Weak scale SUSY emergent from the string landscape

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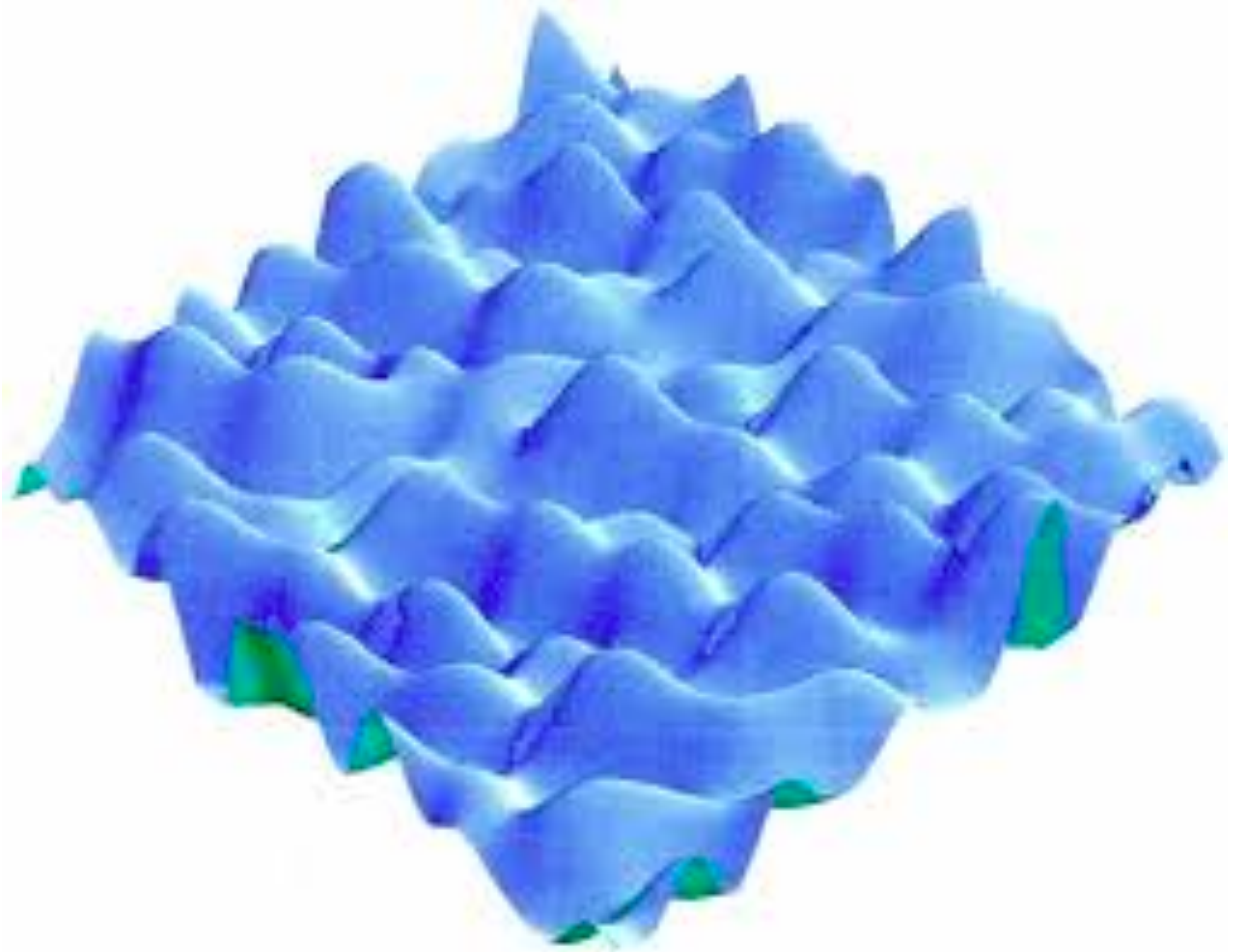
Based on arXiv:2202.07046, 2206.14839

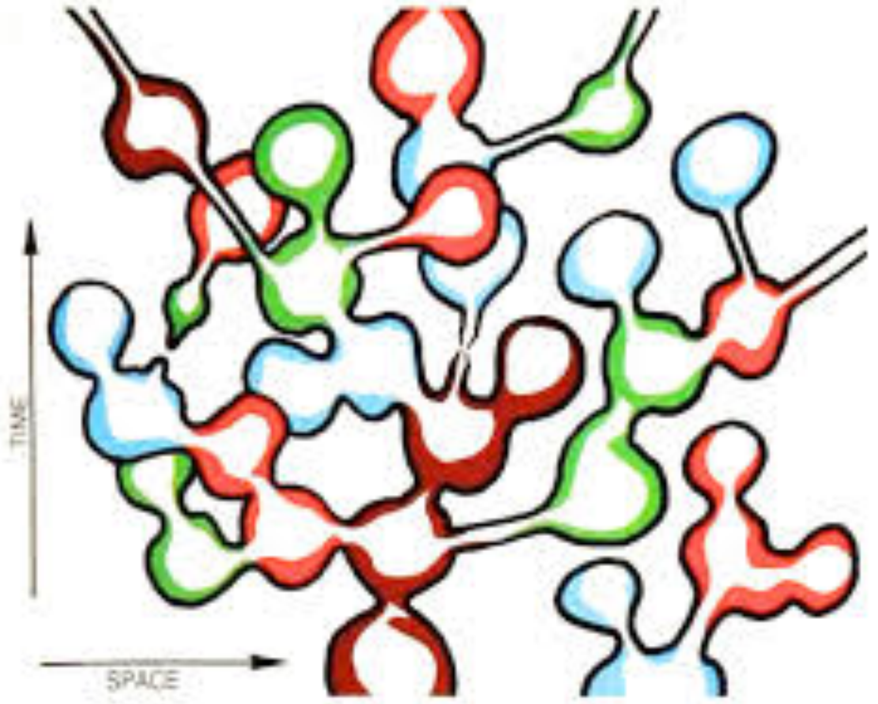
with V. Barger, D. Martinez and S. Salam



Popular review: Bousso&Polchinski, Sci. Am. 291 (2004) 60.

String theory provides most promising setting for unifying quantum gravity with SM

- 1974- string theory proposed as theory of quantum gravity
- 1984- 1st string revolution: anomalies, heterotic string compactified on CY manifold
- 1995-1996: 2nd string revolution: D-branes and string dualities
- 2001: 3rd string revolution: emergence of string landscape (Bousso&Polchinski, Douglas et al., Susskind); ~10^500 flux compactifications => eternal inflation model with each pocket universe with different 4-d laws of physics:

