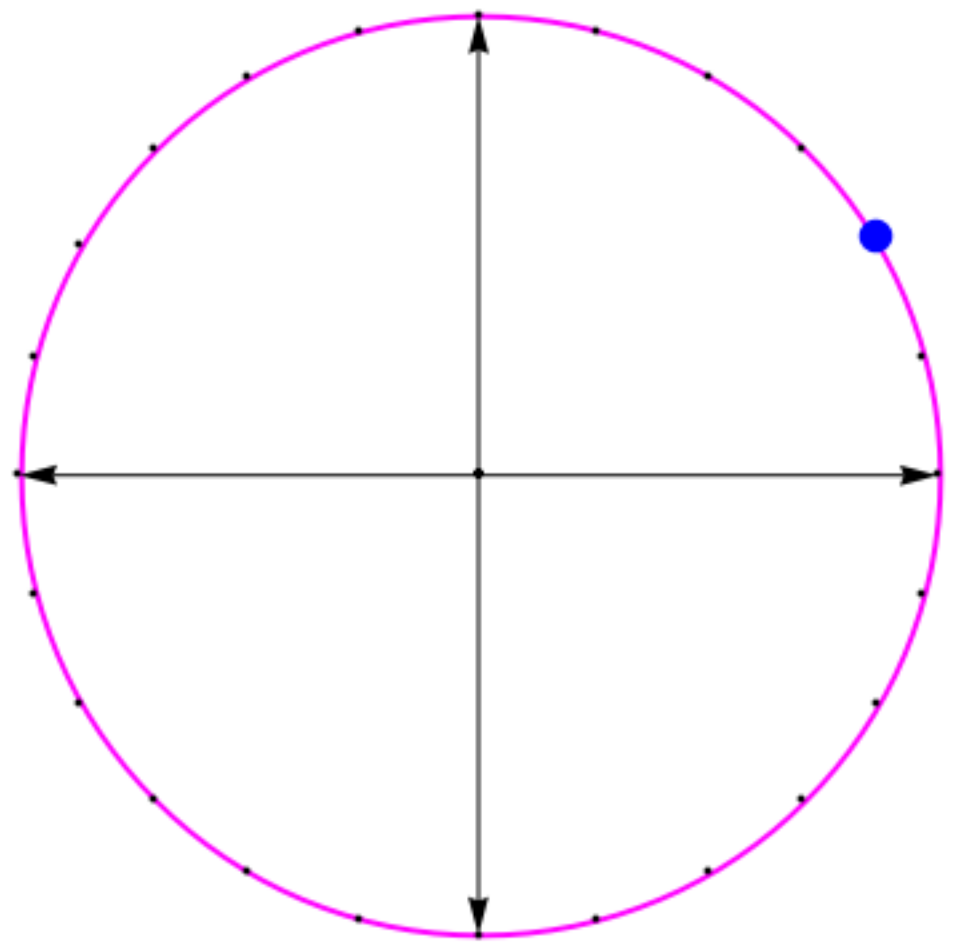
This two-extra -field model based on Z(24)^R symmetry forbids mu term, RPV terms and dim 6 p-decay operators, while maintaining MSSM Yukawa and Majorana nu mass term and to-be mu parameter

$$\begin{aligned} W_{hyCCK} &\ni f_u Q H_u U^c + f_d Q H_d D^c + f_\ell L H_d E^c + f_\nu L H_u N^c + M_N N^c N^c/2 \\ &+ f X^3 Y/m_P + \lambda_\mu X^2 H_u H_d/m_P. \end{aligned}$$

Also W contains an X^8Y^2/mP^7 superpotential; scalar pot'l suppressed by 1/mP^8, gravity safe!

multiplet	H_u	H_d	Q_i	L_i	U_i^c	D_i^c	E_i^c	N_i^c	X	Y
$\mathbb{Z}_{24}^R$ charge	16	12	5	9	5	9	5	1	-1	5
PQ charge	-1	-1	1	1	0	0	0	0	1	-3

Z(24)^R and PQ charge assignments



HB, Barger, Sengupta, arXiv:1810.03713

For large A_f soft terms, Z(24)^R and U(1)_PQ spontaneously broken due to SUSY breaking with vevs~10^11 GeV => f_a~10^11 GeV!

