SUSY dark matter status in light of LHC and ton-scale WIMP DM searches

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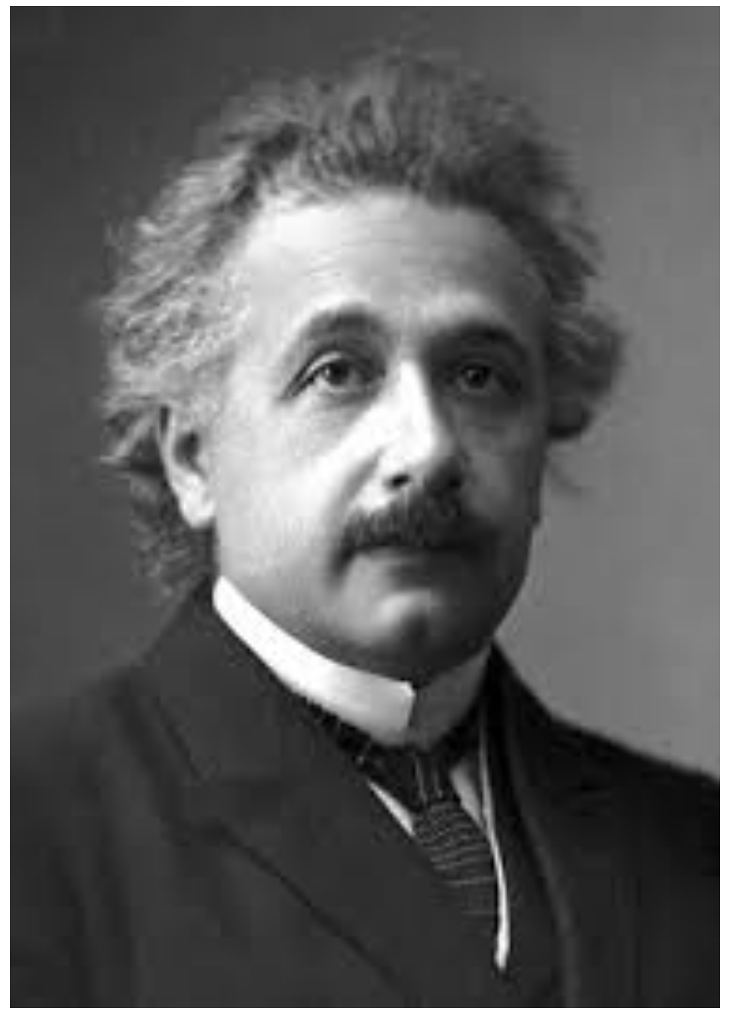
IDM2024 talk
July 12, 2024

twin pillars of guidance:
naturalness & simplicity



``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

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: $\rho_{vac} \sim (0.003\ \mathrm{eV})^4 \ll m_P^4$

anthropic vacua selection from multiverse/string landscape 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), lack of WIMP signals and the rather large value of m(h)~125 GeV

- 1. BG naturalness measure overestimates finetuning by factors of 10-1000 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

PHYSICAL REVIEW D 88, 095013 (2013)

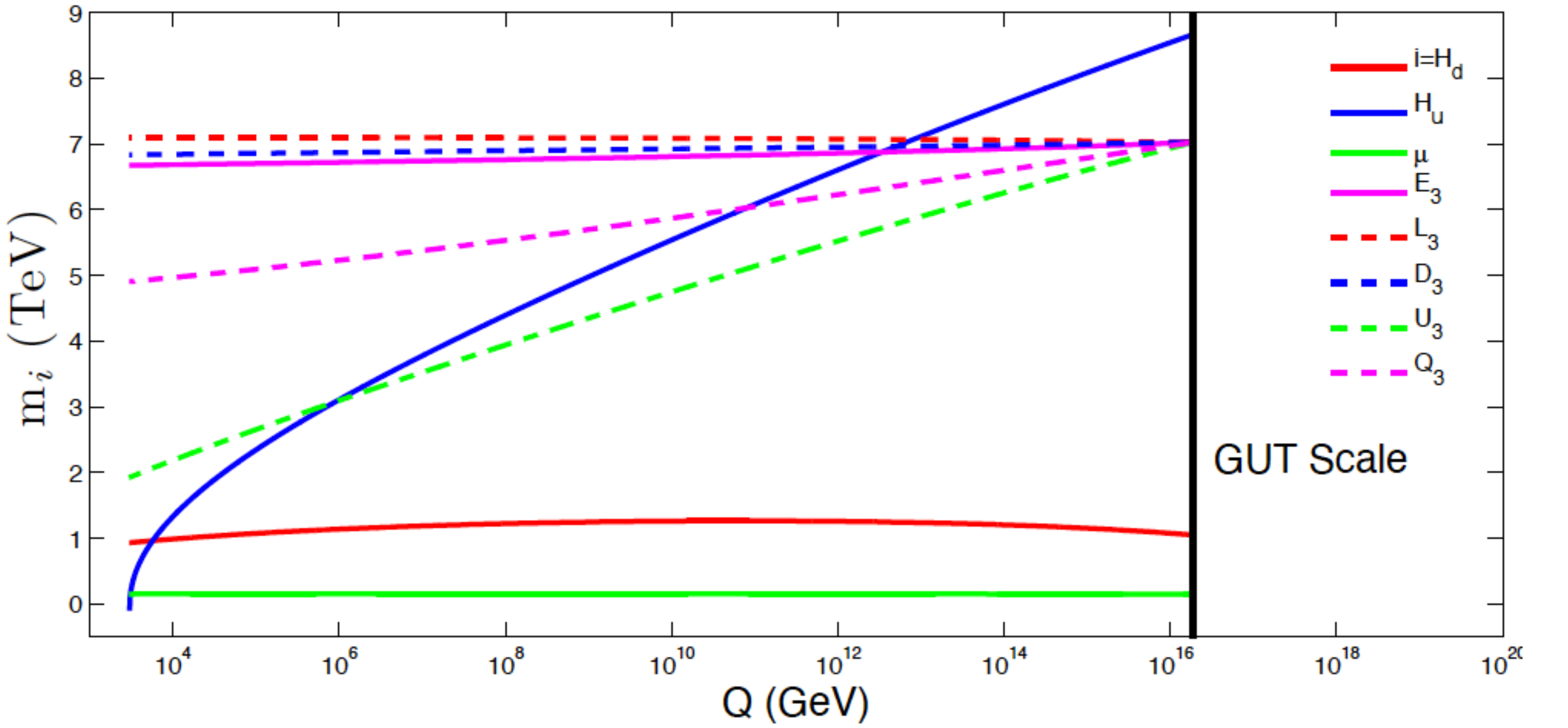
How conventional measures overestimate electroweak fine-tuning in supersymmetric theory

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]

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



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!

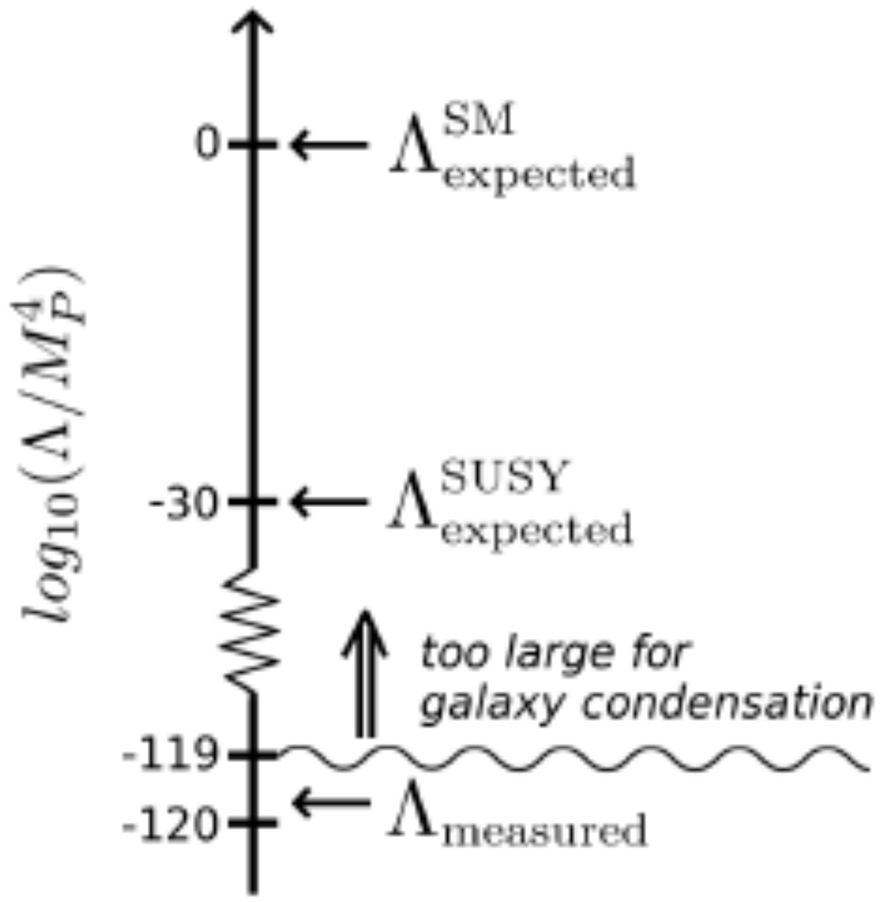
review: see arXiv:2002.03013

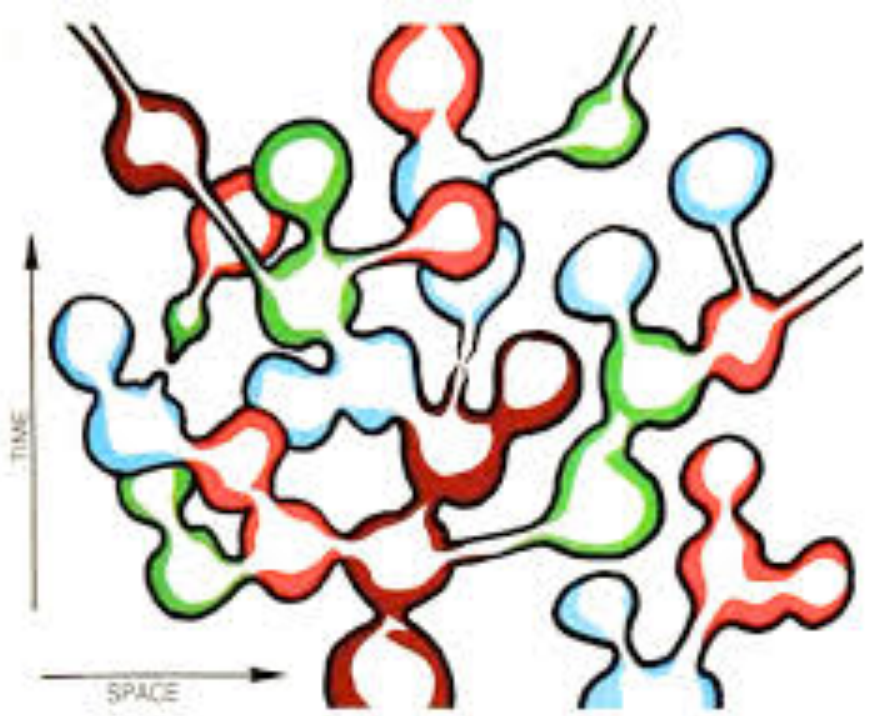
bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	350 GeV
gluino	400-600 GeV	6 TeV
t1	450 GeV	3 TeV
sq/sl	550-700 GeV	10-30 TeV

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

How does this all relate to string landscape?