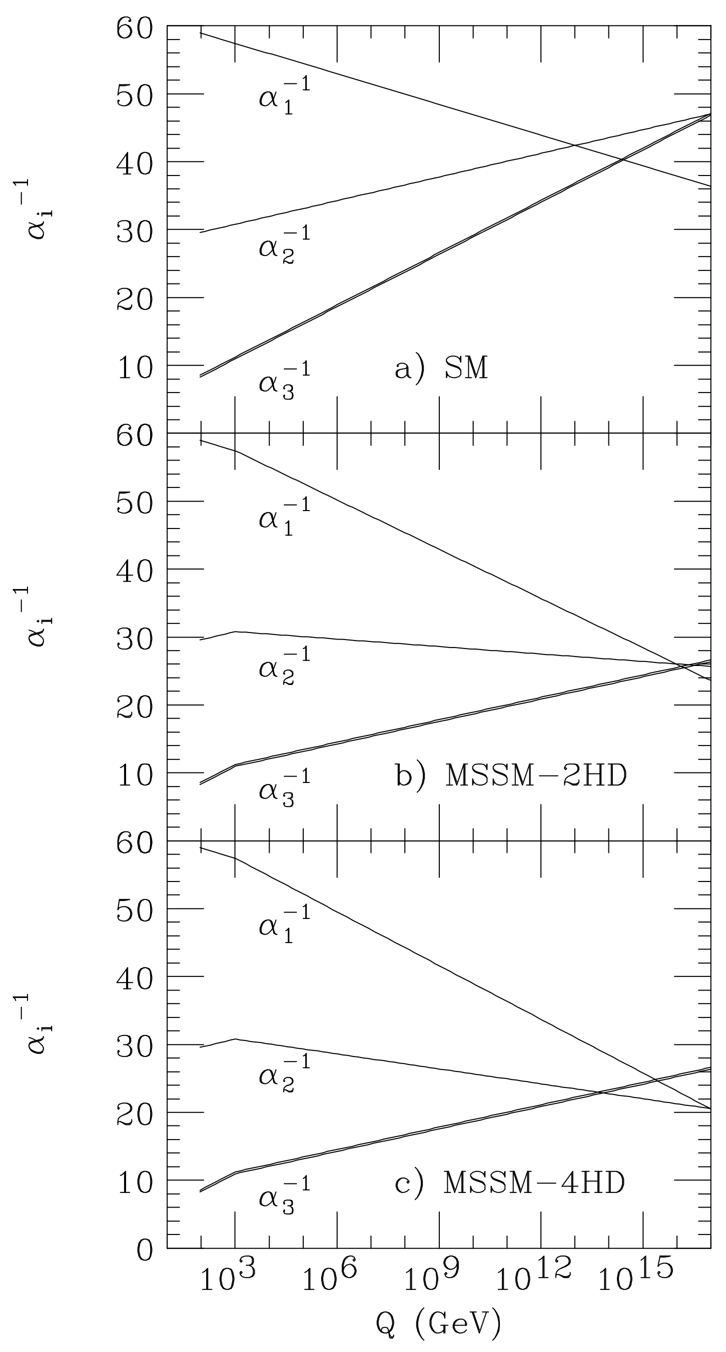


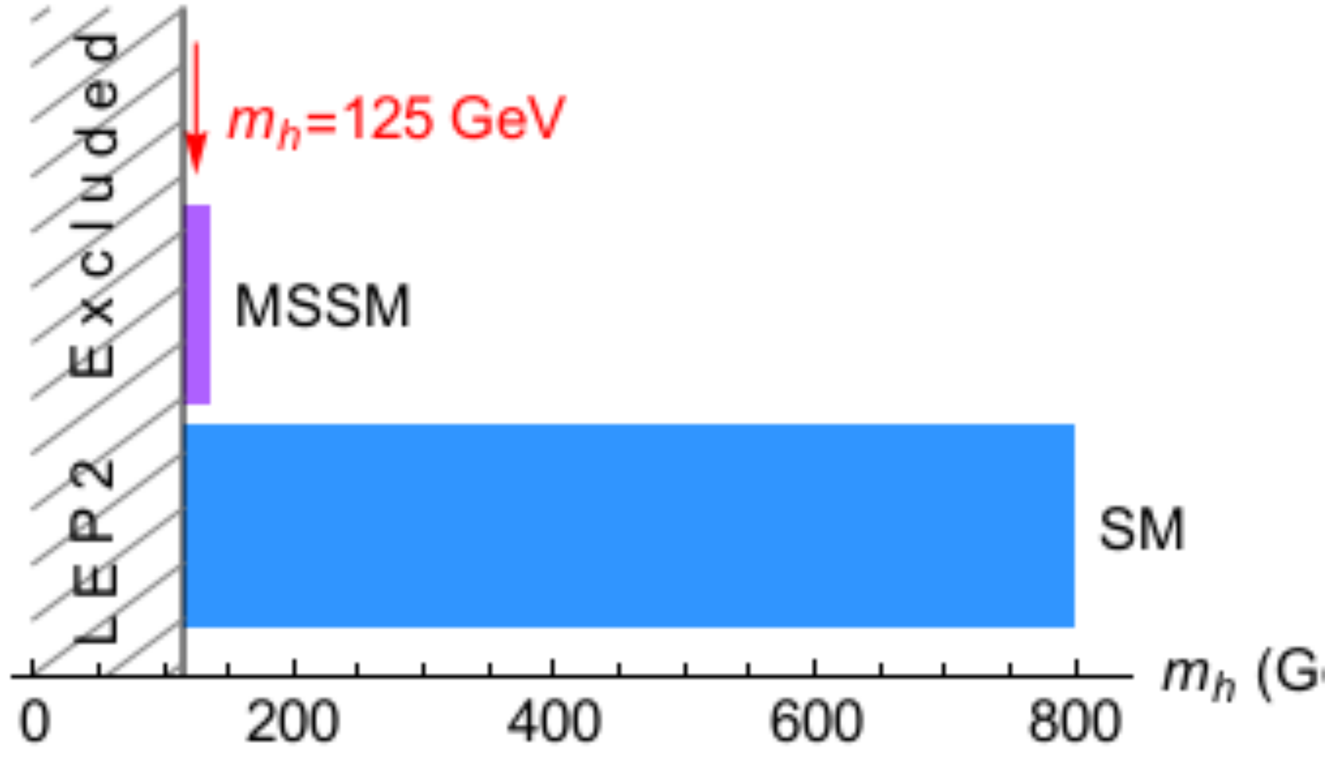
- Setting for Weinberg's anthropic solution to CC problem

landscape phenomenology

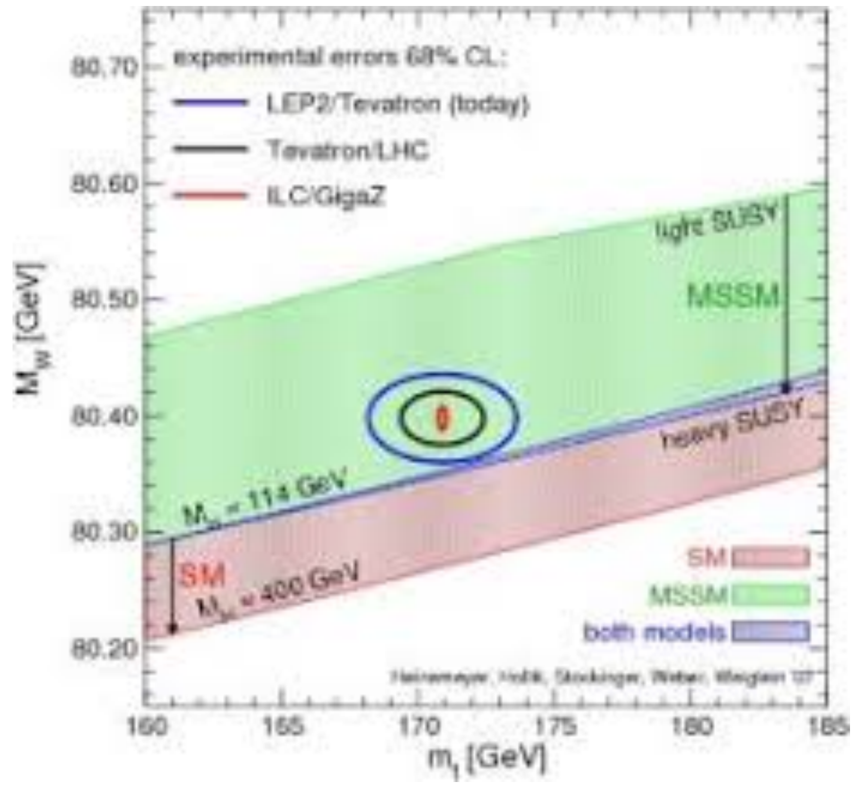
- Candelas et al. (1984) compactification on Ricci-flat manifold with special holonomy (CY 3-fold) => conserved Killing spinor=> leaves some remnant spacetime SUSY in LE-EFT
- Acharya conjecture: only such compactifications lead to stable universes- otherwise Witten's bubble of nothing
- Dine et al.: metastable vacua actually stable under SUSY; broken SUSY leaves lifetime longer than age of universe $\Gamma \sim \exp(-m_P^2/m_{3/2}^2)$
- hard (but perhaps not impossible) to construct viable compactifications without remnant spacetime SUSY
- But is SUSY broken at some high scale >> m(weak) or ~m(weak) in which case solution to gauge hierarchy problem

WSS supported by virtual quantum effects





- gauge coupling unification
- m(top) in right range for radiative EWSB
- m(Higgs)~125 GeV in accord with MSSM
- precision EW (Sven): prefers heavy SUSY over SM