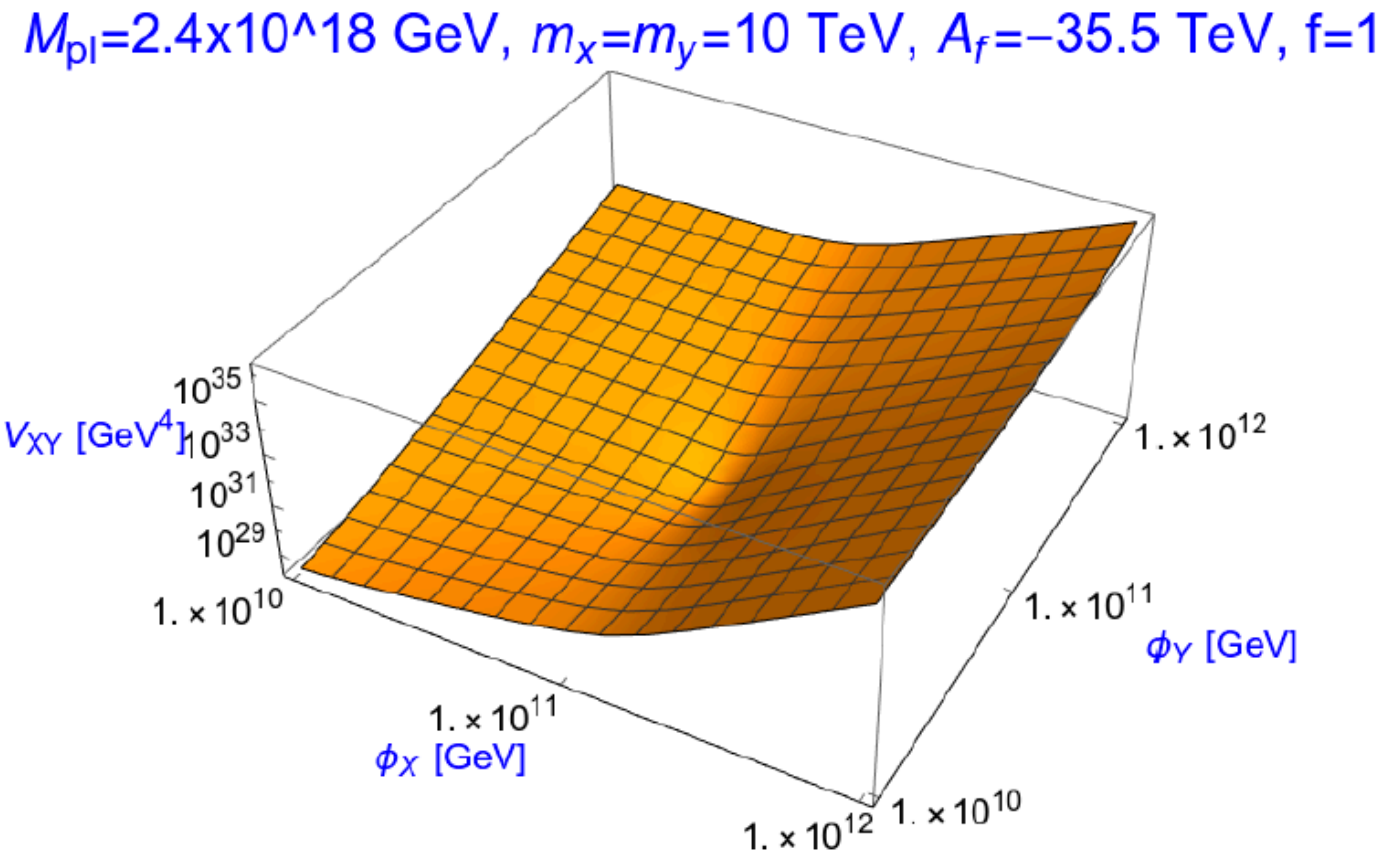


Figure 1: Scalar potential V_{GSPQ} versus ϕ_X and ϕ_Y for $m_X = m_Y \equiv m_{3/2} = 10$ TeV, $f = 1$ and $A_f = -35.5$ TeV.