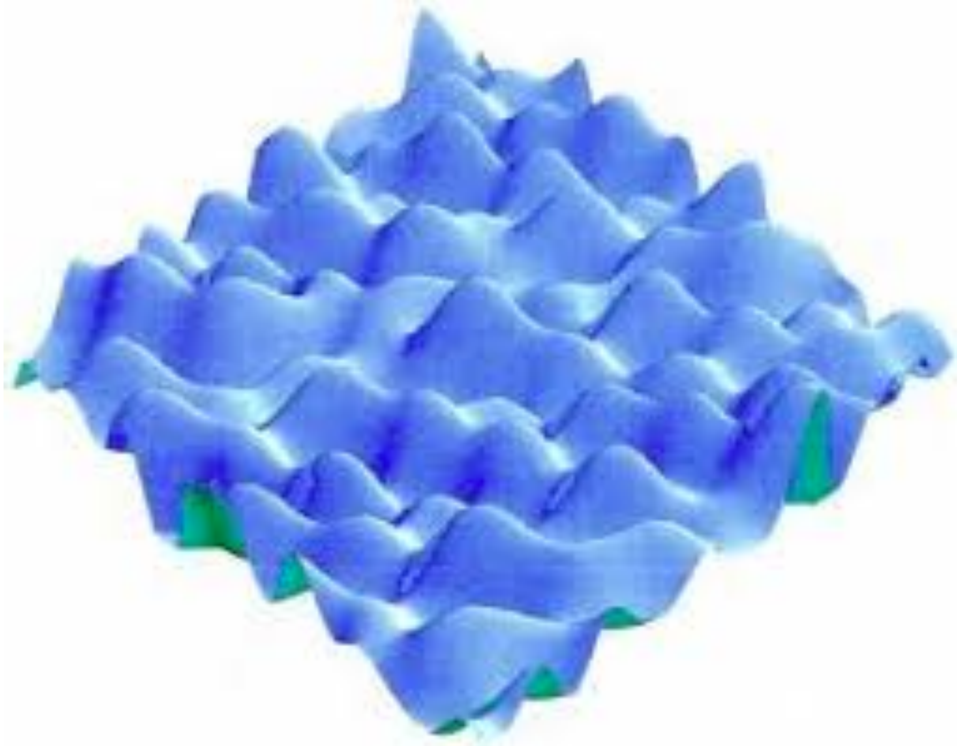
It is sometimes invoked that maybe we should abandon naturalness:
after all, isn't the cosmological constant (CC) fine-tuned?





eternally inflating multiverse

In the landscape with 10^500 vacua with different CCs, then the tiny value of the CC may not be surprising since larger values would lead to runaway pocket universes where galaxies wouldn't condense- anthropics: no observers in such universes (Weinberg)



Bousso & Polchinski

The CC is as natural as possible subject to the condition that it leads to galaxy condensation

For some recent review material, see M. Douglas, The String Theory Landscape, 2018, Universe 5 (2019) 7, 176

In fertile patch of vacua with MSSM as weak scale effective theory
but with no preferred SUSY breaking scale...

$$dP/d\mathcal{O} \sim f_{prior} \cdot f_{selection}$$

What is f(prior) for SUSY breaking scale?

In string theory, usually multiple (~10) hidden sectors
containing a variety of F- and D- breaking fields

For comparable <Fi> and <Dj> values, then expect

$$f_{prior} \sim m_{soft}^{2n_F+n_D-1}$$

Douglas ansatz

arXiv:0405279

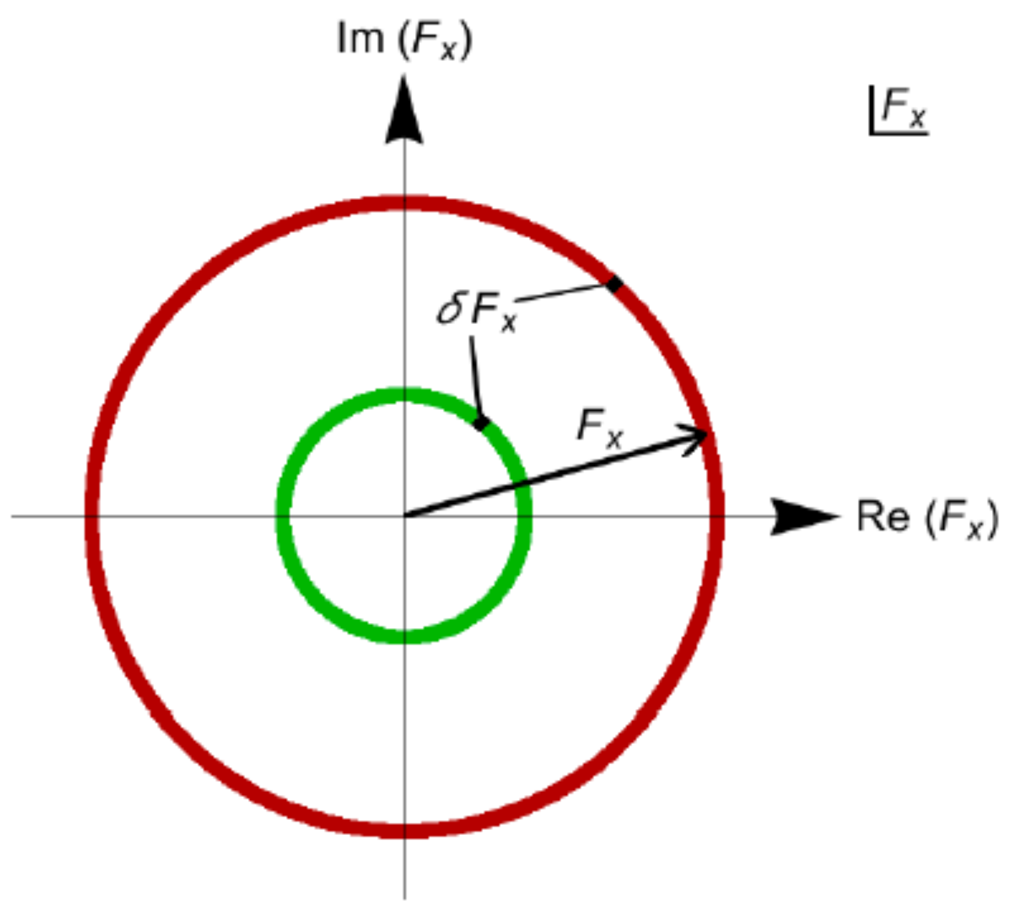


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

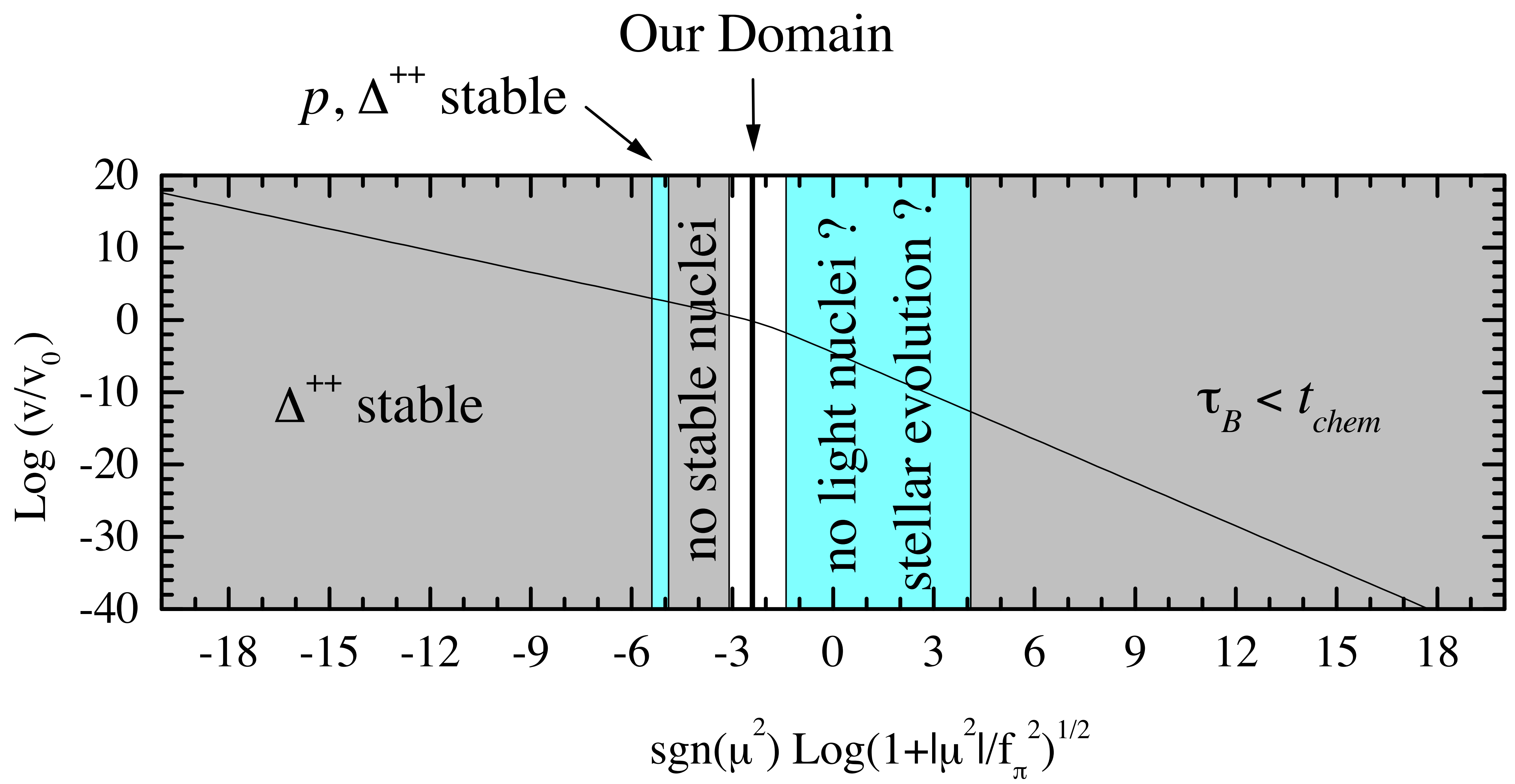
Under single F-term
SUSY breaking,
expect linearly increasing
statistical selection
of soft terms

For uniform values of SUSY breaking fields,
expect landscape to prefer
high scale of SUSY breaking!

$$m_{hidden}^4 = \sum_i F_i F_i^\dagger + D_\alpha D_\alpha$$

Anthropic selection of magnitude of weak scale?

Agrawal, Barr, Donoghue, Seckel result (1998):
pocket-universe value of weak scale
cannot deviate by more than
factor 2-5 from its measured value
lest disasters occur in nuclear physics: no nuclei, no atoms
(violates atomic principle)