WSS from the landscape: the setup

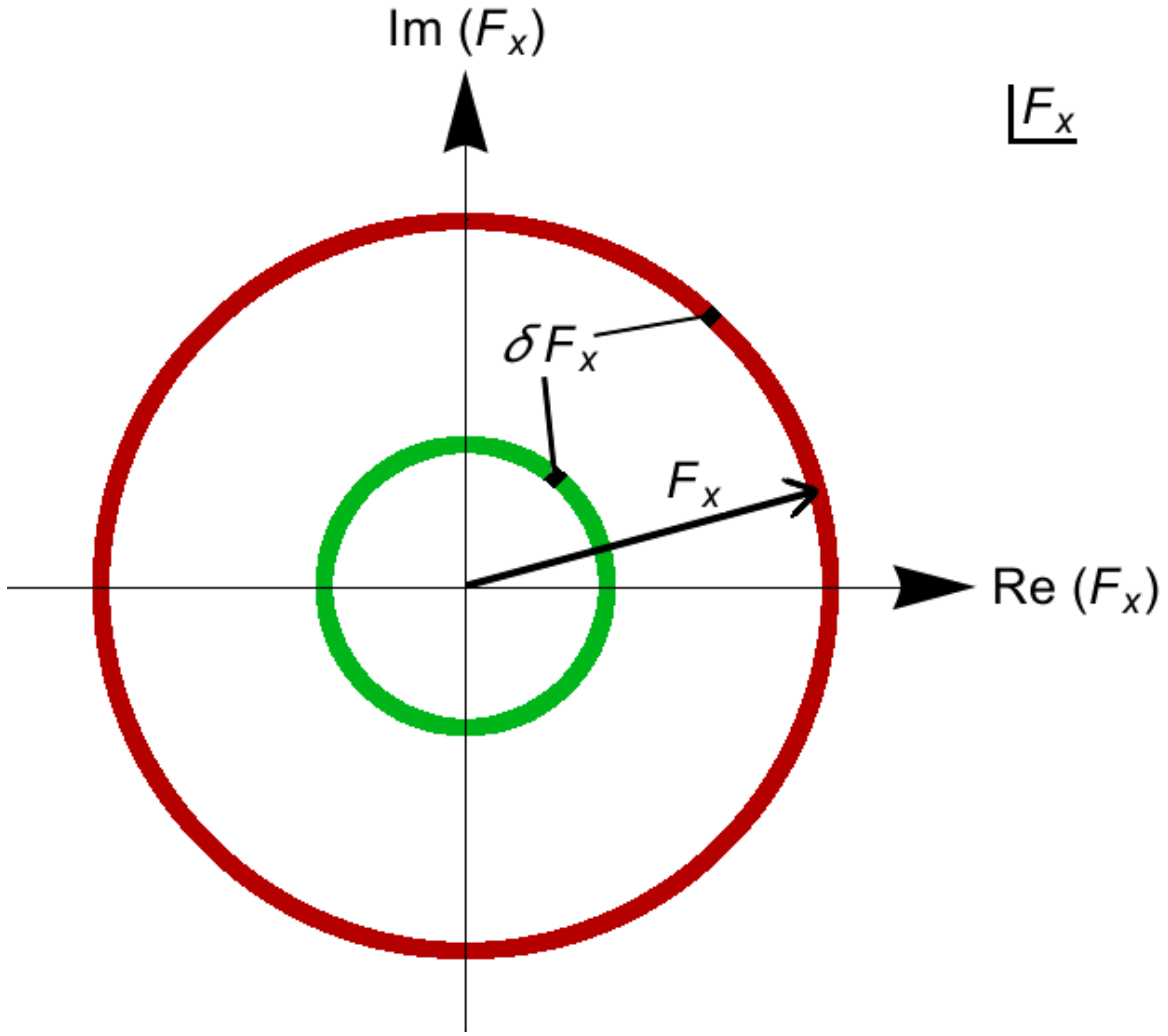
- flux compactification leaving remnant N=1 spacetime SUSY
- moduli stabilized ala KKLT via flux and non-perturbative effects
- parsimony: assume SM+SUSY (=MSSM) plus e.g. possible PQ sector/moduli in LE-EFT
- friendly/predictive patch of landscape: only CC and SUSY breaking scale scan (ADK)
- different dependence of soft terms on hidden sector: gaugino masses, scalar masses, A and B terms effectively scan independently
- Douglas: CC selection doesn't impact SUSY breaking selection

$$dN_{vac} \sim f_{SUSY} \cdot f_{EWSB} \cdot dm^2_{SUSY}$$

Gravity/moduli mediated SUSY breaking

$$m_{hidden}^4 = \sum_i F_i^\dagger F_i + \sum_\alpha D_\alpha D_\alpha \sim (10^{11}\ \text{GeV})^4$$

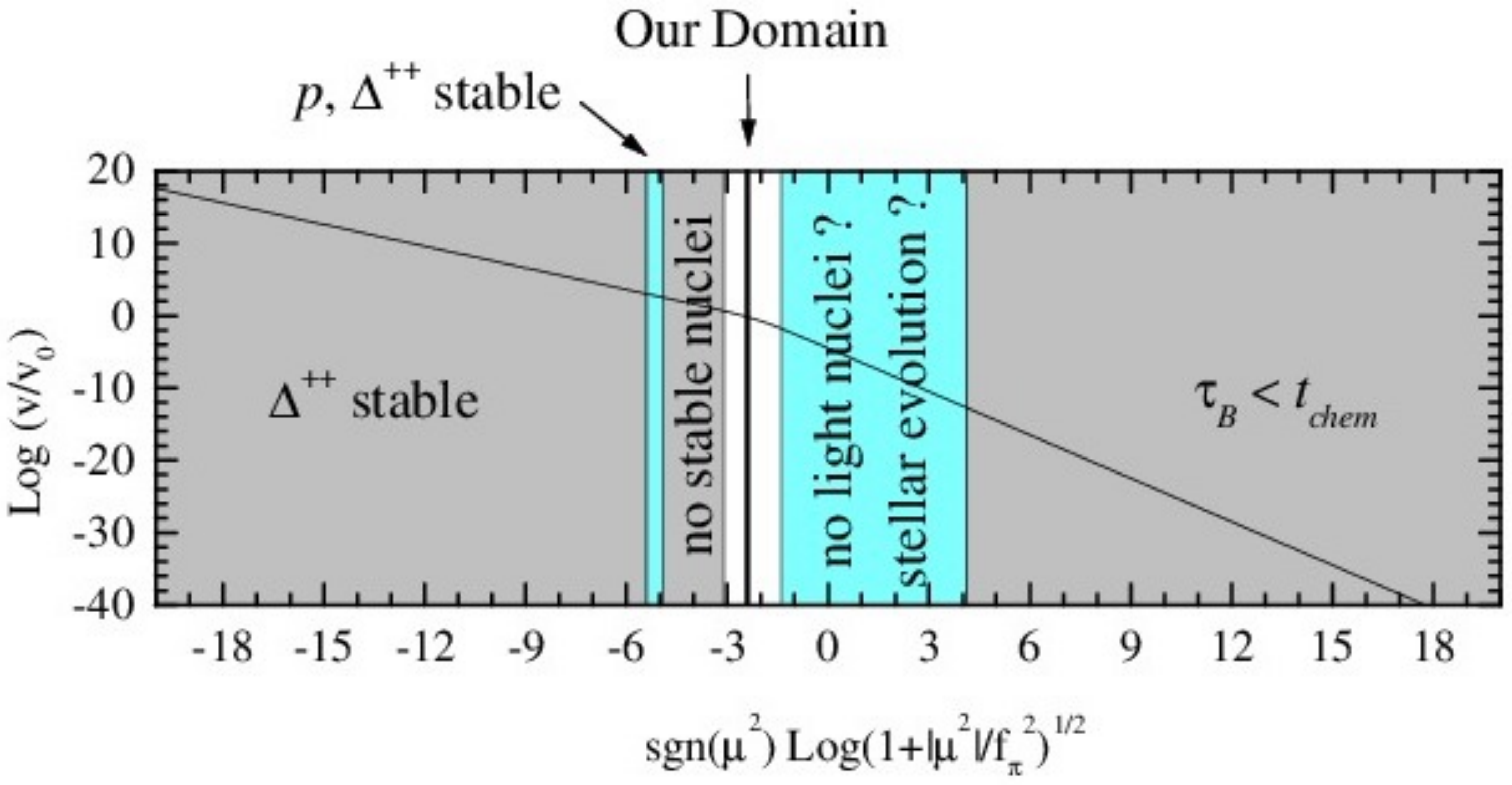
$$m_{soft} \sim m_{hidden}^2 / m_P \sim 1\ \text{TeV}$$