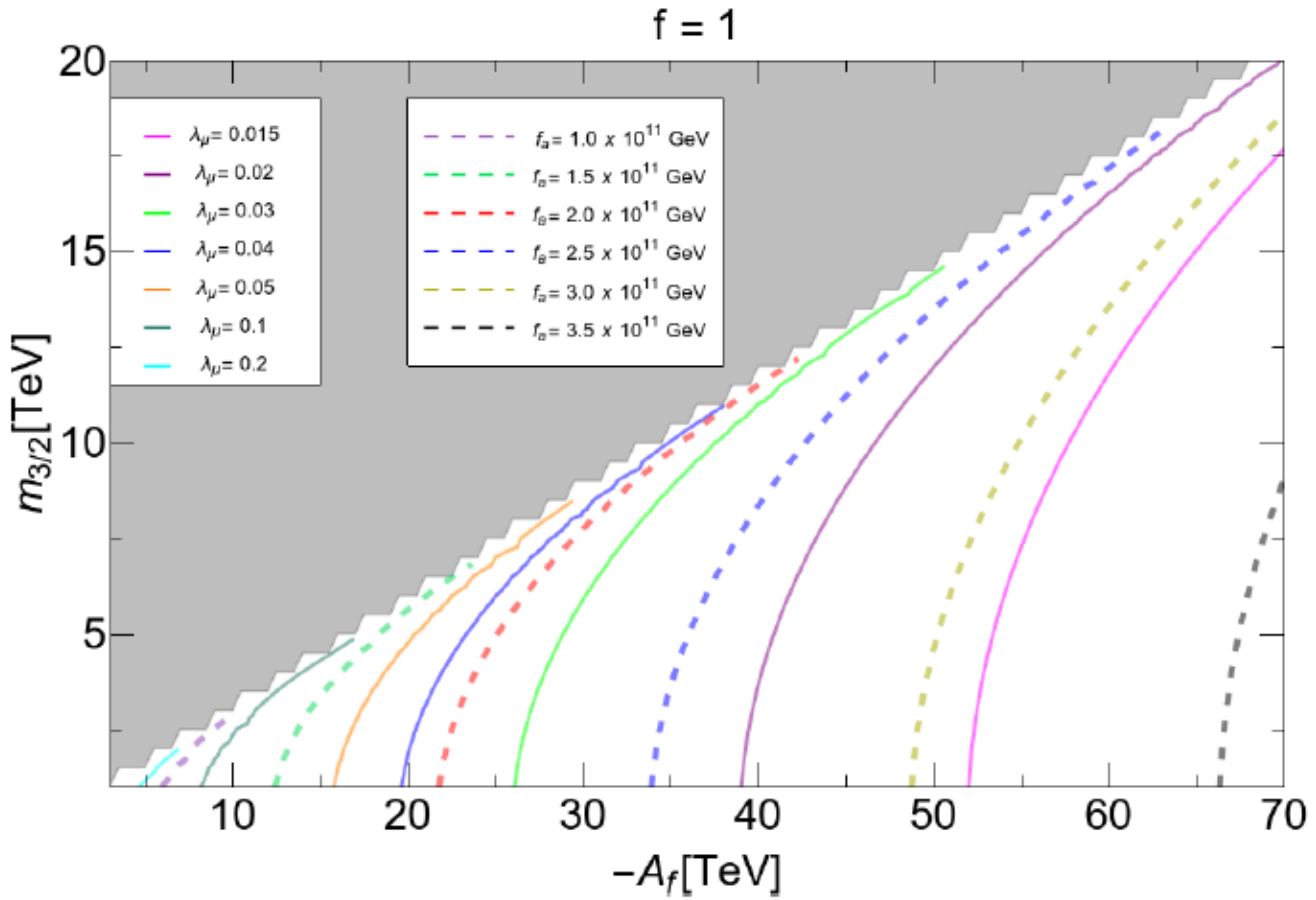


Figure 2: Representative values of λ_μ required for $\mu = 150$ GeV in the $m_{3/2}$ vs. $-A_f$ plane of the GSPQ model for $f = 1$. We also show several contours of f_a.

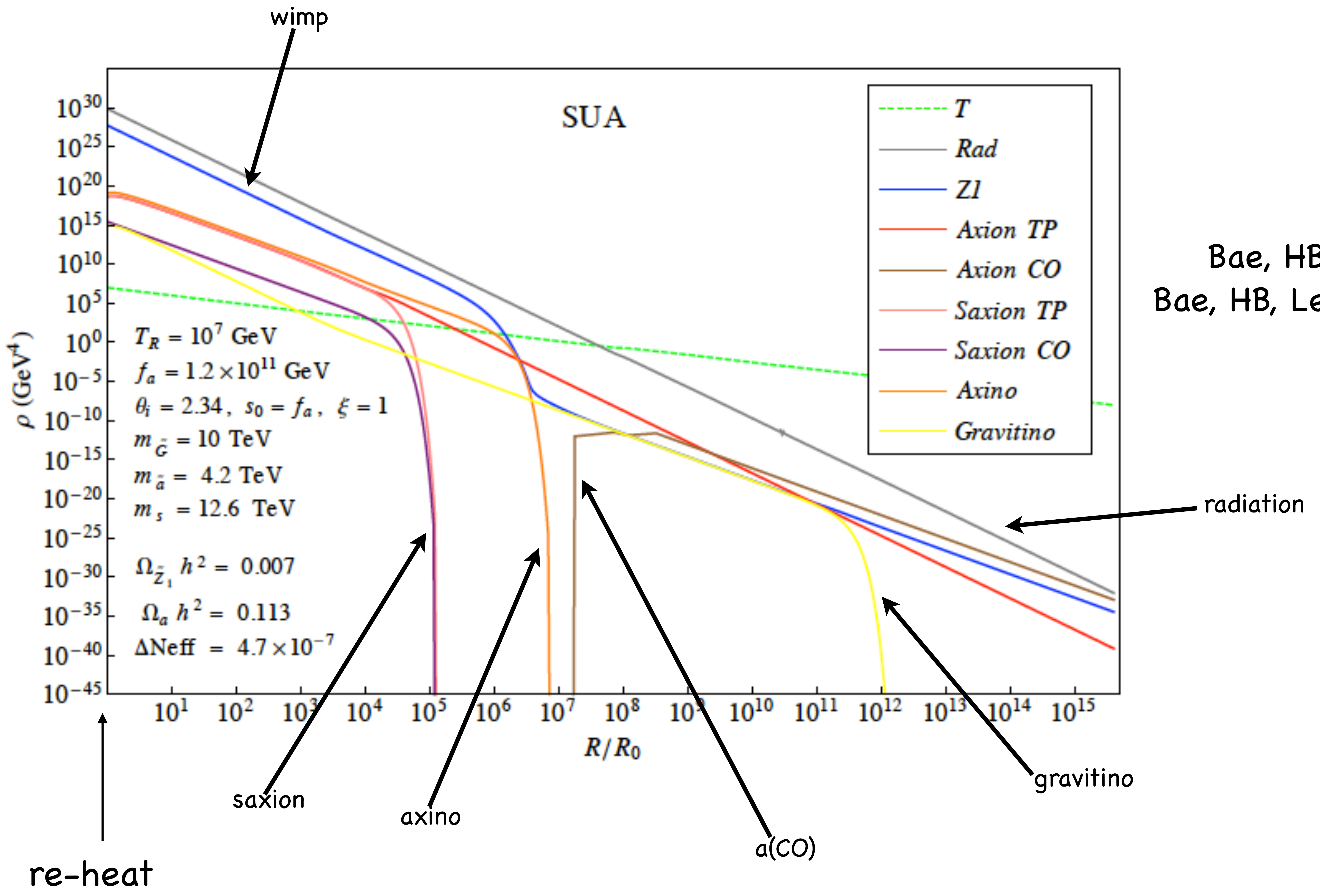
Z(24)^R model can easily accommodate mu~100-300 GeV consistent with EW naturalness

axion quality problem/SUSY mu problem/f_a problem: all solved!