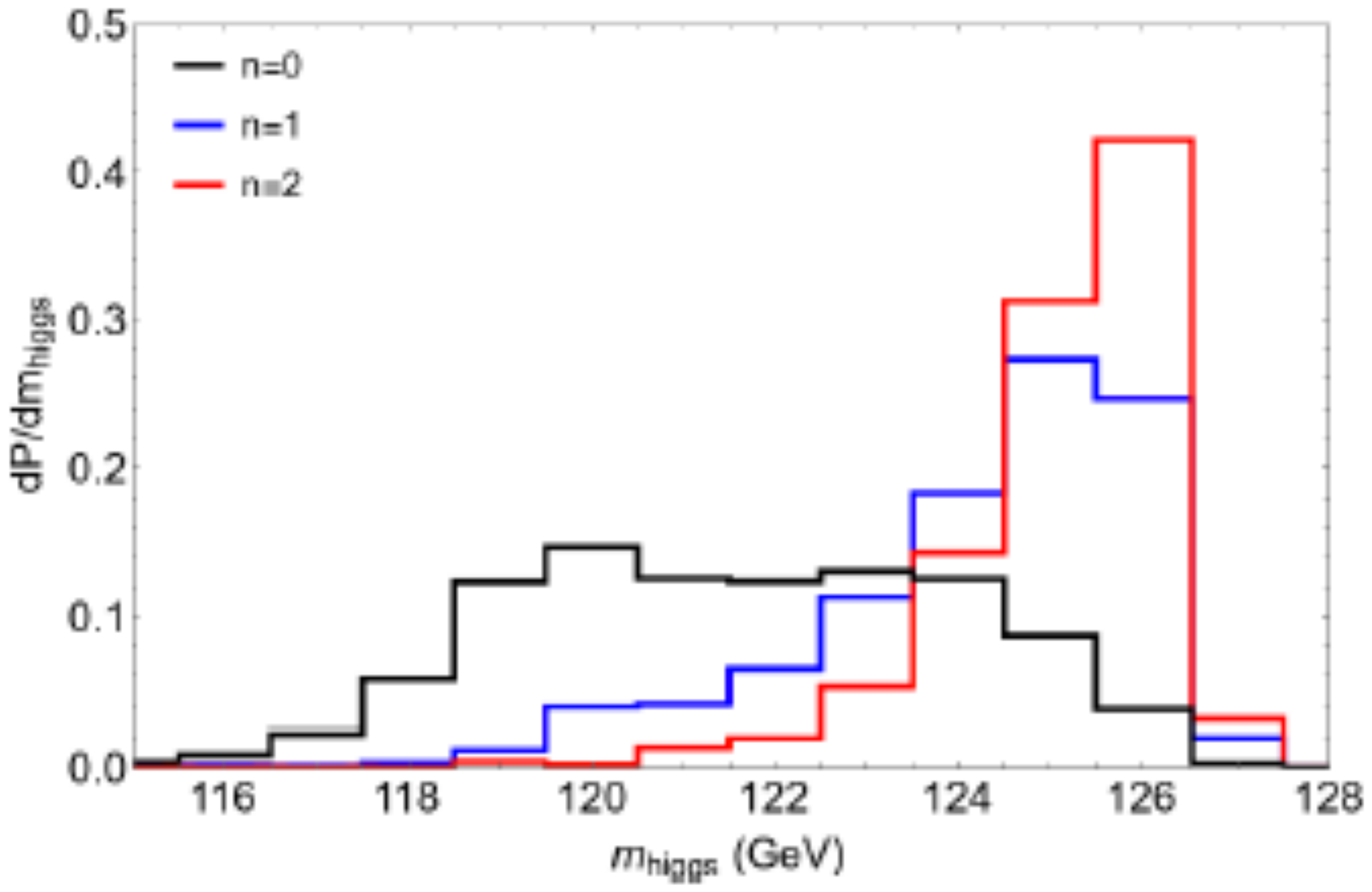


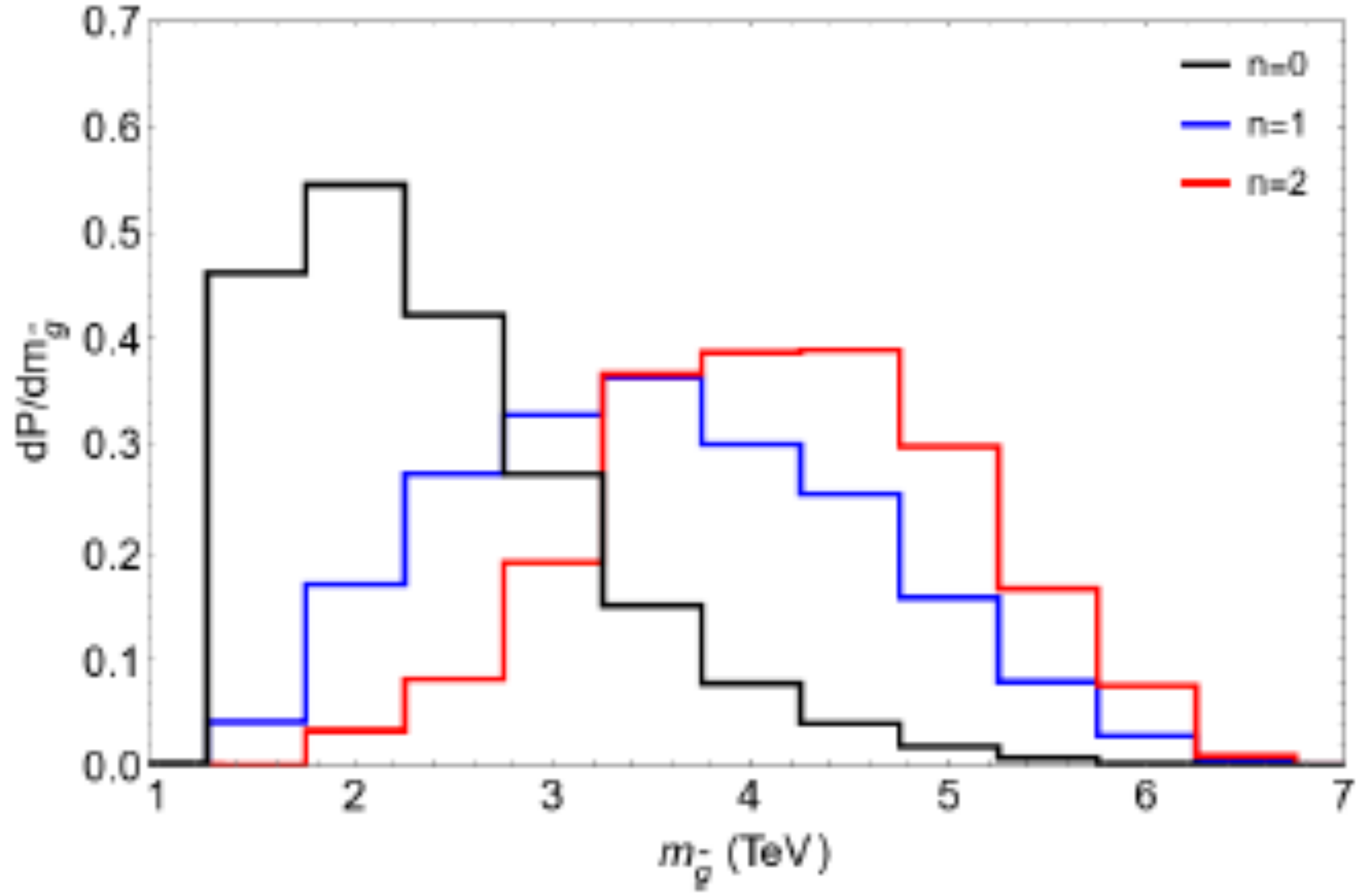
m(weak) must lie within ABDS window to have atoms/chemistry:
~50 GeV < m(weak) < ~350 GeV

ABDS window <=> DEW<~30

SUSY from the multiverse

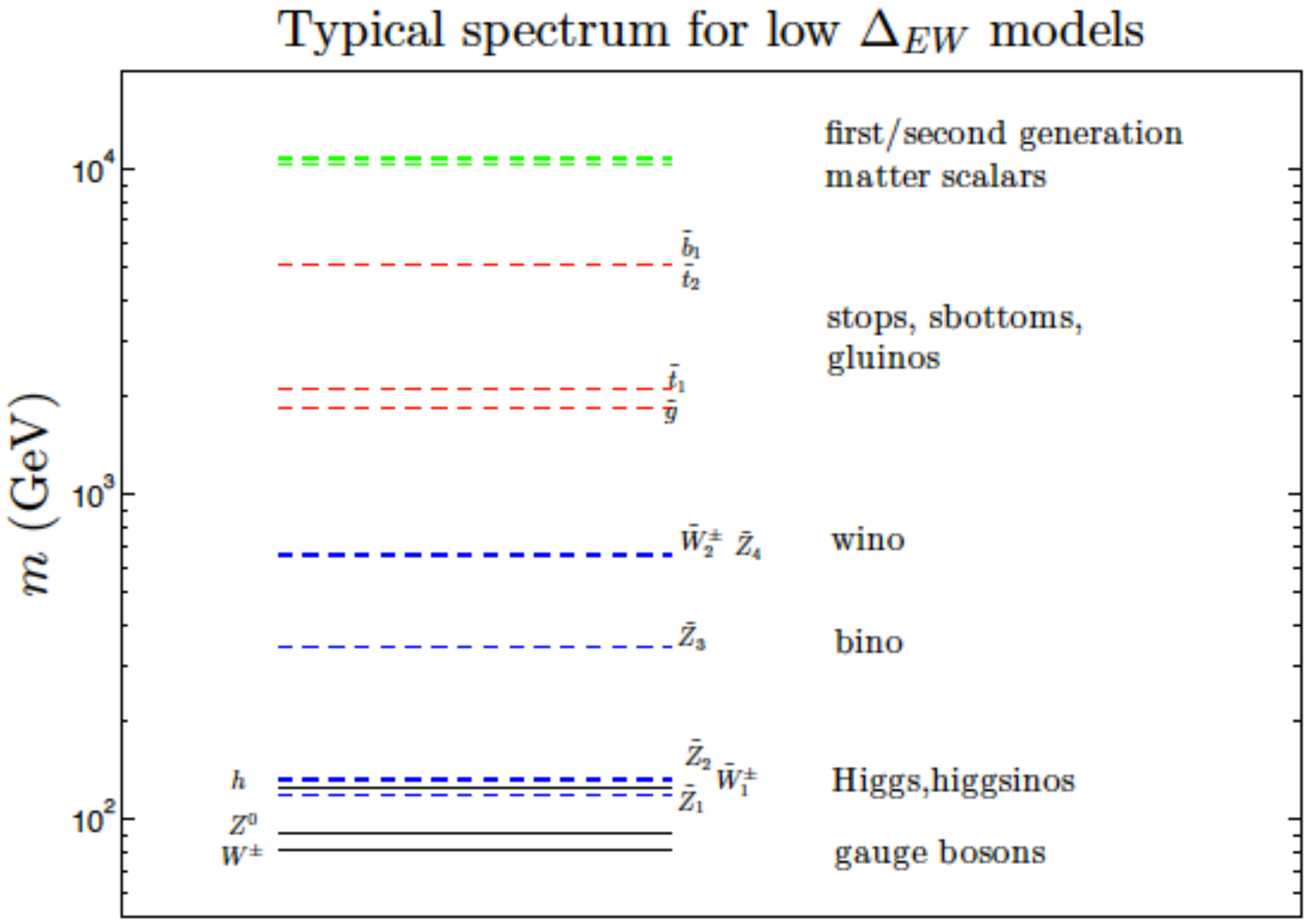
- 10^500 string vacua: each -> different 4-d laws of physics
- only CC, weak scale/SUSY breaking scale scans in multiverse (Weinberg, ADK)
- power-law draw of landscape to large soft terms (Douglas, Susskind)
- derived value for pocket-universe weak scale must lie ~(2-5)m(weak)~100 GeV: ABDS window/atomic 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



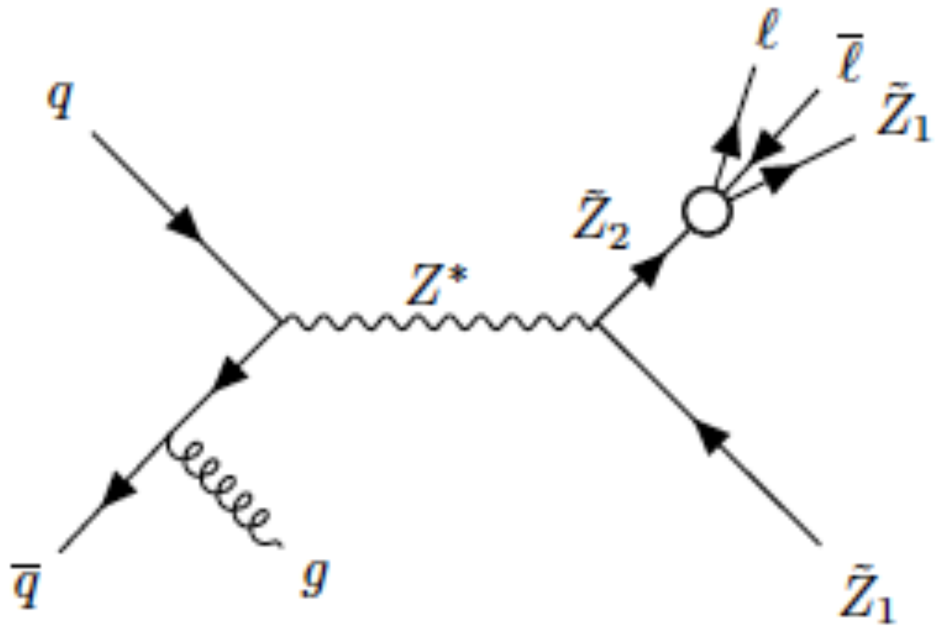
There is a Little Hierarchy, but it is no problem

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

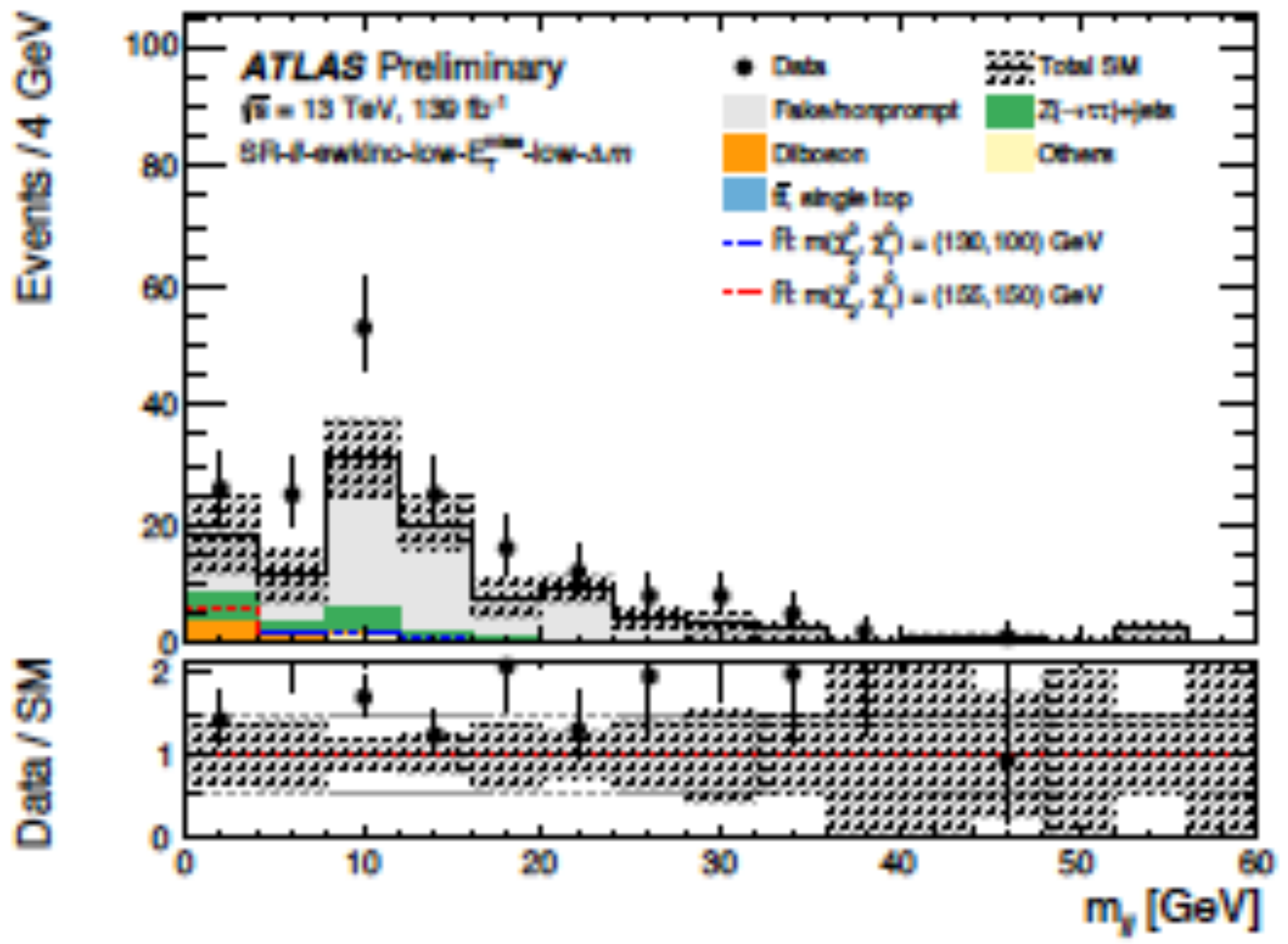
higgsinos likely the lightest superparticles!