- textbook case SUSY breaking via single F-term distributed randomly as complex number: linear draw to large soft terms
- more SUSY breaking fields: stronger power-law draw to large soft terms (Douglas)

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

Agrawal, Barr, Donoghue, Seckel (ABDS) window (1997)



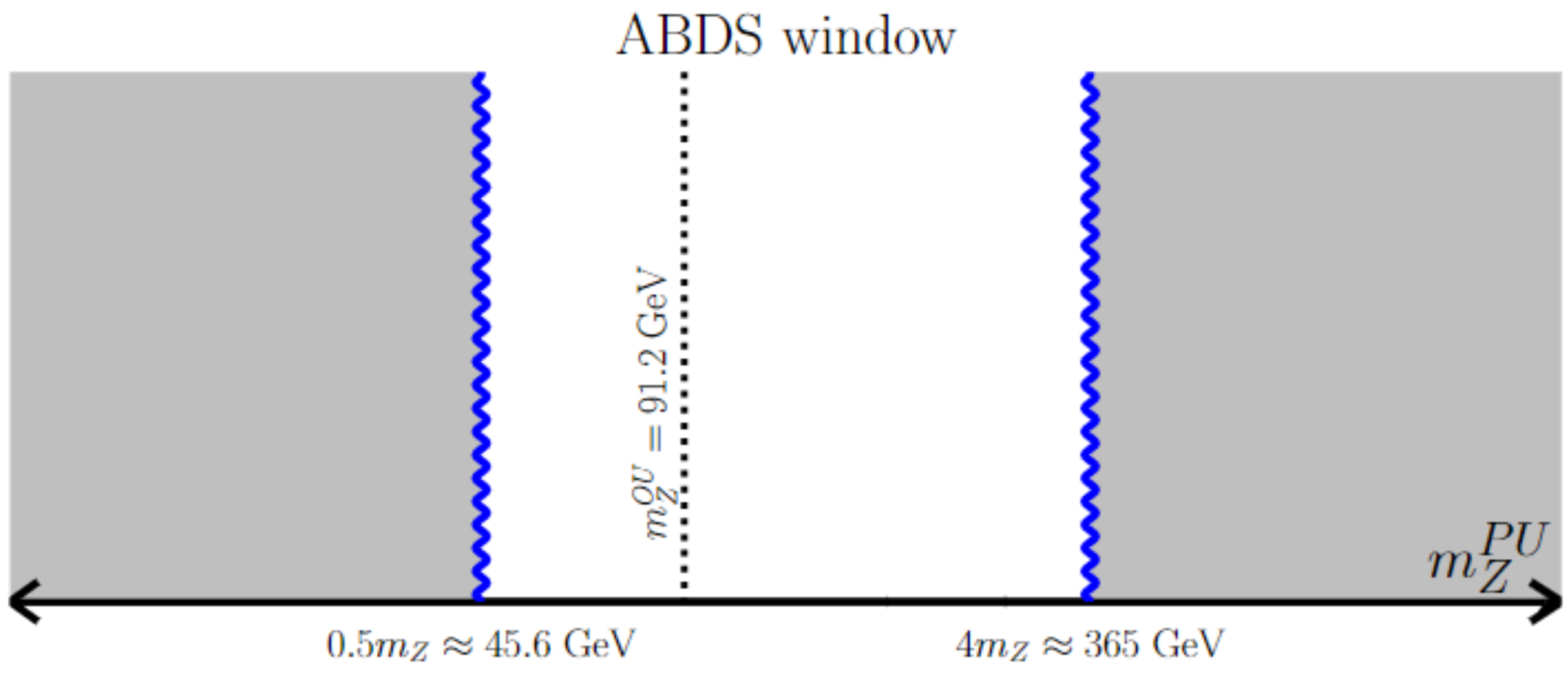
for complex nuclei (hence atoms) to exist (atomic principle/anthropic requirement), then

$$m_{weak}^{OU}/2 <\sim m_{weak}^{PU} <\sim (2-5)m_{weak}^{OU}$$

value of mweak in pocket universe close to the value measured in our universe; otherwise, no atoms as we know them!

an underrated prediction of MSSM: magnitude of weak scale

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



(usually this relation is finetuned in mu or mHu to make m(Z)~91.2 GeV)

Recent work: place on more quantitative footing:
scan soft SUSY breaking parameters in NUHM3 model
as m(soft)^n along with f(EWFT) penalty^*,**

We scan according to m^n_{soft} over:

- $m_0(1,2)$: $0.1 - 40$ TeV,
- $m_0(3)$: $0.1 - 20$ TeV,
- $m_{1/2}$: $0.5 - 10$ TeV,
- A_0 : $0 - \; -60$ TeV,
- m_A : $0.3 - 10$ TeV,

$\tan\beta$: $3 - 60$ (flat)

mu=150 GeV (fixed)

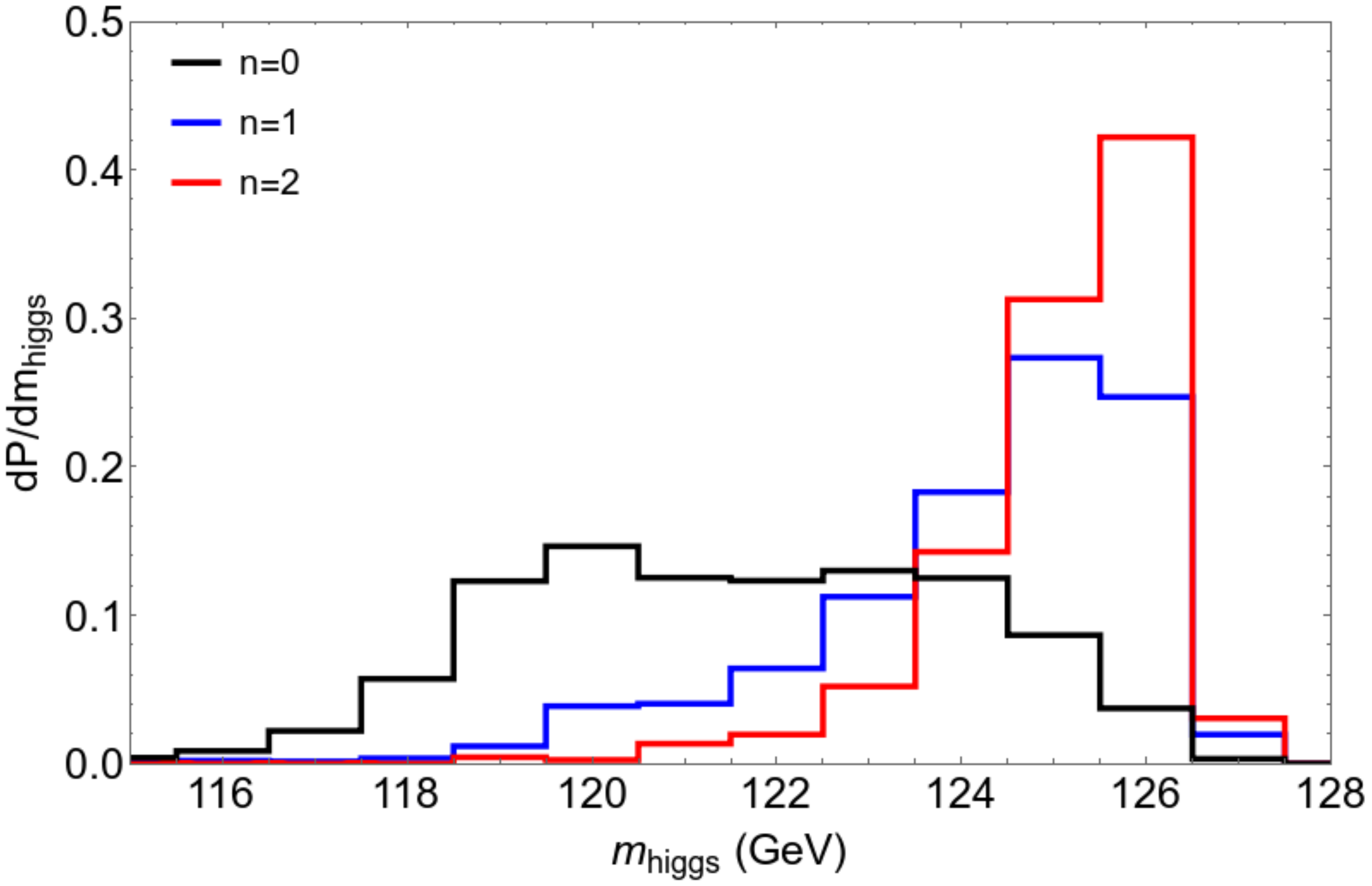
(*upper limits chosen beyond those set by ABDS window)