mixed axion-neutralino production in early universe

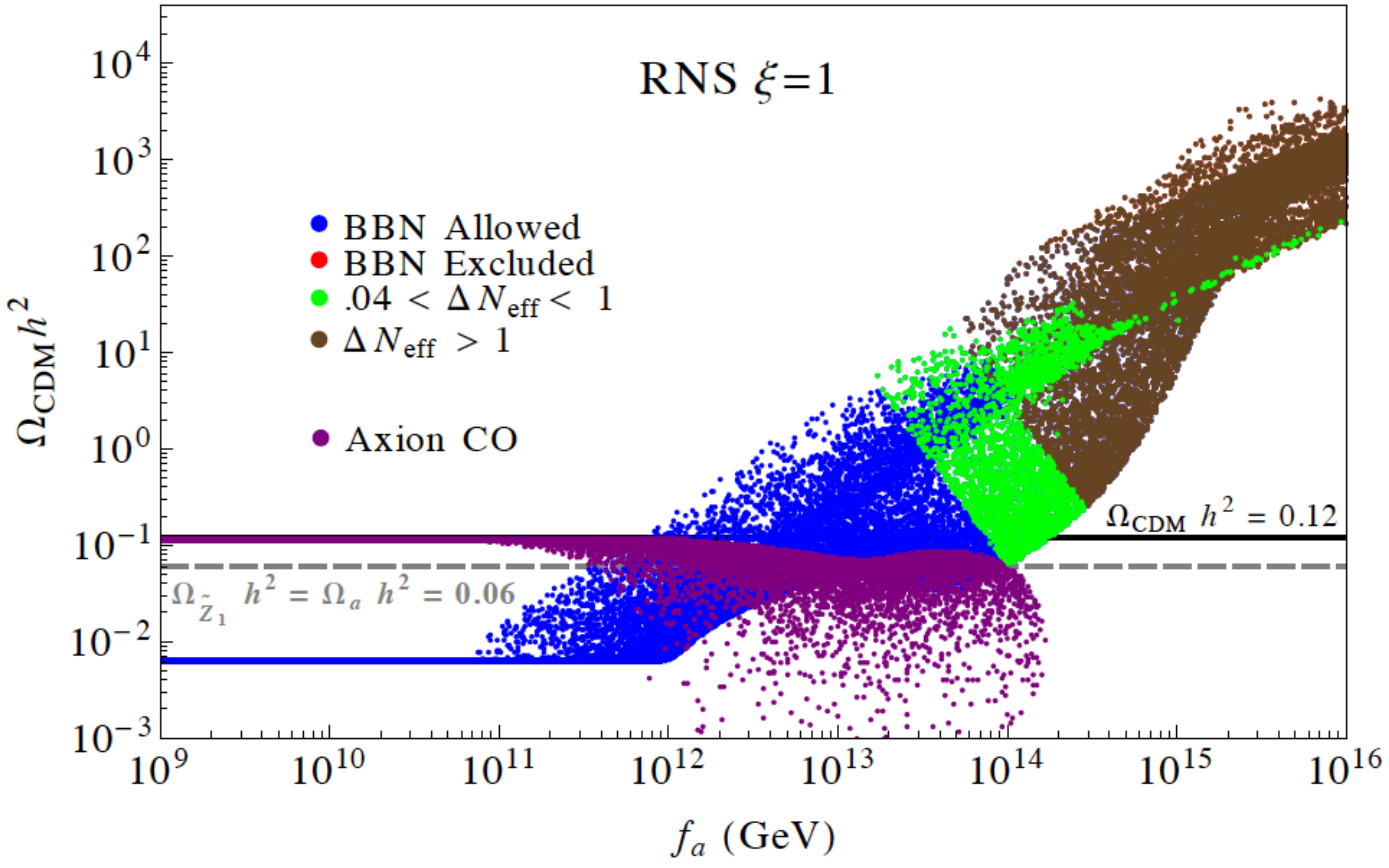
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: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