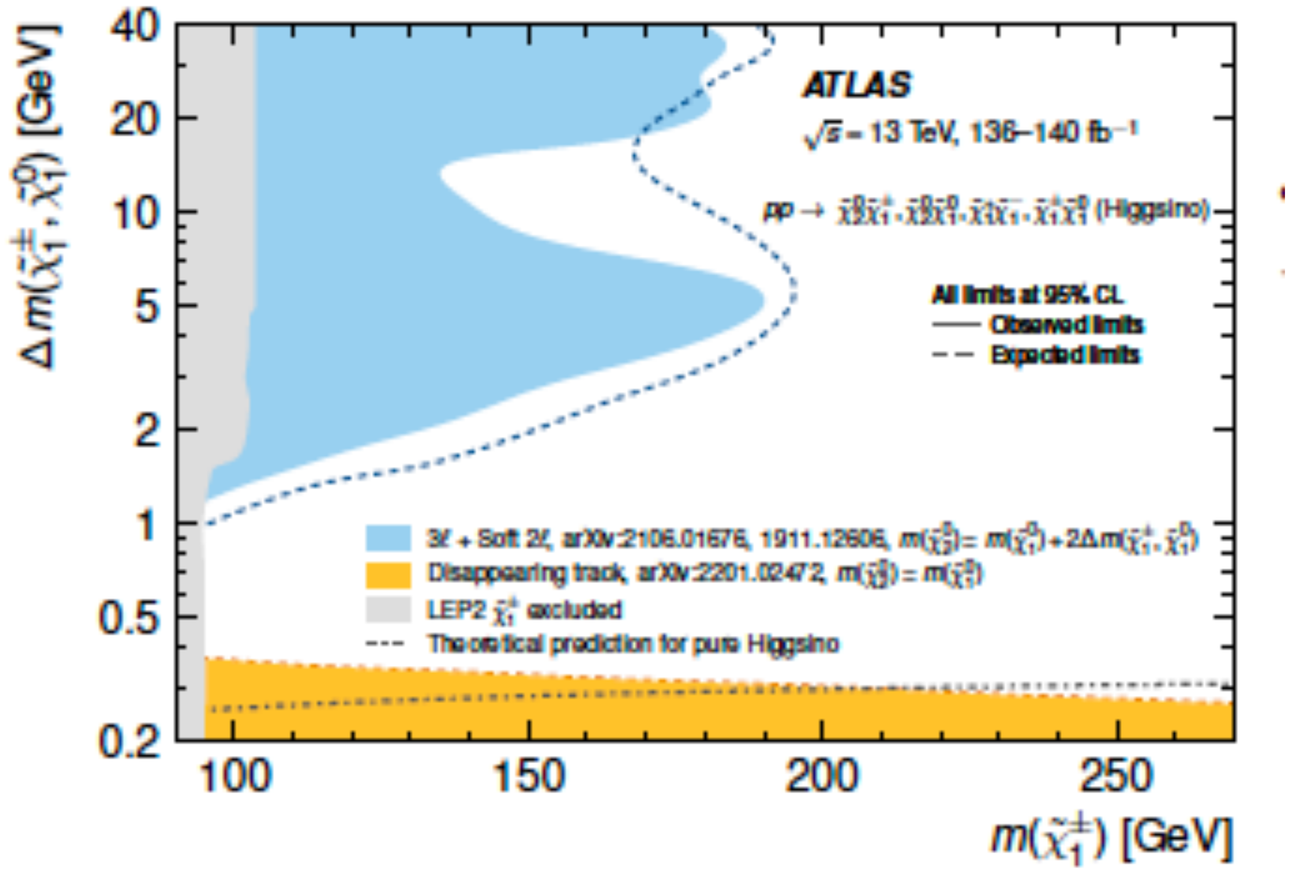
Natural SUSY: only higgsinos need lie close to weak scale

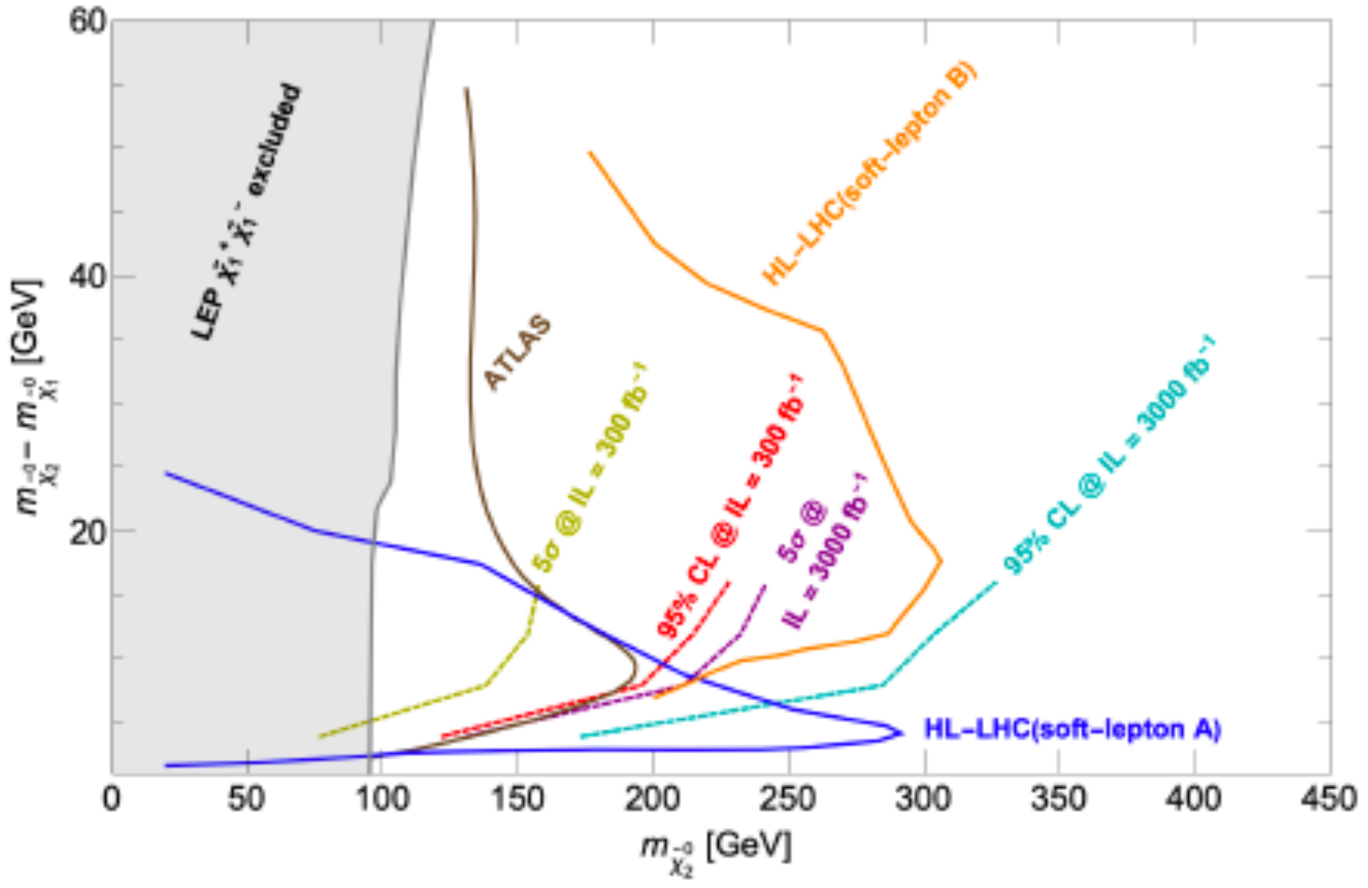
Soft dilepton+jet+MET signature from higgsino pair production



HB, Barger, Huang, 1107.5581;
C. Han, A.Kobakidze, N. Liu, Saavedra, L. Wu, J. Yang, 1310.4274
Z. Han, Kribs, Martin, Menon, 1401.1235;
HB, Mustafayev, Tata; 1409.7058;
C. Han, Kim, Munir, Park, 1502.03734;
HB, Barger, Savoy, Tata, 1604.07438;
HB, Barger, Salam, Sengupta, Tata,2007.09252;
HB, Barger, Sengupta, Tata, 2109.14030



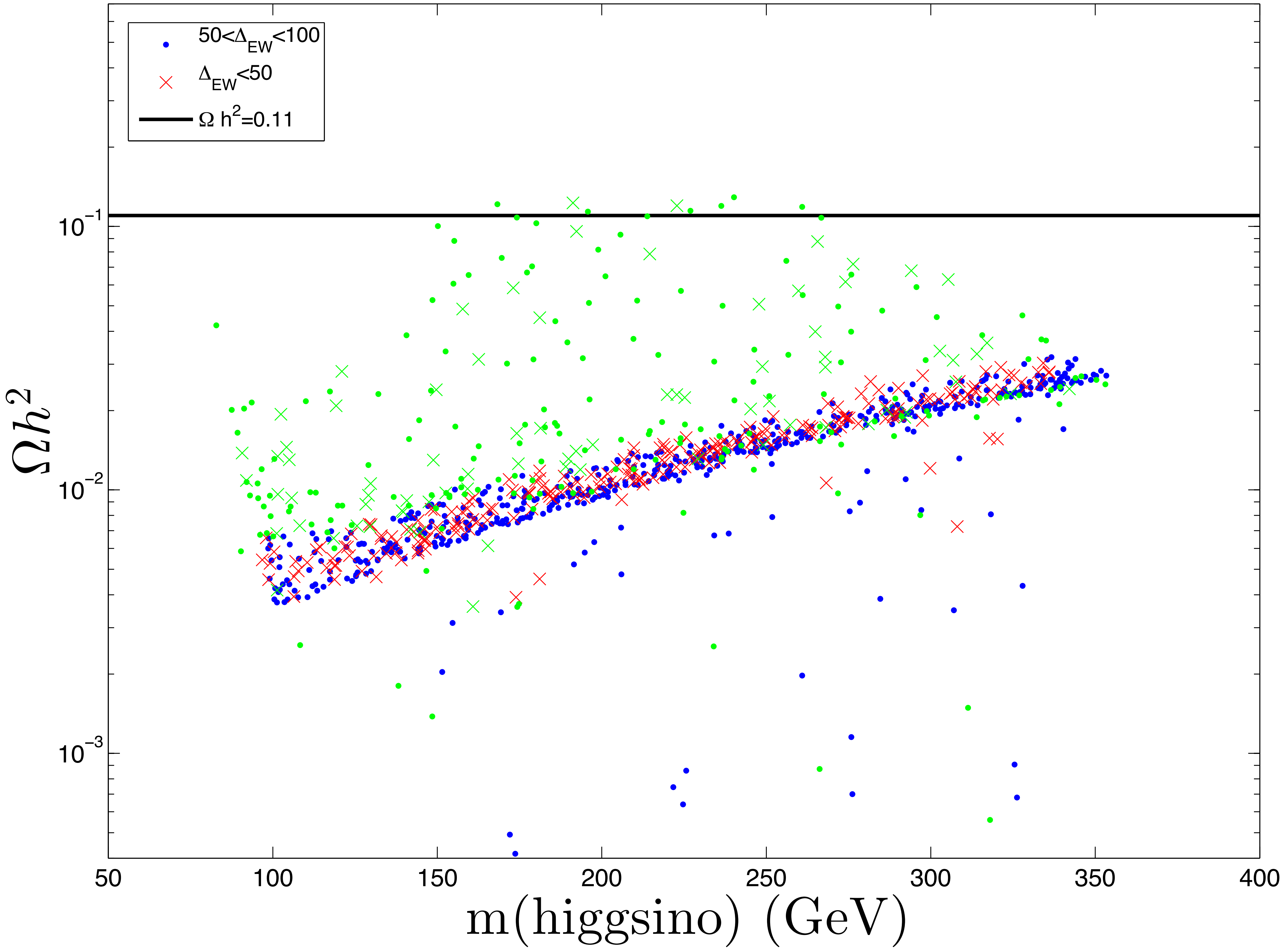




It appears that HL-LHC can see much (but not all) of natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues

ATLAS/CMS: 2-sigma excess from Run 2!