(**then rescale to mZ=91.2 GeV to gain predictions for Our Universe (OU))

HB, Barger, Serce, Sinha, JHEP 1803 (2018) 002

Making the picture more quantitative:

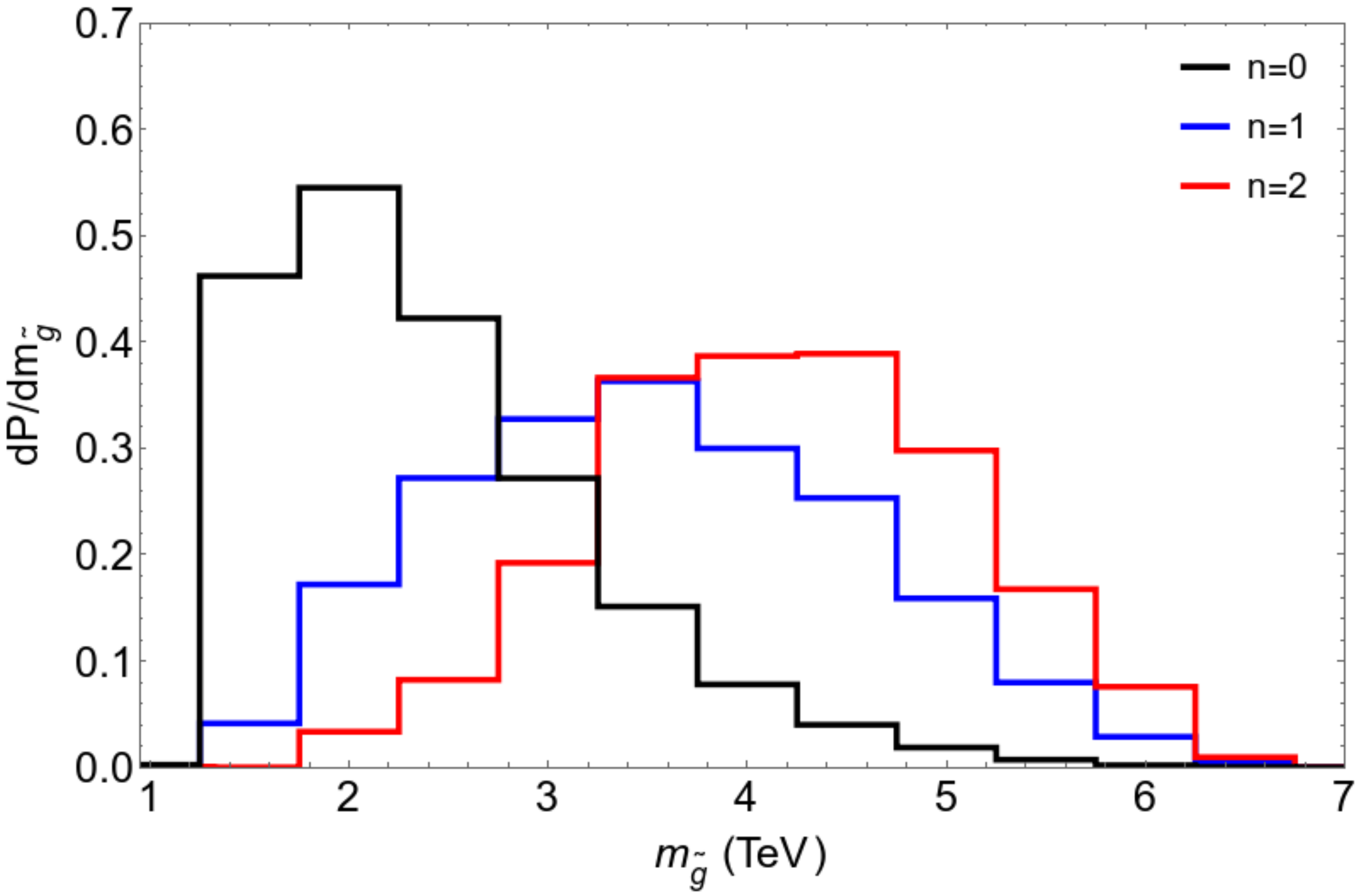
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



m(h)~125 most favored for n=1,2

HB,Barger, Serce, Sinha, arXiv:1712.01399

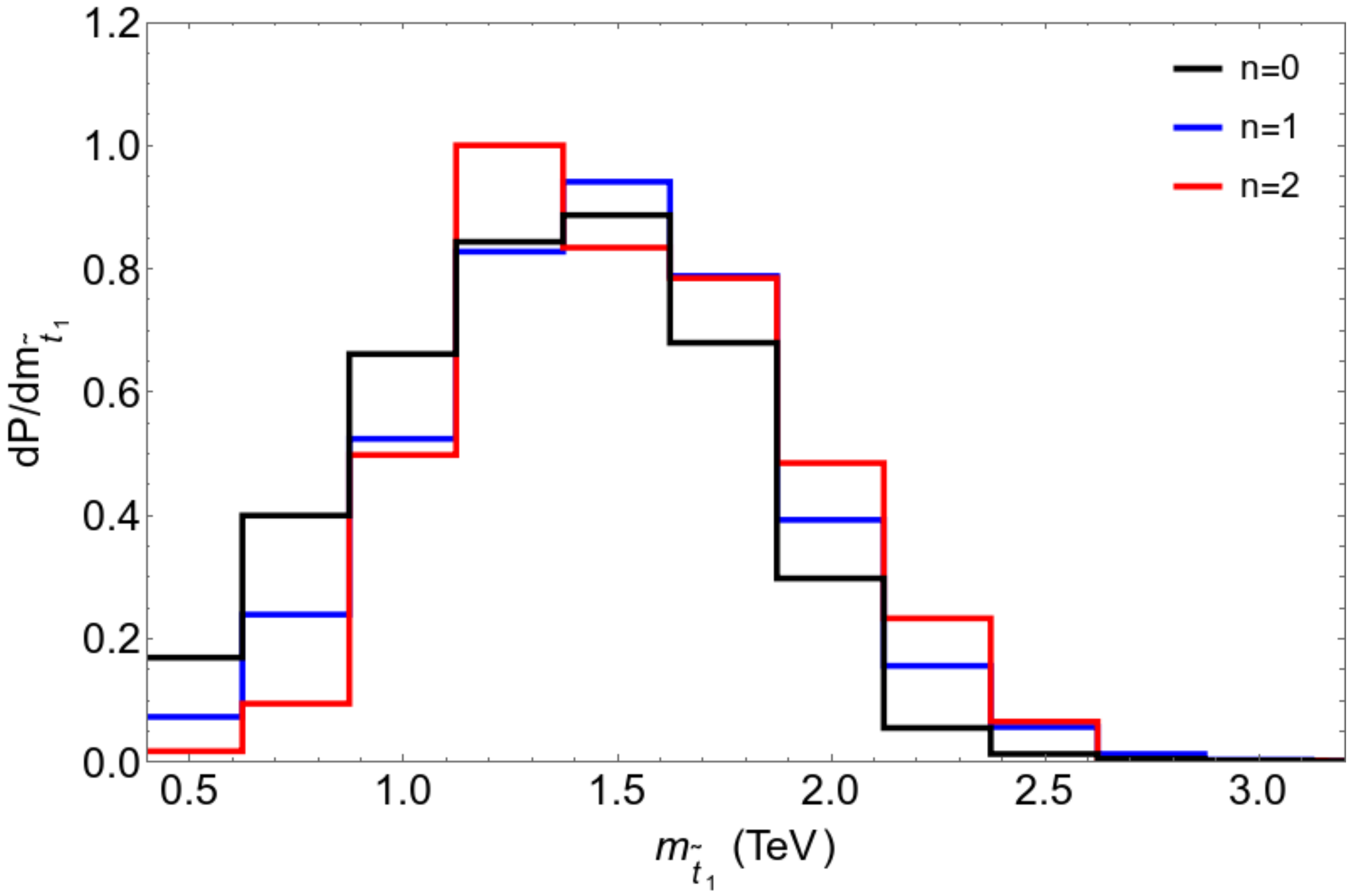
What is corresponding distribution for gluino mass?



gluino typically beyond LHC 14 reach
(need higher energy hadron collider)

HB, Barger, Serce, Sinha, arXiv:1712.01399

and top-squark mass m(t1)?