DM production in SUSY DFSZ: solve eight coupled Boltzmann equations



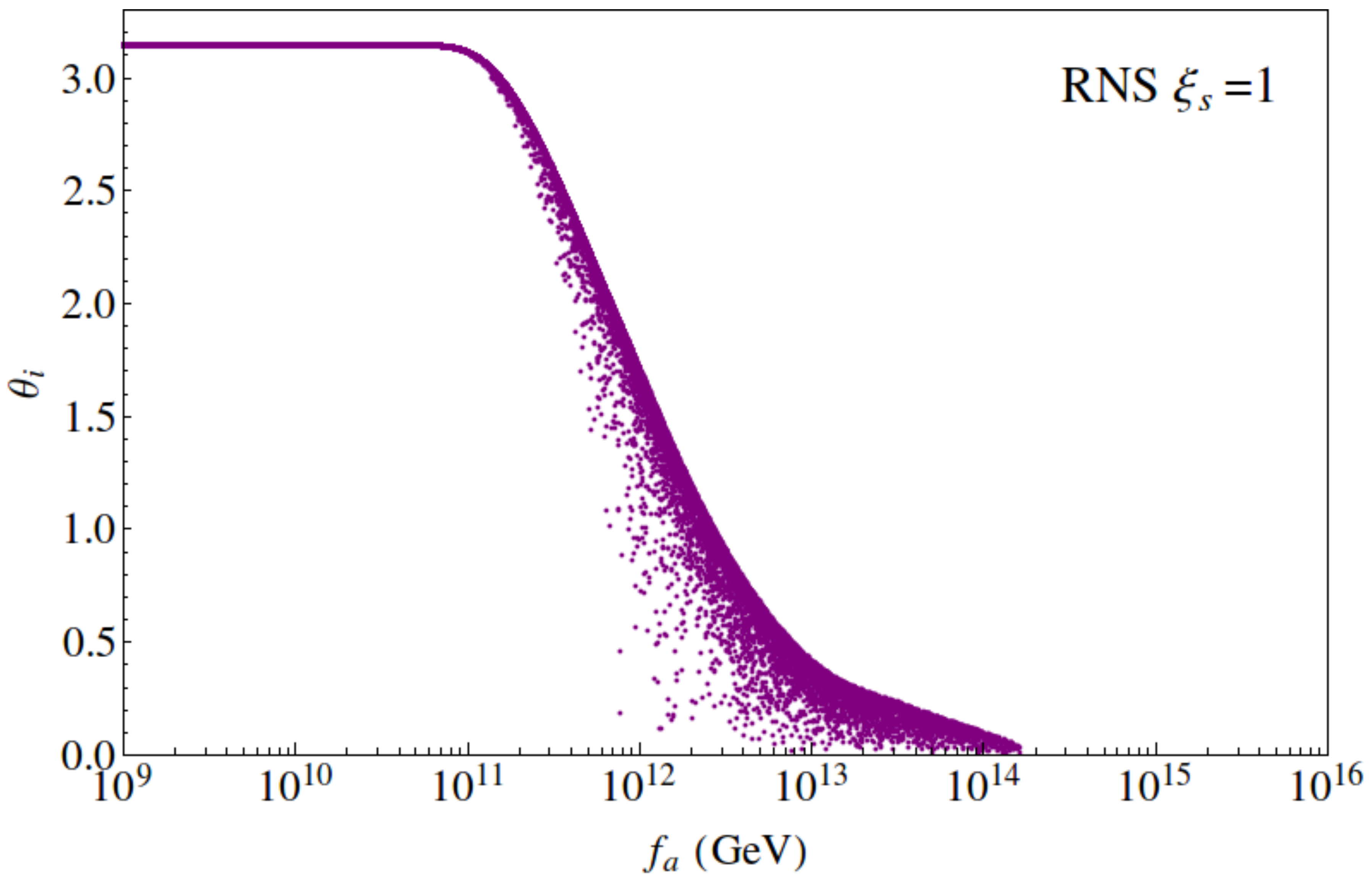
Bae, HB, Chun;
Bae, HB, Lessa, Serce

neutralino/axion relic densities vs f_a (axion decay constant)