‘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 $f_a \sim 10^{11}$ GeV; but don't want $m(h) \to$ 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 $f_a \sim 10^{11}$ GeV? link to SUSY breaking scale $\sqrt{F_x} \sim 10^{11}$ GeV
- axion quality problem: higher dim op's can destroy $\bar{\theta} < 10^{-10}$: 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

Kamionkowski, March-Russell, 1992

- Also forbids/suppresses RPV/p-decay operators
- $\mu \sim \lambda_\mu f_a^2/m_P$

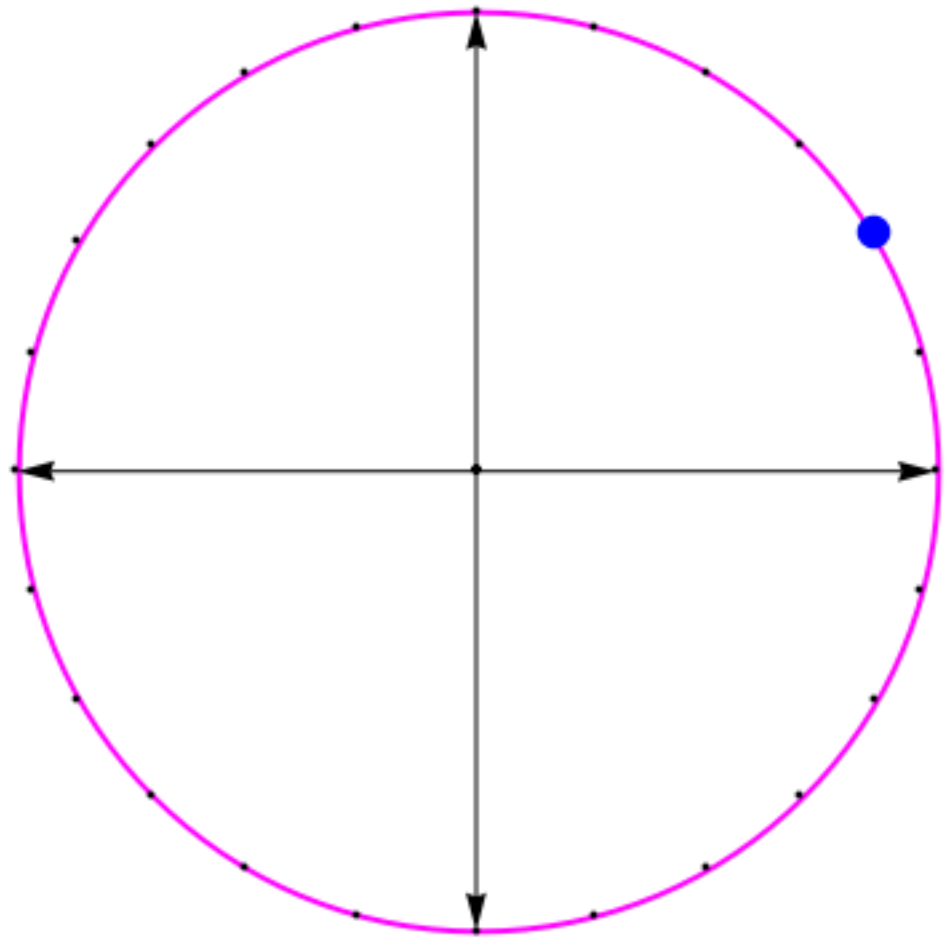
This two-extra -field model based on Z(24)^R symmetry forbids mu term, RPV terms and dim 6 p-decay operators, while maintaining MSSM Yukawa and Majorana nu mass term and to-be mu parameter

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

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

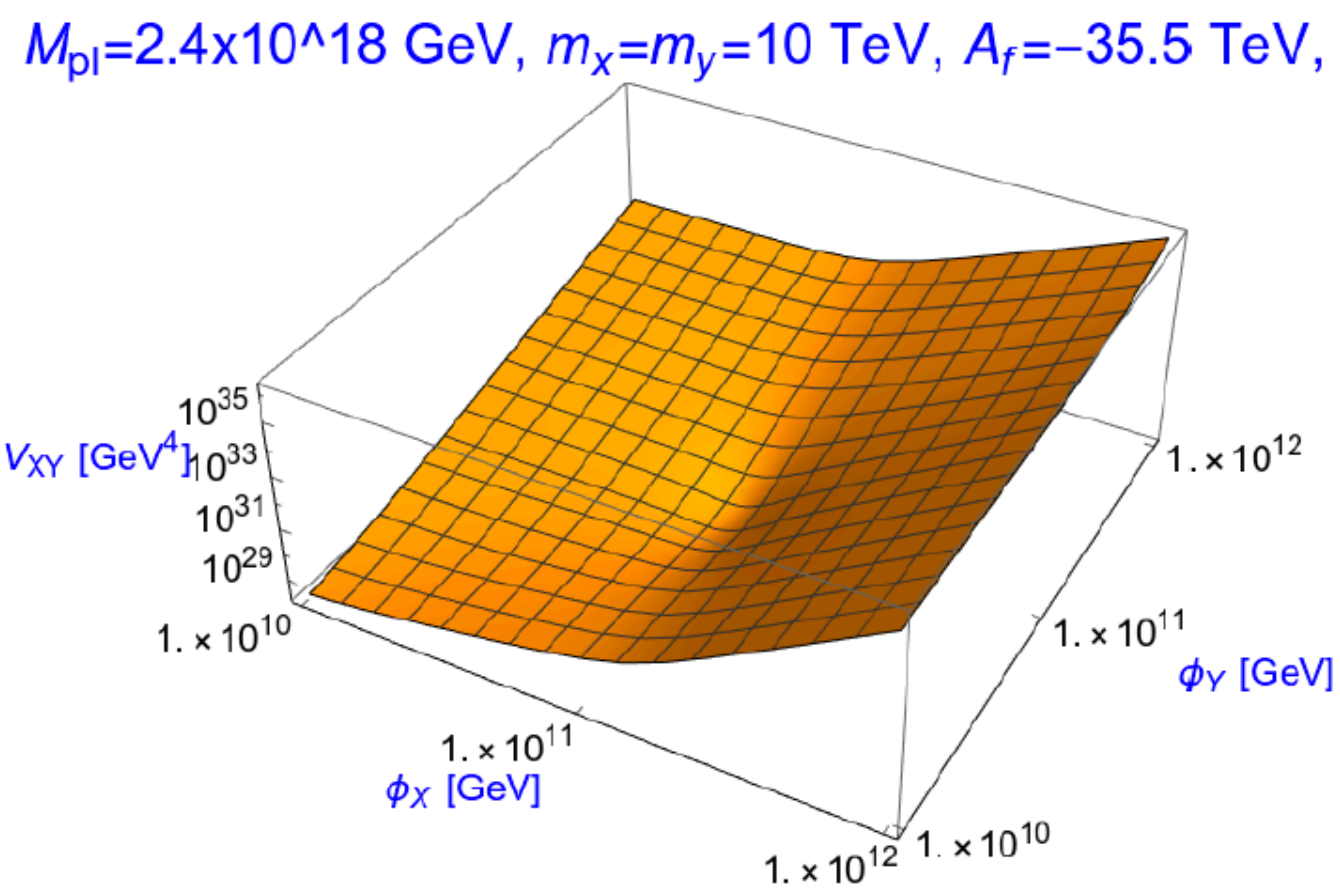
multiplet	H_u	H_d	Q_i	L_i	U_i^c	D_i^c	E_i^c	N_i^c	X	Y
$\mathbb{Z}_{24}^R$ charge	16	12	5	9	5	9	5	1	-1	5
PQ charge	-1	-1	1	1	0	0	0	0	1	-3

Z(24)^R and PQ charge assignments



HB, Barger, Sengupta, arXiv:1810.03713;
Bhattiprolu&Martin, arXiv:2106.14964

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!



f_a in cosmological sweet spot!

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.

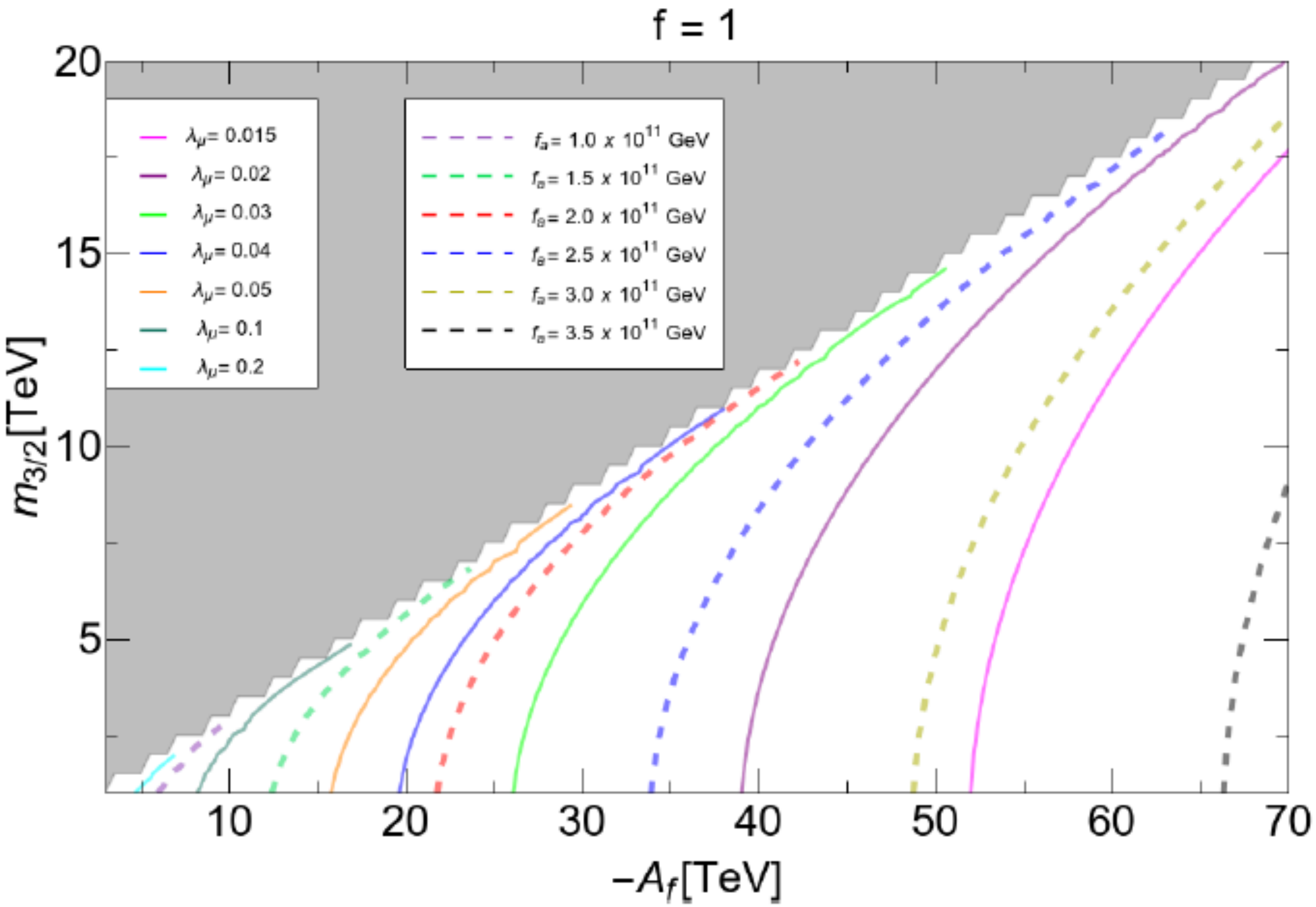


Figure 2: Representative values of λ_μ required for $\mu = 150$ GeV in the $m_{3/2}$ vs. $-A_f$ plane of the GSPQ model for $f = 1$. We also show several contours of f_a.