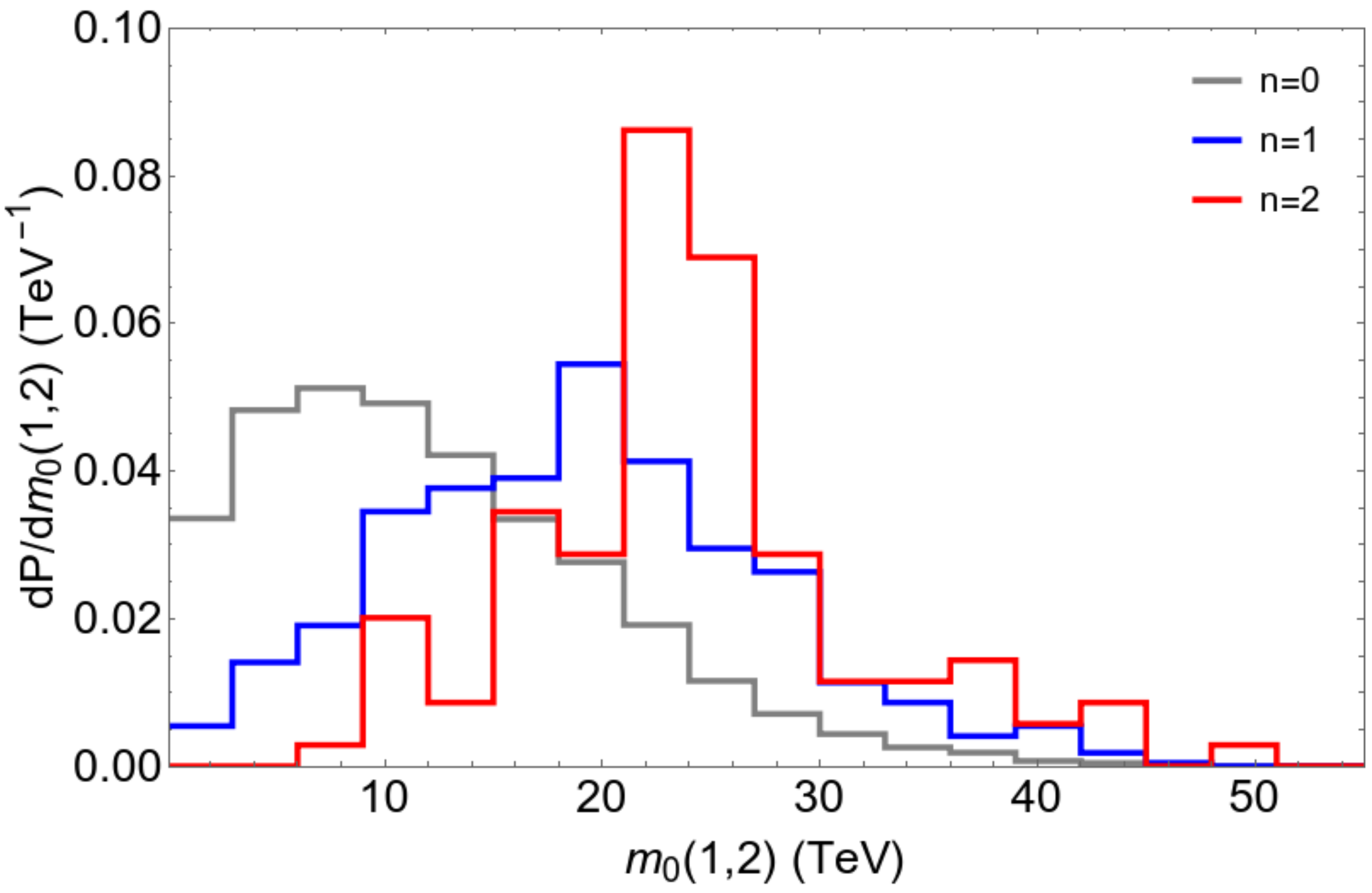
m(t1) typically beyond present LHC reach

HB,Barger, Serce, Sinha, arXiv:1712.01399 first/second generation sfermions pulled to 10-40 TeV:

landscape mixed decoupling/quasi-degeneracy sol'n

to SUSY flavor/CP problems

HB, Barger, Sengupta, arXiv:1910.00090



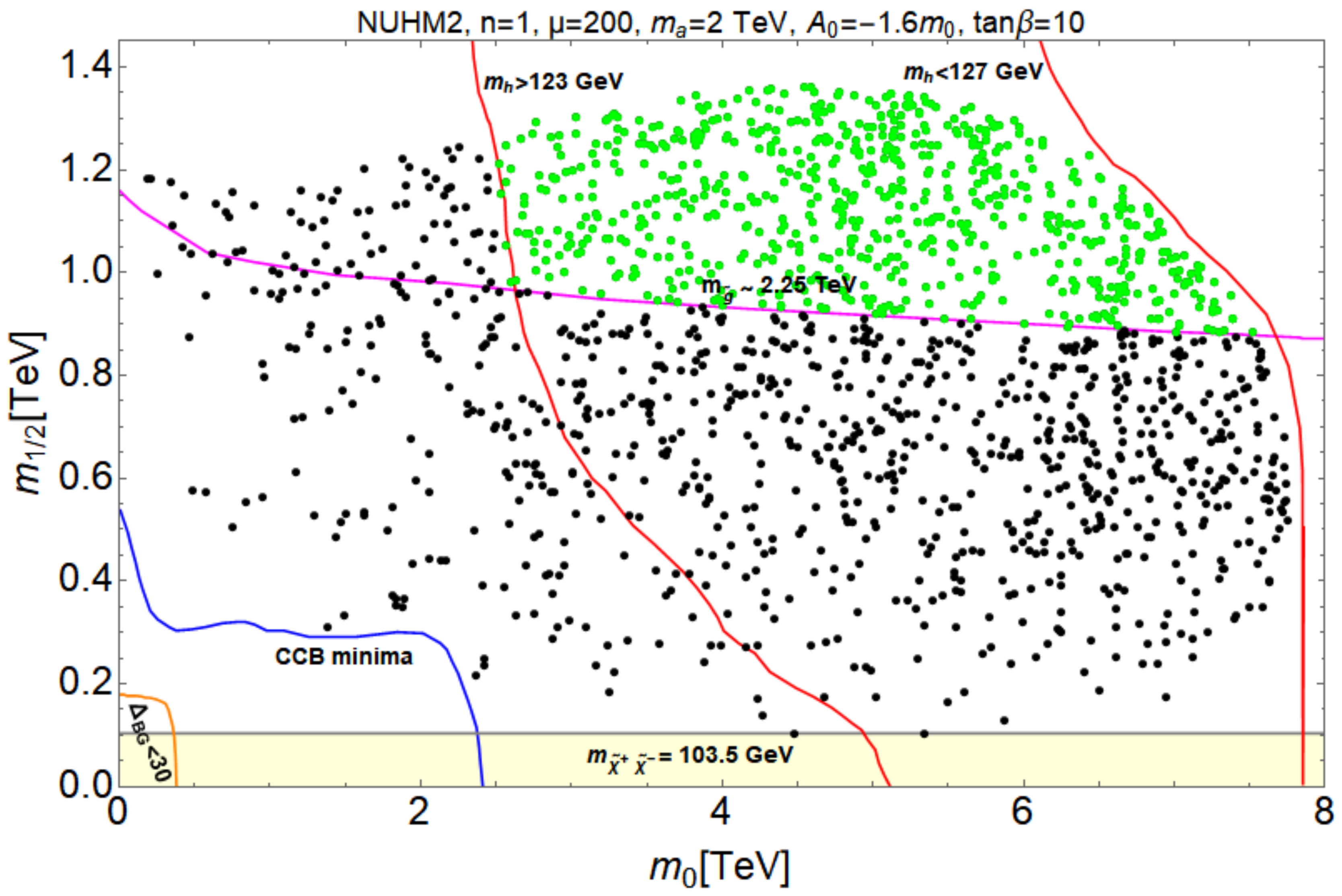
Stringy naturalness (Douglas): higher density of points are more stringy natural!