higgsino abundance

axion abundance

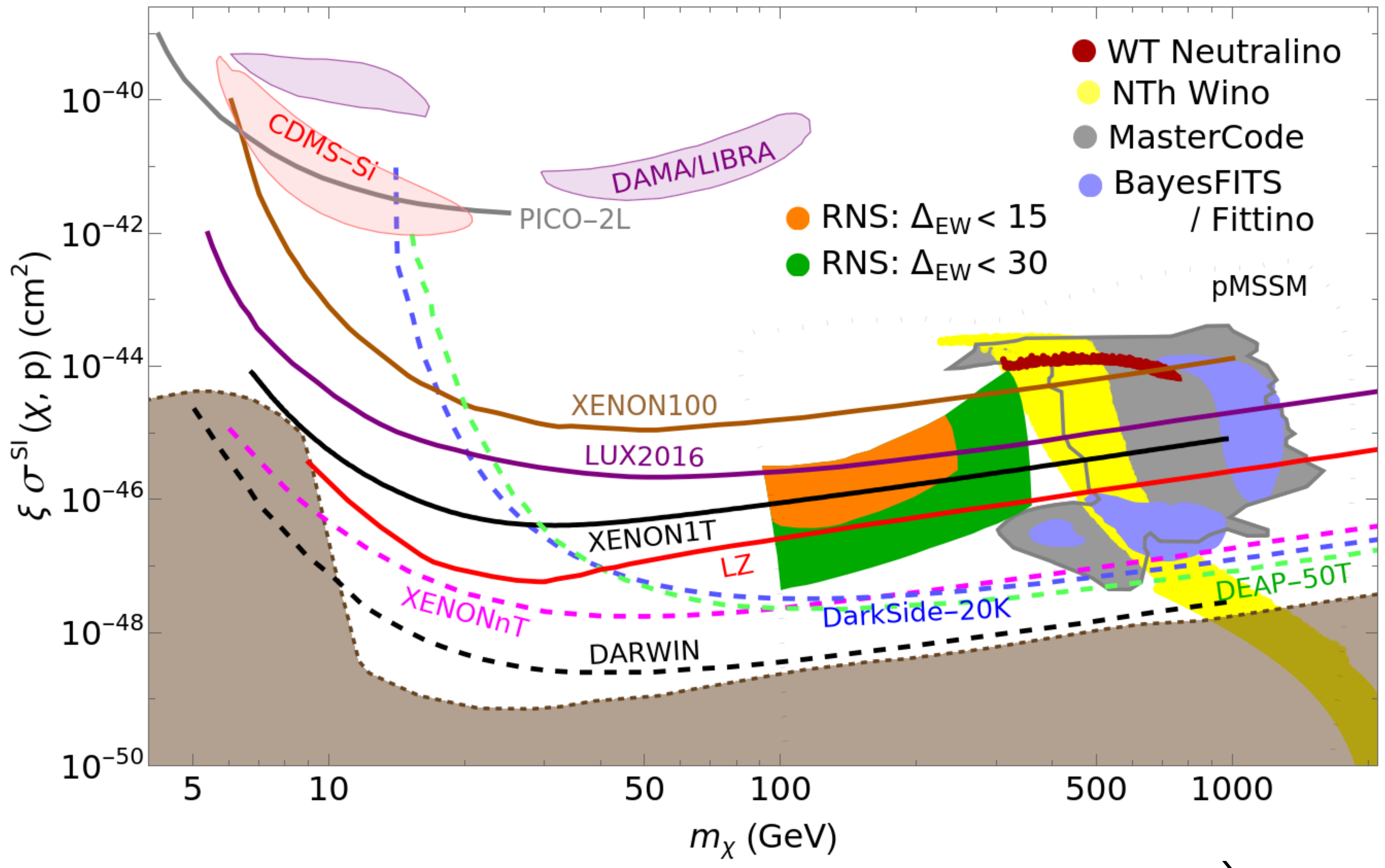


mainly axion CDM
for fa<~10^12 GeV;
for higher fa, then get increasing wimp abundance

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

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

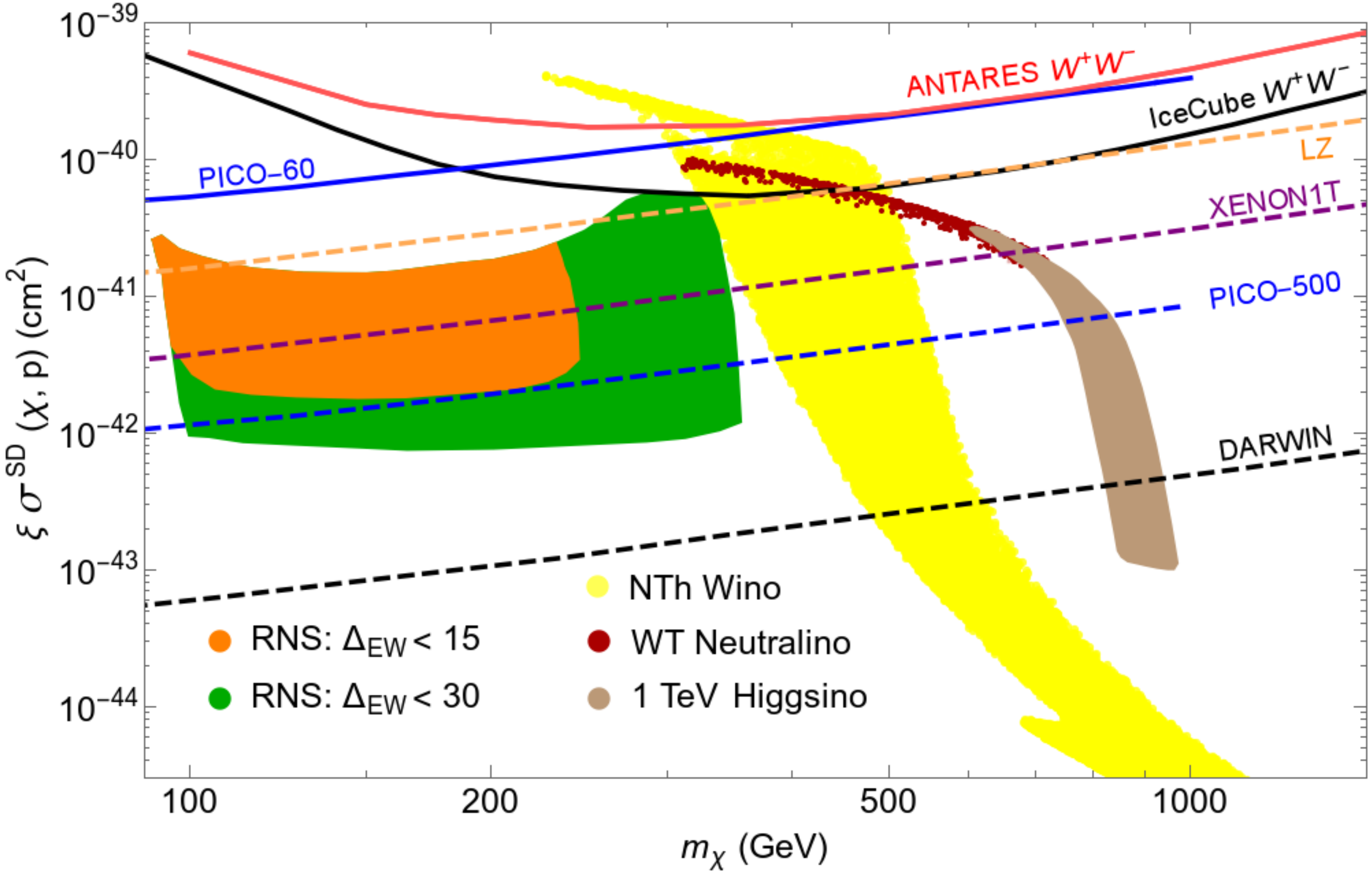
$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

includes latest LZ2022 results!