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

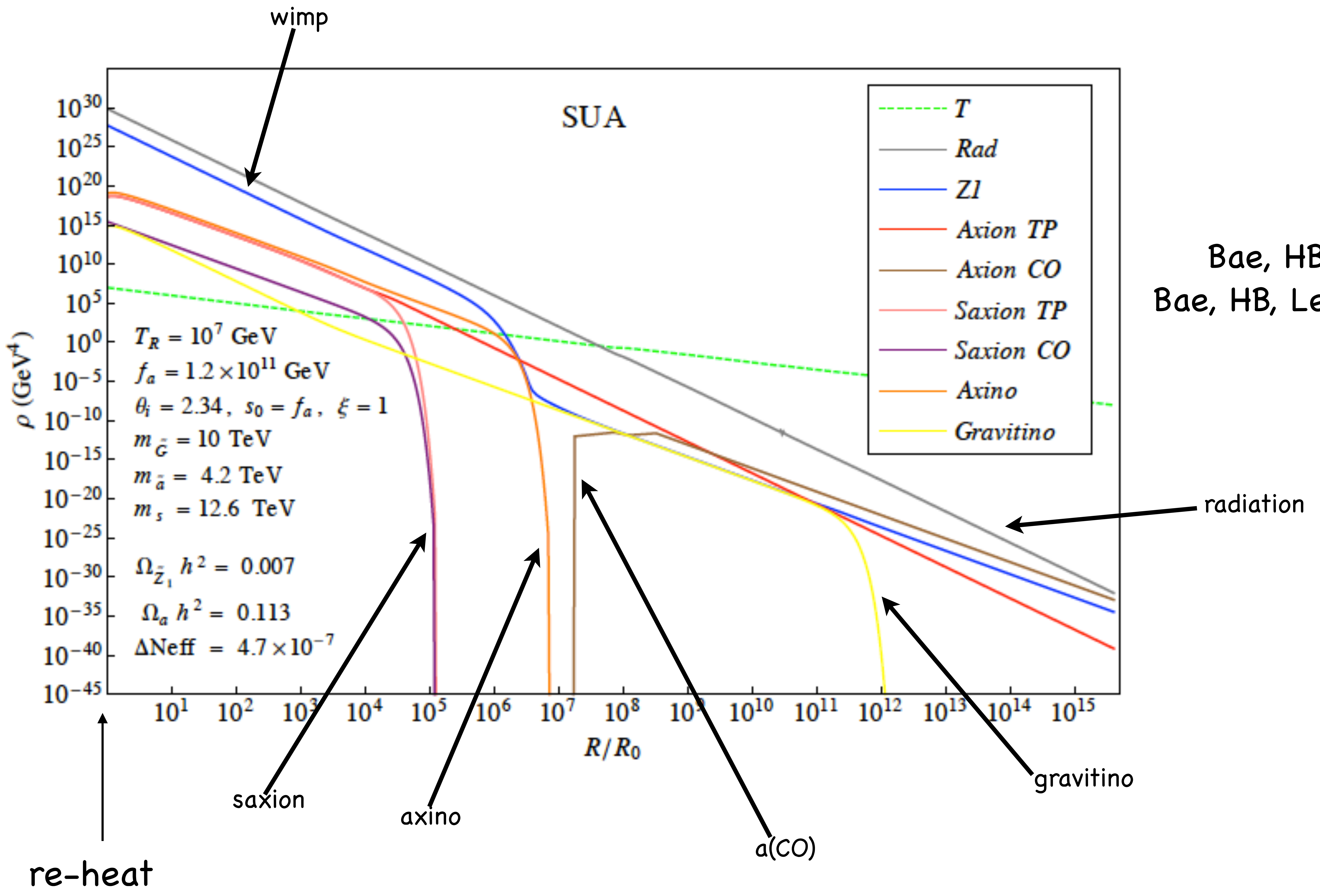
axion quality problem/SUSY mu problem/f_a problem: all solved!

HB, Barger, Sengupta, arXiv:1810.04844

mixed axion-neutralino production in early universe

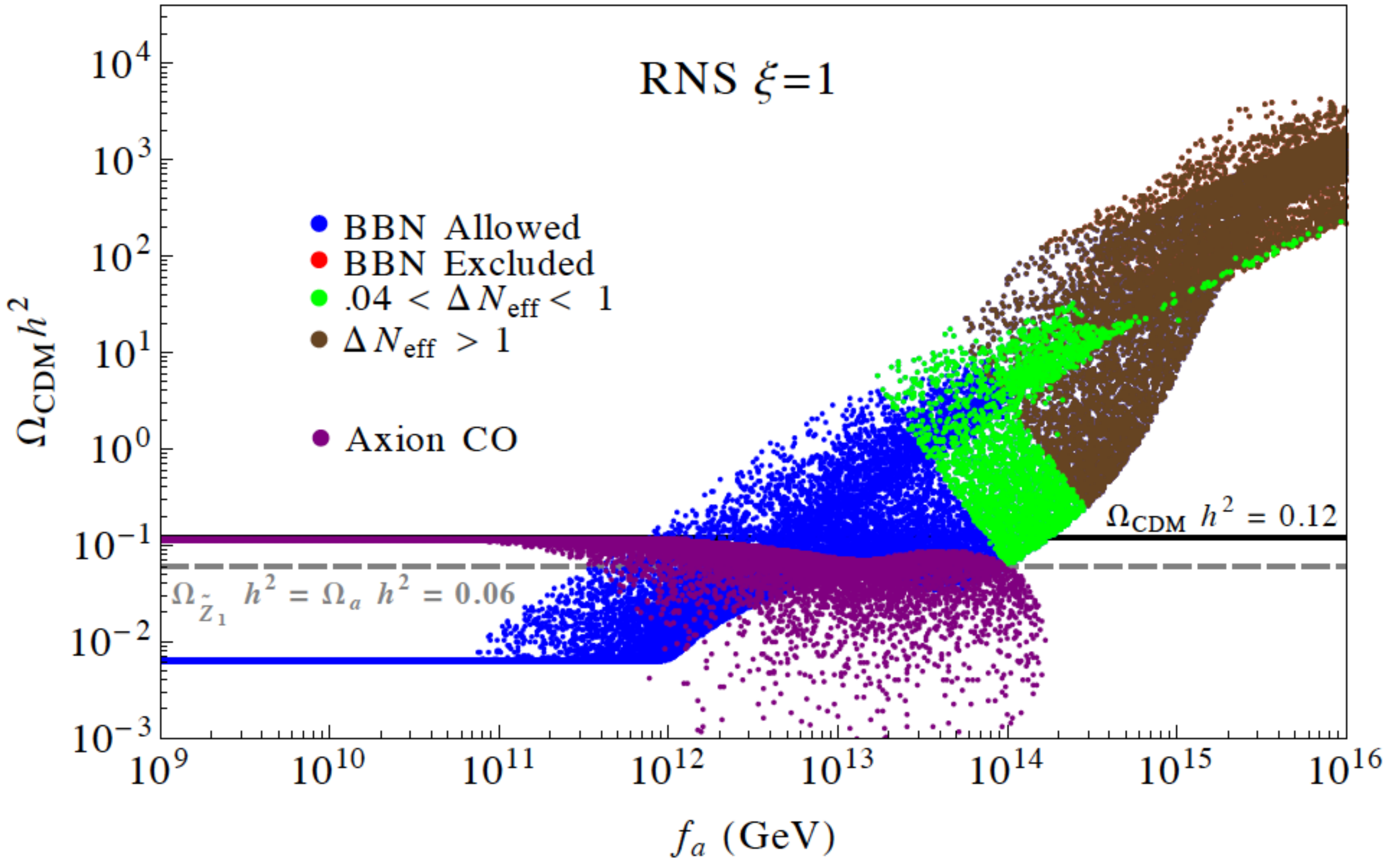
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: 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