conventional natural: favor low m0, mhf

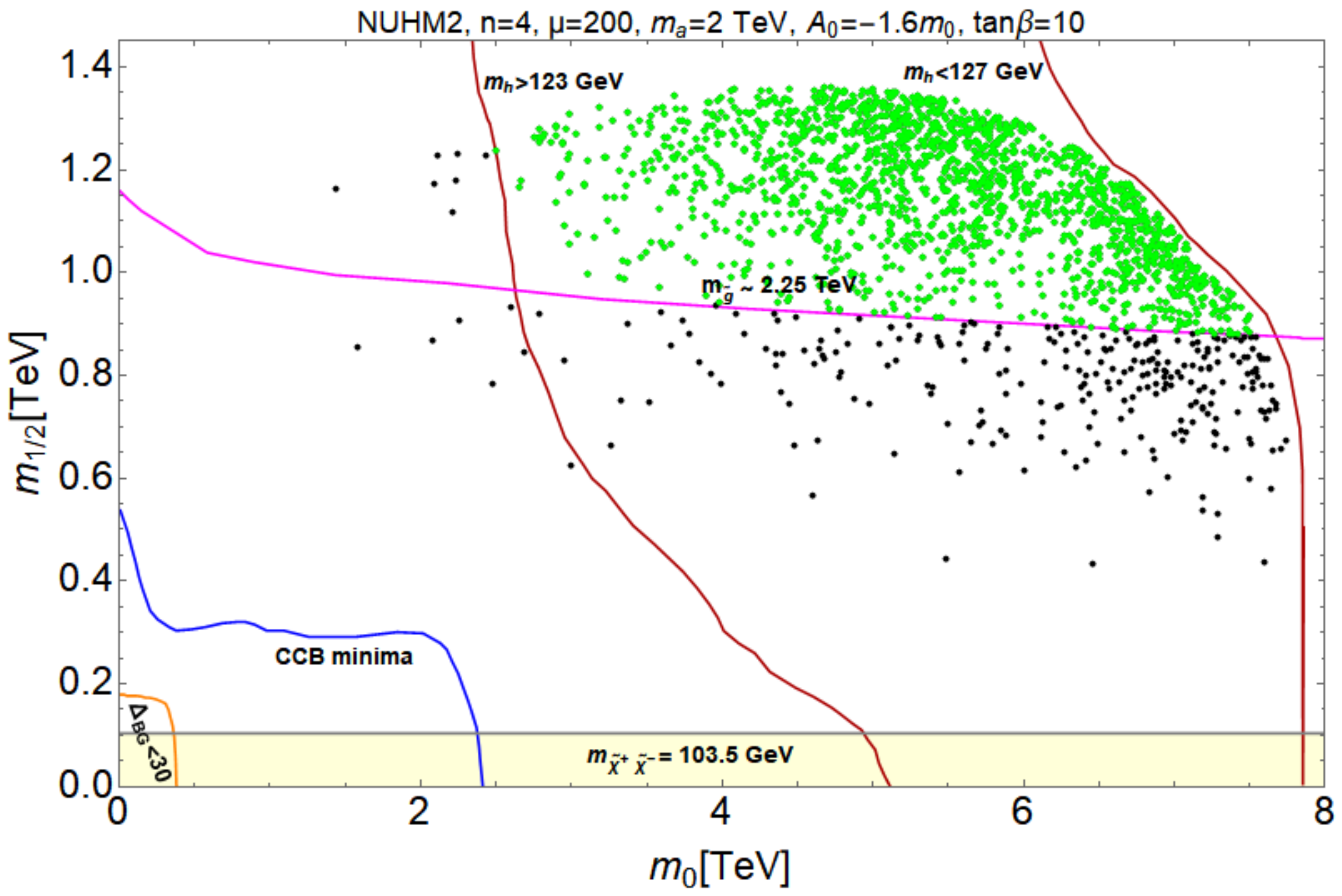
stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741

Living dangerously: Arkani-Hamed, Dimopoulos, Kachru, hep-ph/0501082



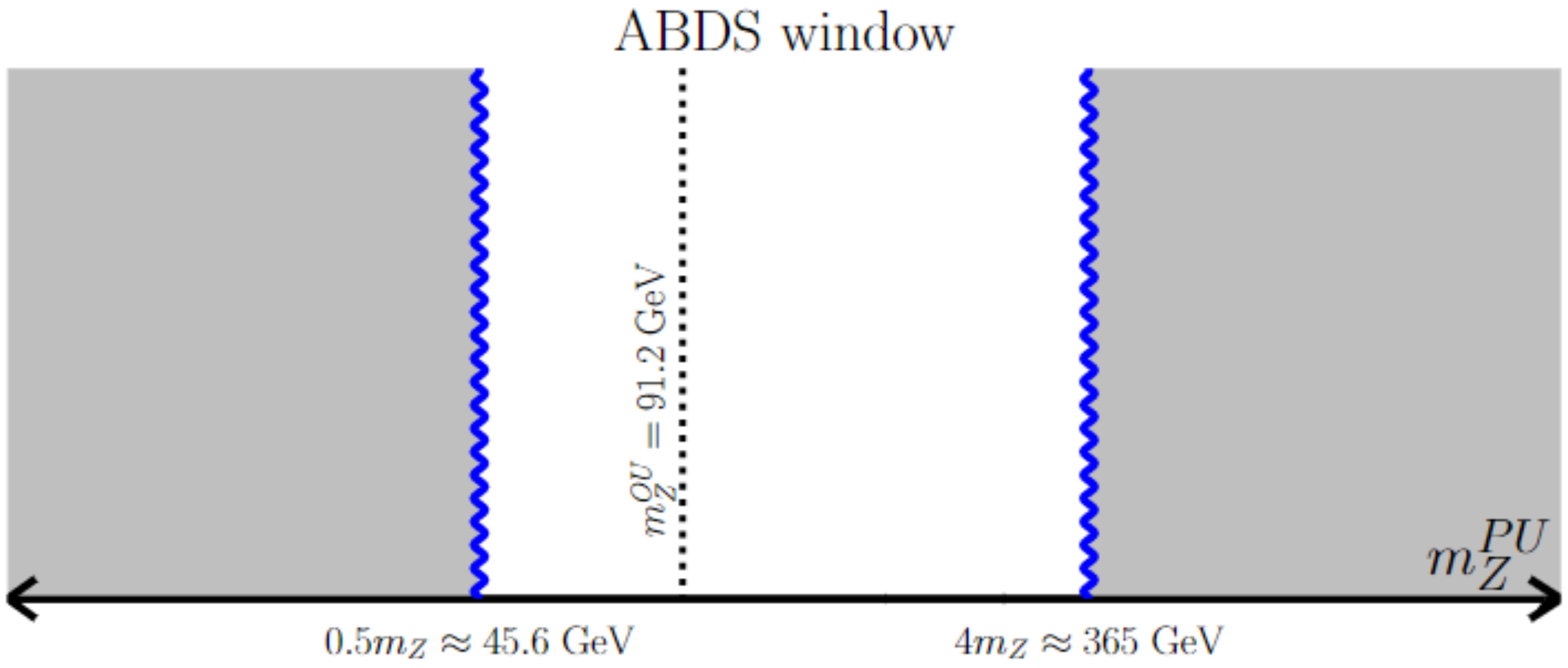
$$m(soft)^1$$



$$m(soft)^4$$

Under stringy naturalness, a 3 TeV gluino is more natural than a 300 GeV gluino!