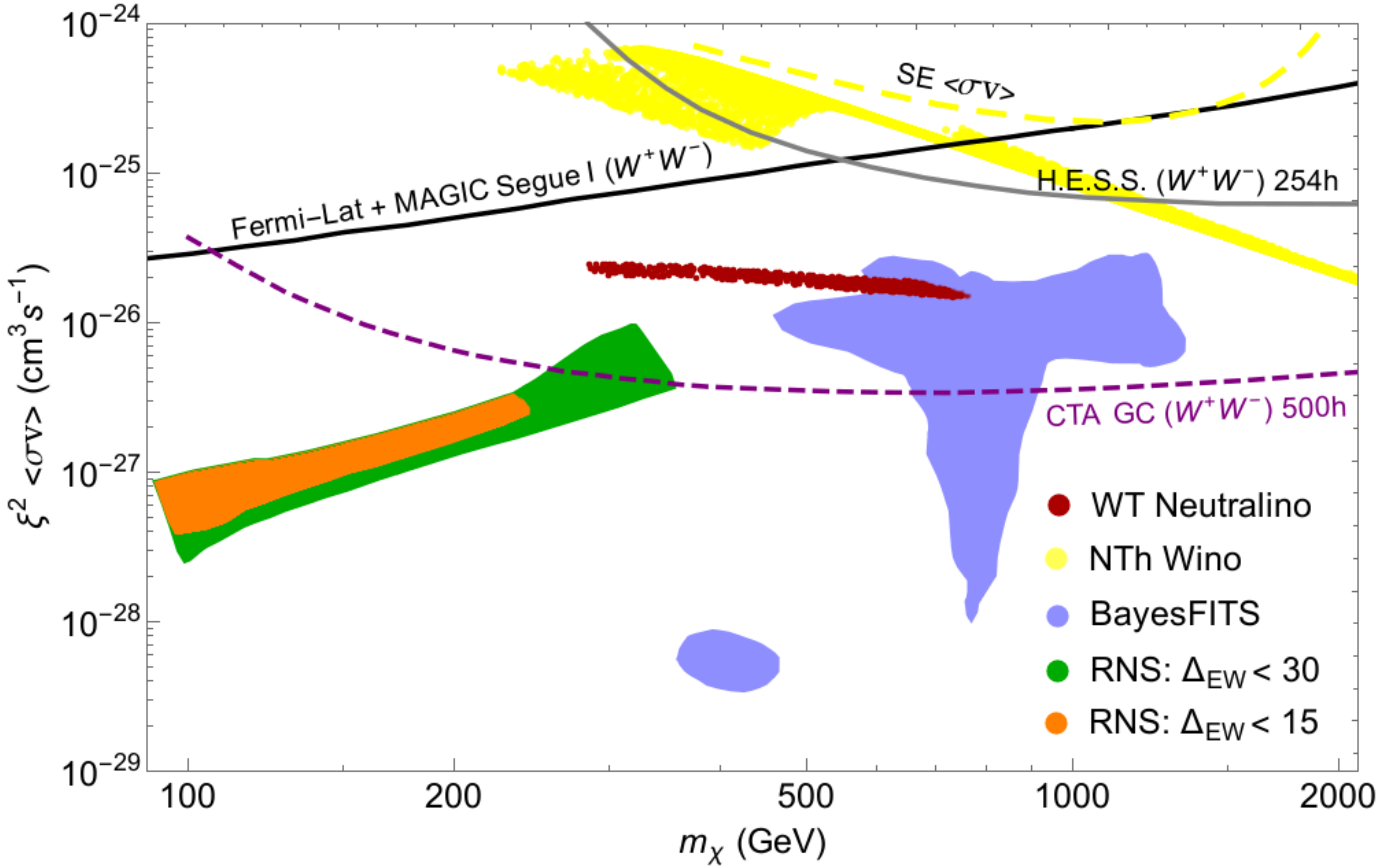
natural SUSY

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

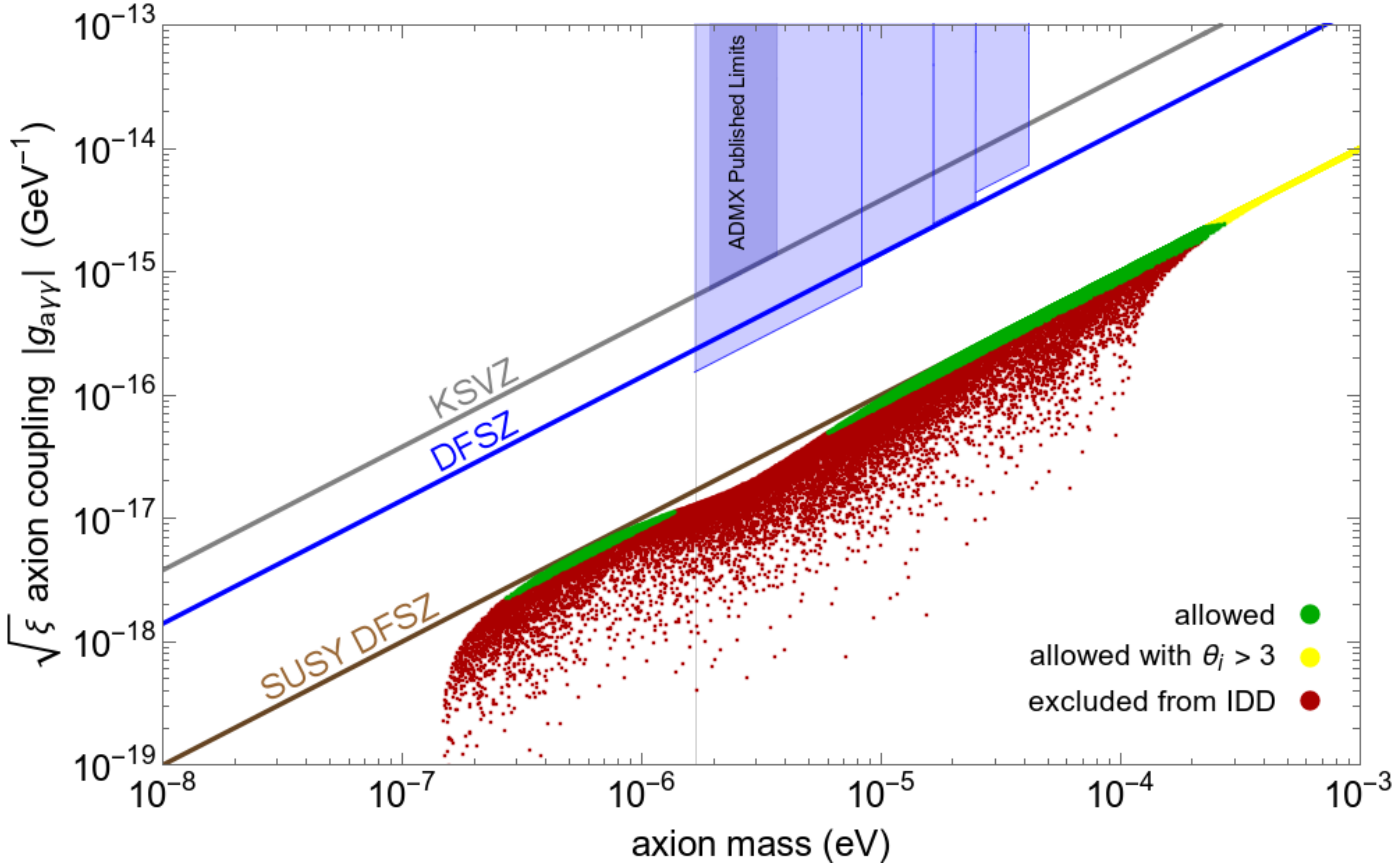
Prospects for SD WIMP searches:

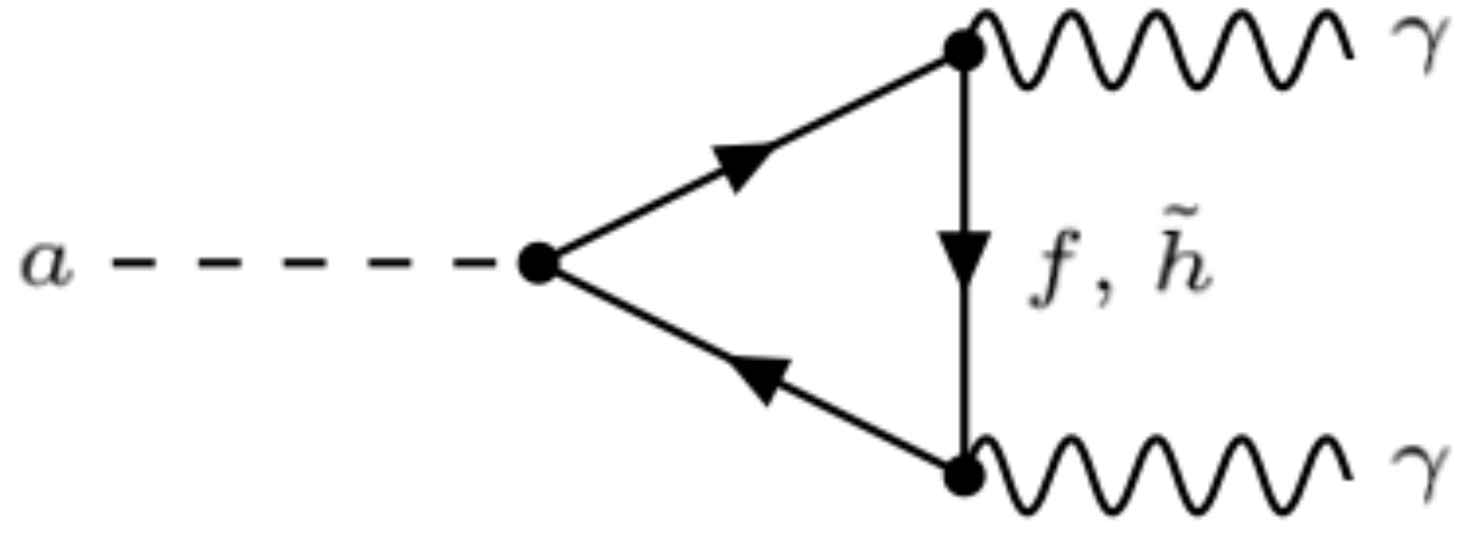


Prospects for IDD WIMP searches:



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!

takeaways

- SUSY naturalness tension due to faulty naturalness estimates
- SUSY with radiatively driven naturalness, LSP is higgsino-like
- landscape statistics: mh~125 GeV with sparticles beyond present LHC limits
- higgsino DM thermally underproduced, but SUSY <=> axions so expect mixed (DFSZ) axion+WIMP DM: (at least) 2 DM particles
- discrete R-symmetry: e.g. Z(24)^R => axion quality, other issues!
- higgsino-like WIMPs not yet detected: much lower abundance ~1/10th
- SUSY DFSZ axion coupling highly suppressed, hard to detect

Recent work: add light string modulus

- HB, Barger, Robert Wiley Deal
- compute all modulus decays to (PQ)MSSM particles
- cosmological moduli problem => m(phi)>100 TeV
- moduli-induced gravitino and LSP problem: m(phi)>~5000 TeV
- possible dark radiation decay to ALPs in LVS moduli stabilization
- anthropic sol'n to CMP: anthropic selection of low phi_0~10^-7
- see e.g. 2111.05971, 2201.06633, 2204.01130, 2301.12546