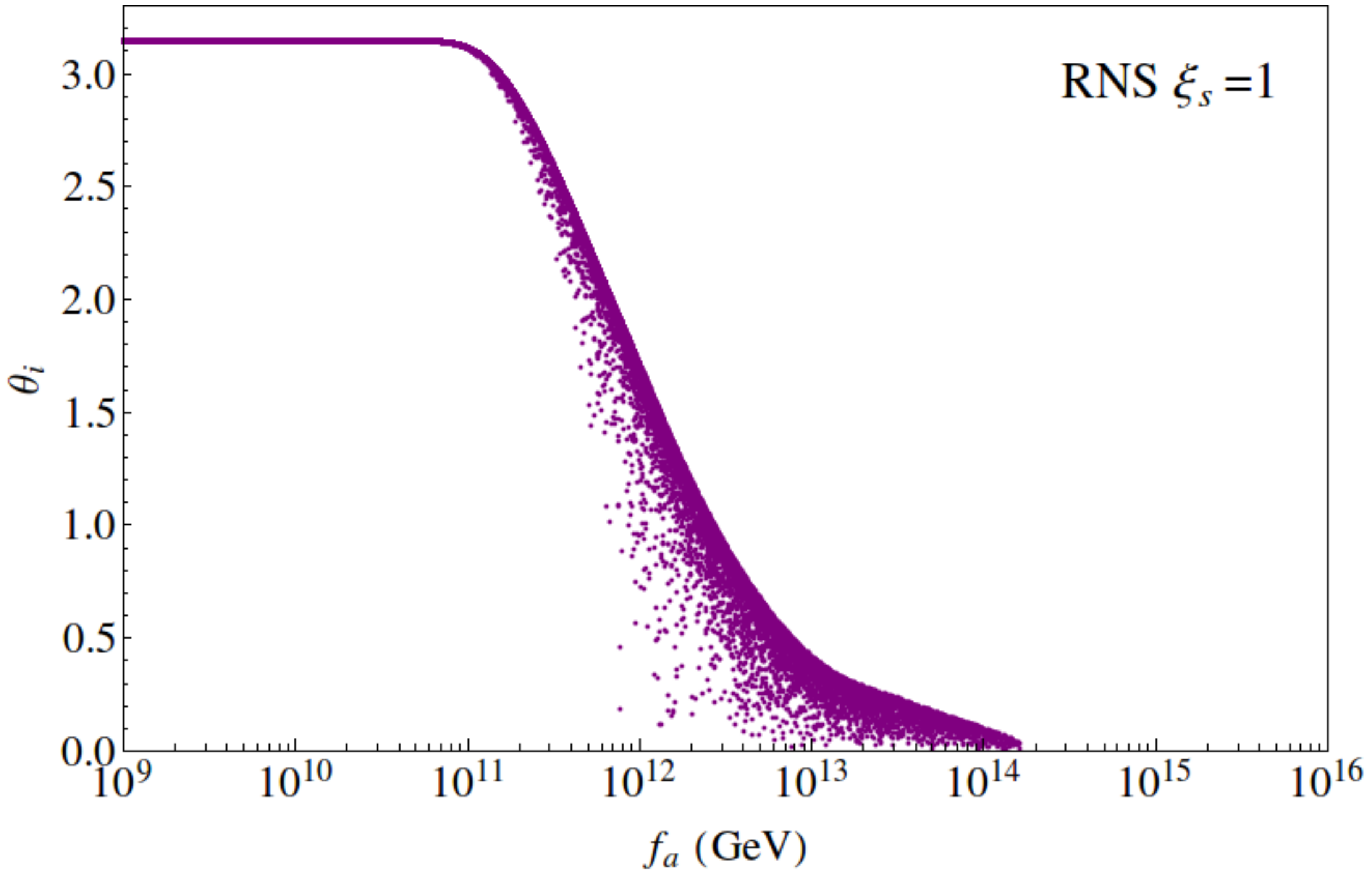
Bae, HB, Chun;
Bae, HB, Lessa, Serce

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



higgsino abundance

axion abundance

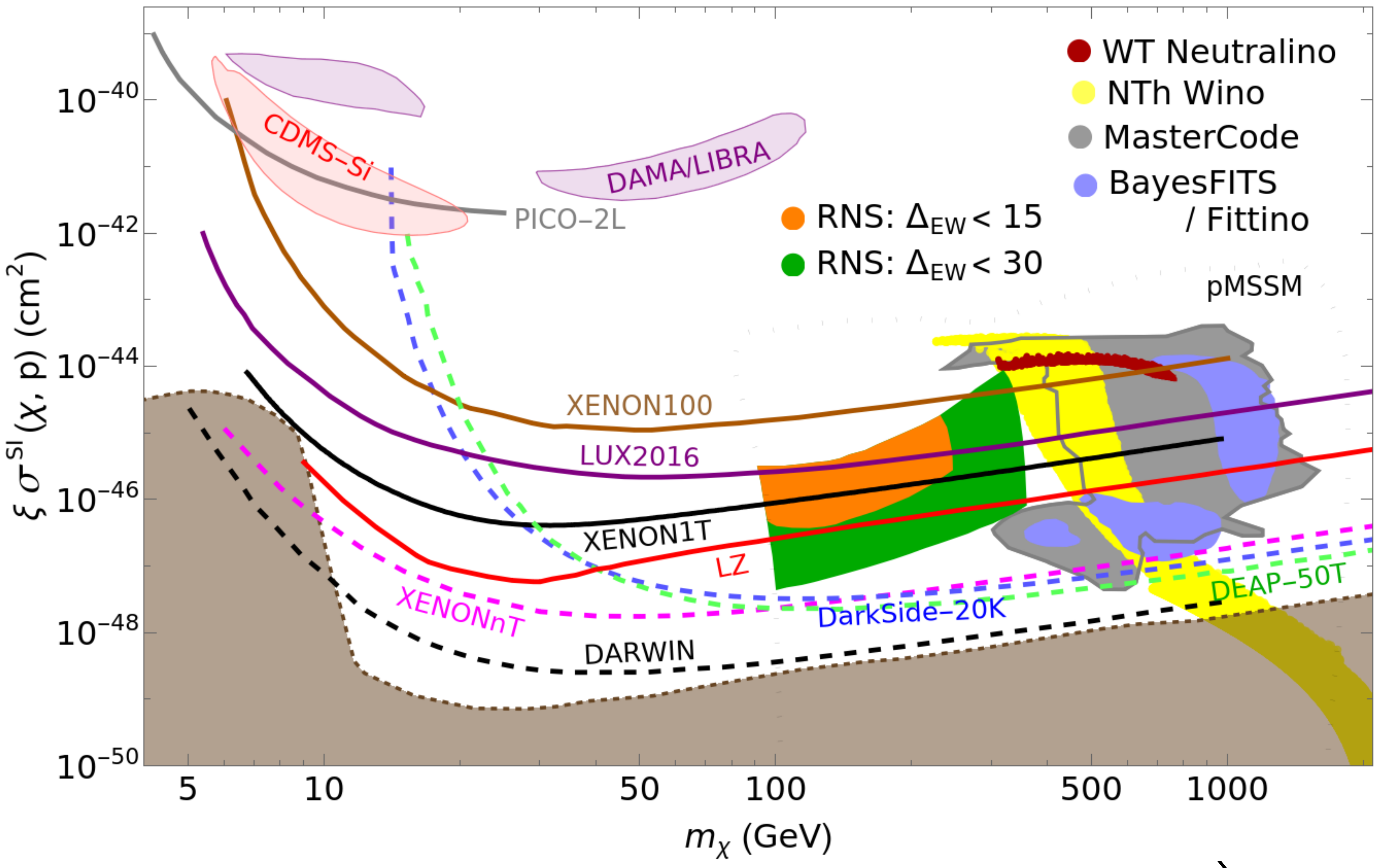


mainly axion CDM
for fa<~10^12 GeV;
for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce, arXiv:1406.4138

Direct higgsino detection rescaled for minimal local abundance

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



HB, Barger,Serce, arXiv:1609.06735

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

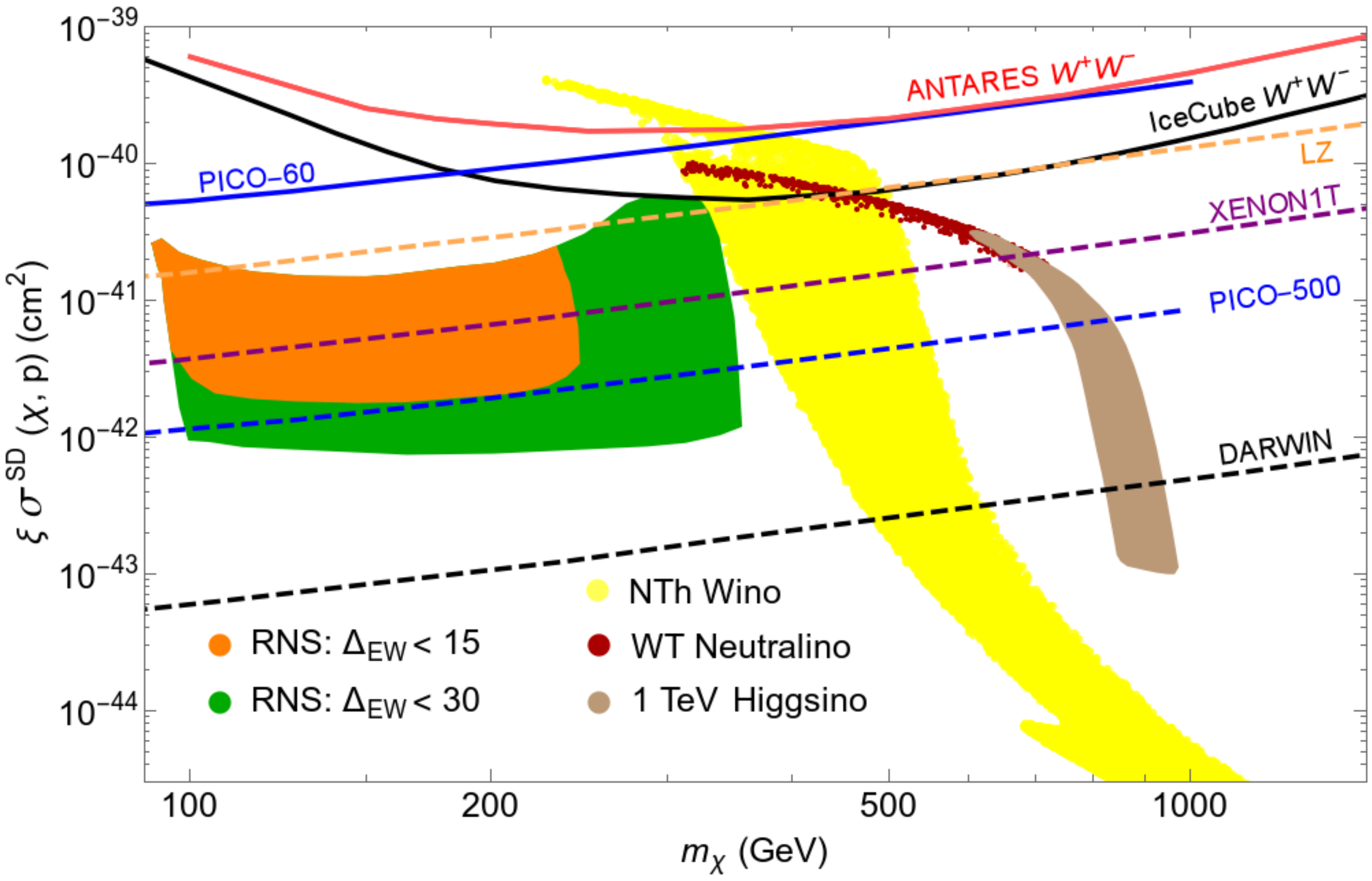
$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

update includes LZ2022 results!

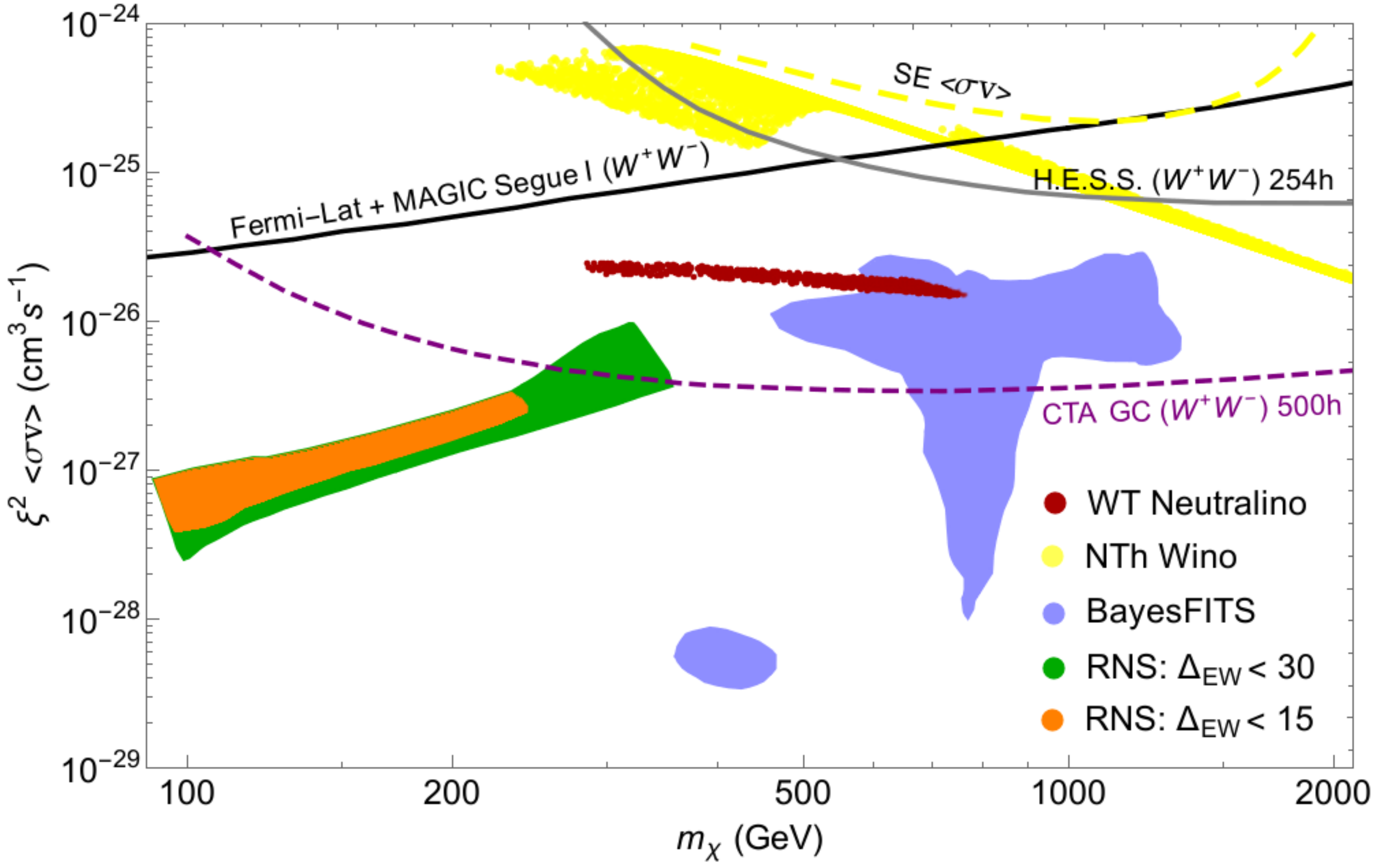
natural SUSY

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

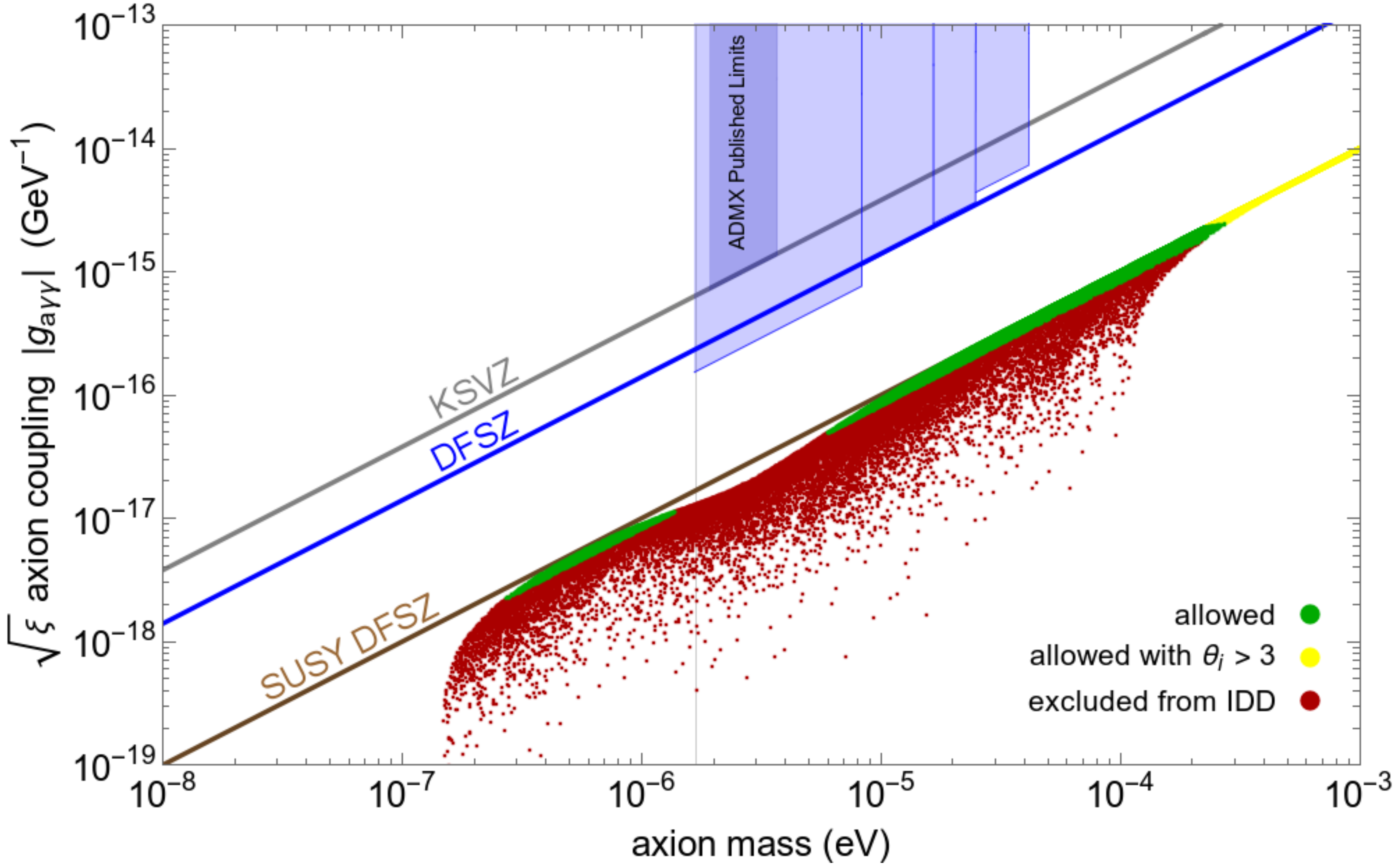
Prospects for SD WIMP searches:

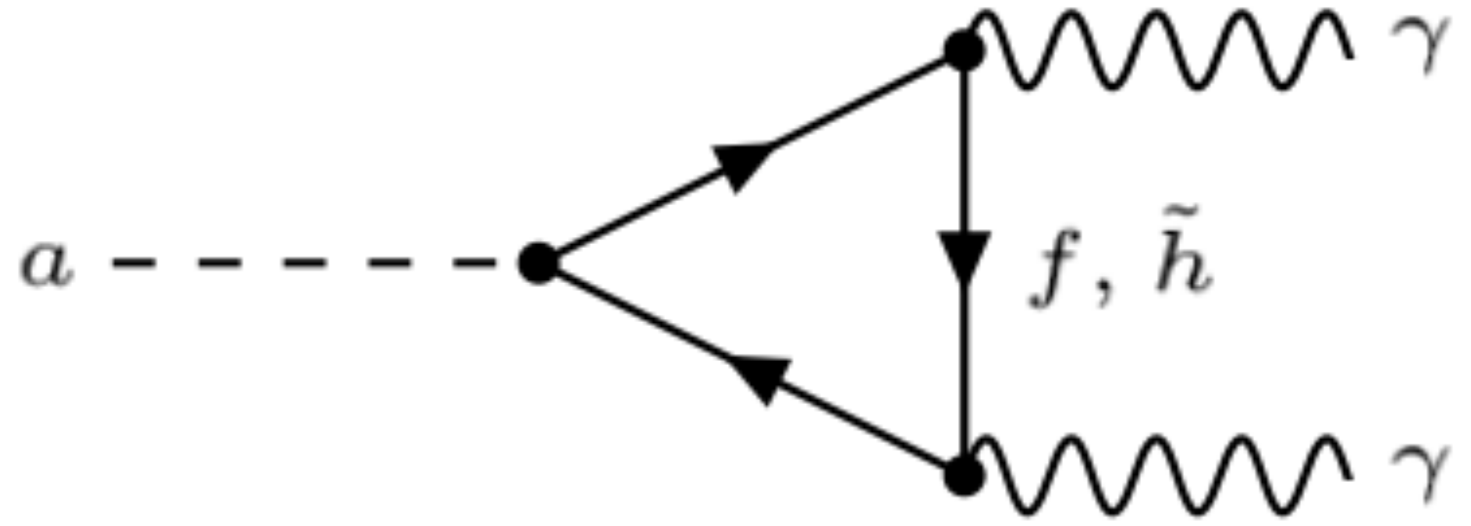


Prospects for IDD WIMP searches:



suppressed by square of diminished WIMP abundance





E/N=6/3

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

may need to probe broader and deeper!

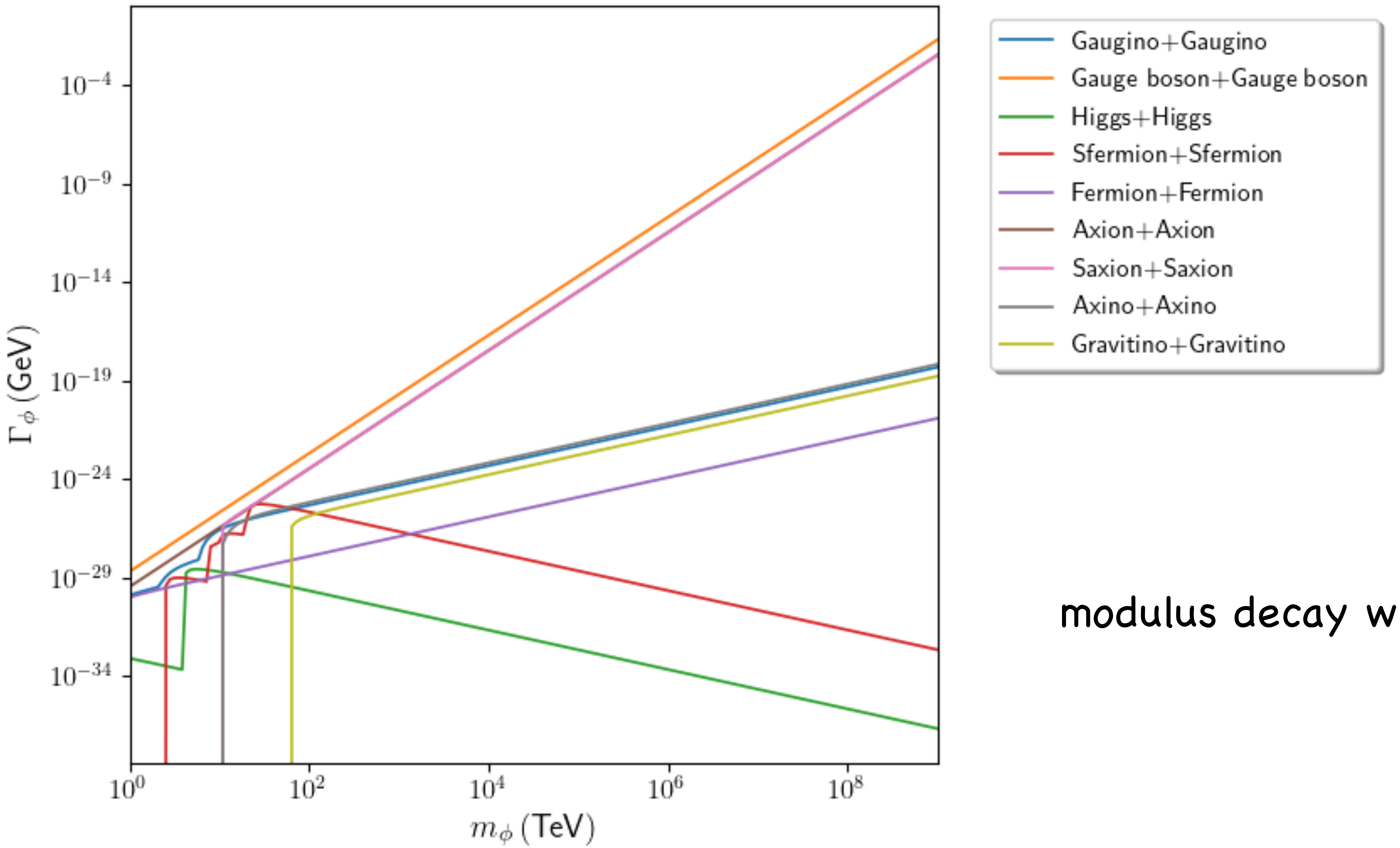
Bae, HB, Serce, arXiv:1705.01134

Recent work: add light string modulus

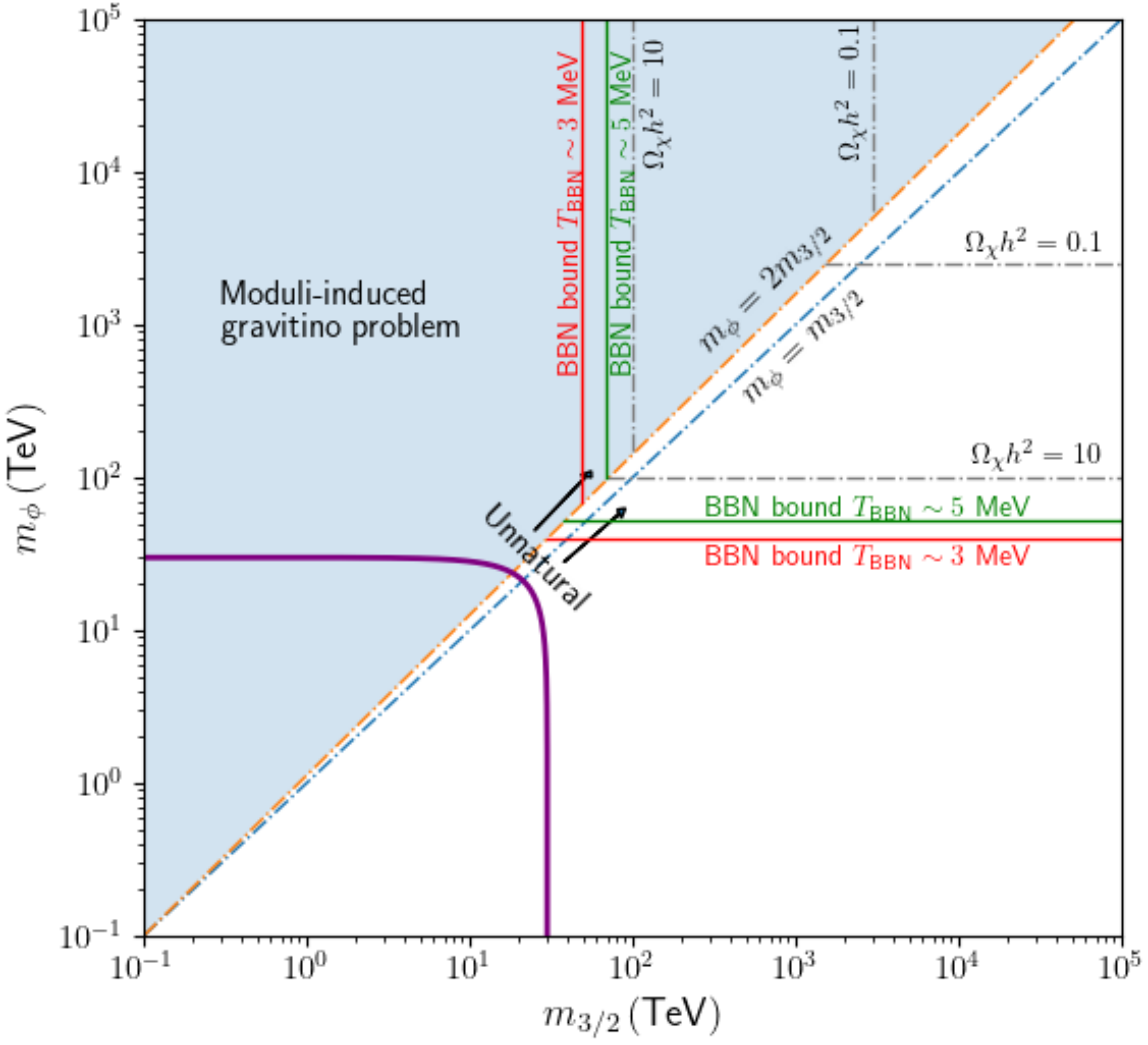
- compute all modulus decays to (PQ)MSSM particles
- 9-10 coupled Boltzmann equations needed axion/WIMP/ALP for relic abundance
- cosmological moduli problem (BBN) => m(phi)>100 TeV
- moduli-induced gravitino and LSP problem: m(phi)>~5000 TeV
- possible dark radiation decay to ALPs in LVS moduli stabilization
- anthropic sol'n to CMP: anthropic selection of low phi_0~10^-7
- see e.g. HB, Barger, Wiley Deal 2111.05971, 2201.06633, 2204.01130, 2301.12546

takeaways

- SUSY naturalness tension due to faulty early 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
- 5 populations of 2 DM particles: TP&DP WIMPs, TP, DP&CO axions
- discrete R-symmetry: e.g. Z(24)^R => axion quality, U(1)_PQ, RPC, proton stability, mu solution!
- higgsino-like WIMPs not yet detected: much lower abundance ~1/10th
- SUSY DFSZ axion coupling highly suppressed, hard to detect
- stringy moduli: favor KKLT with m(modulus)>>m(3/2)>>m(soft) to solve Cosmological Moduli Problem



modulus decay widths in PQMSSM



need mphi>~ 5000 TeV to avoid moduli-induced LSP problem

favors models such as KKLT where msoft<<m32<<mphi

HB, Barger,WileyDeal,arXiv:2201.06633