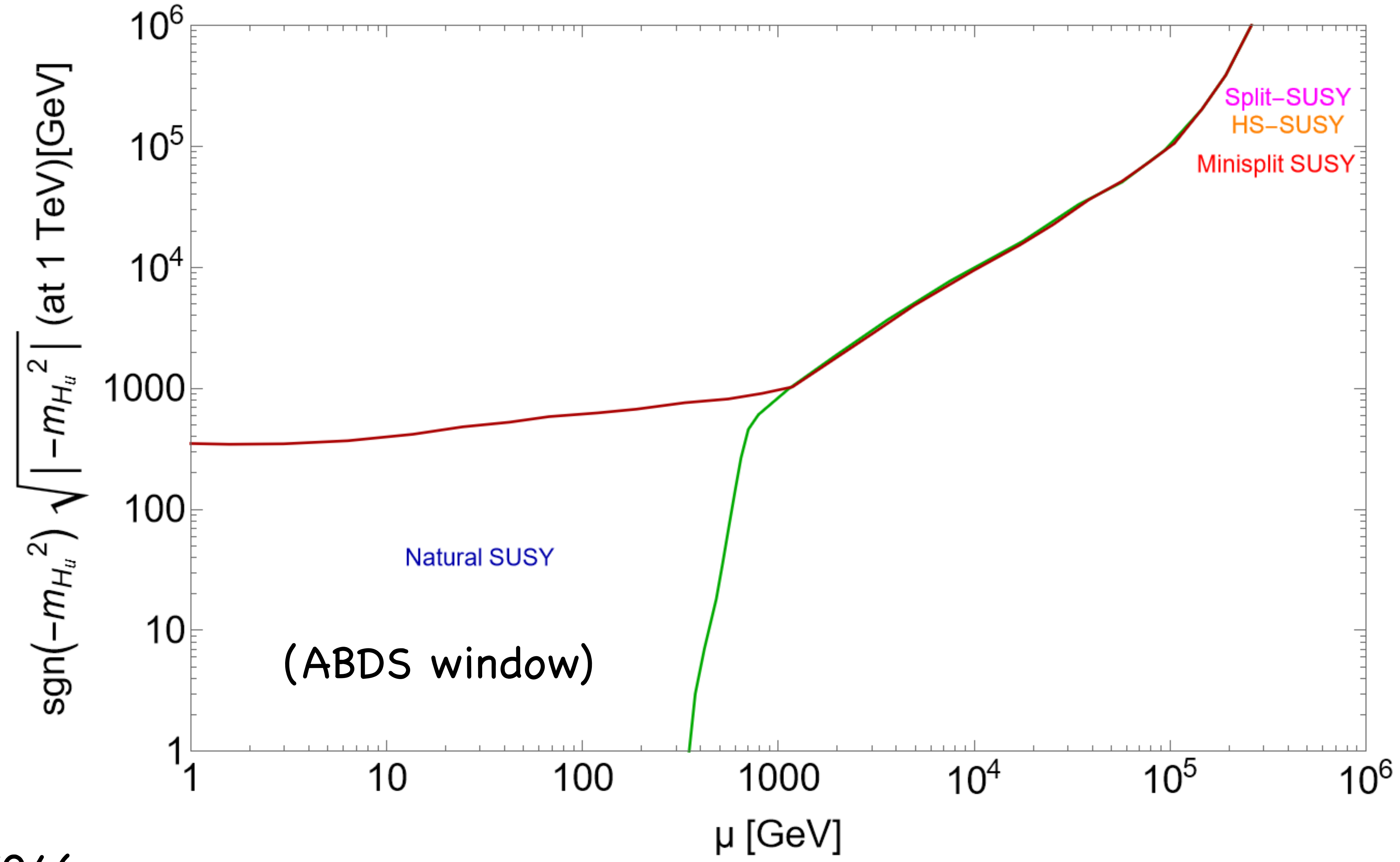
why natural SUSY more likely than finetuned SUSY from landscape



ABDS window in
mu vs. mHu plane

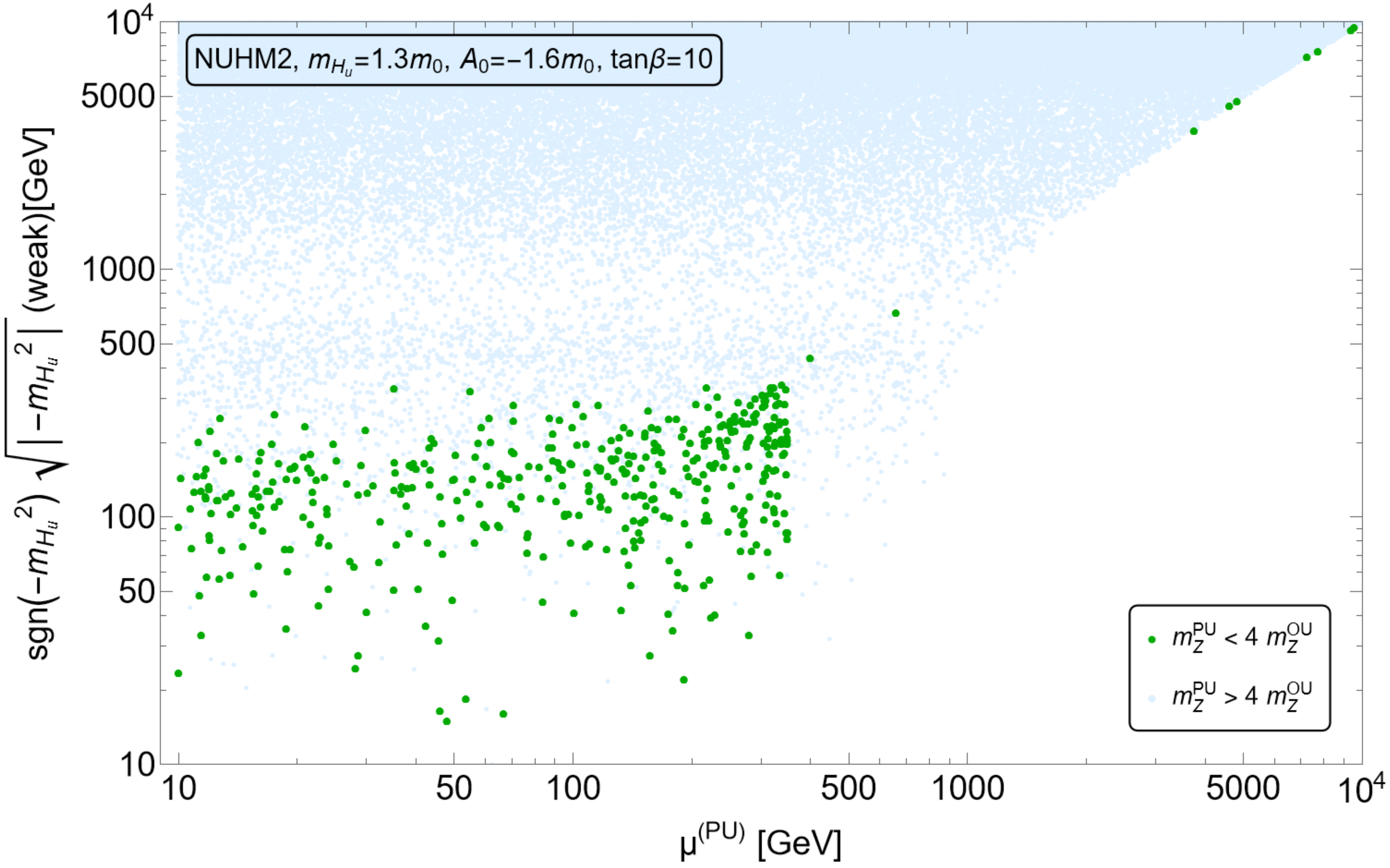
volume of scan space
shrinks to teensy values for
finetuned SUSY

radiatively-driven natural SUSY
(RNS) most likely to emerge
from landscape!



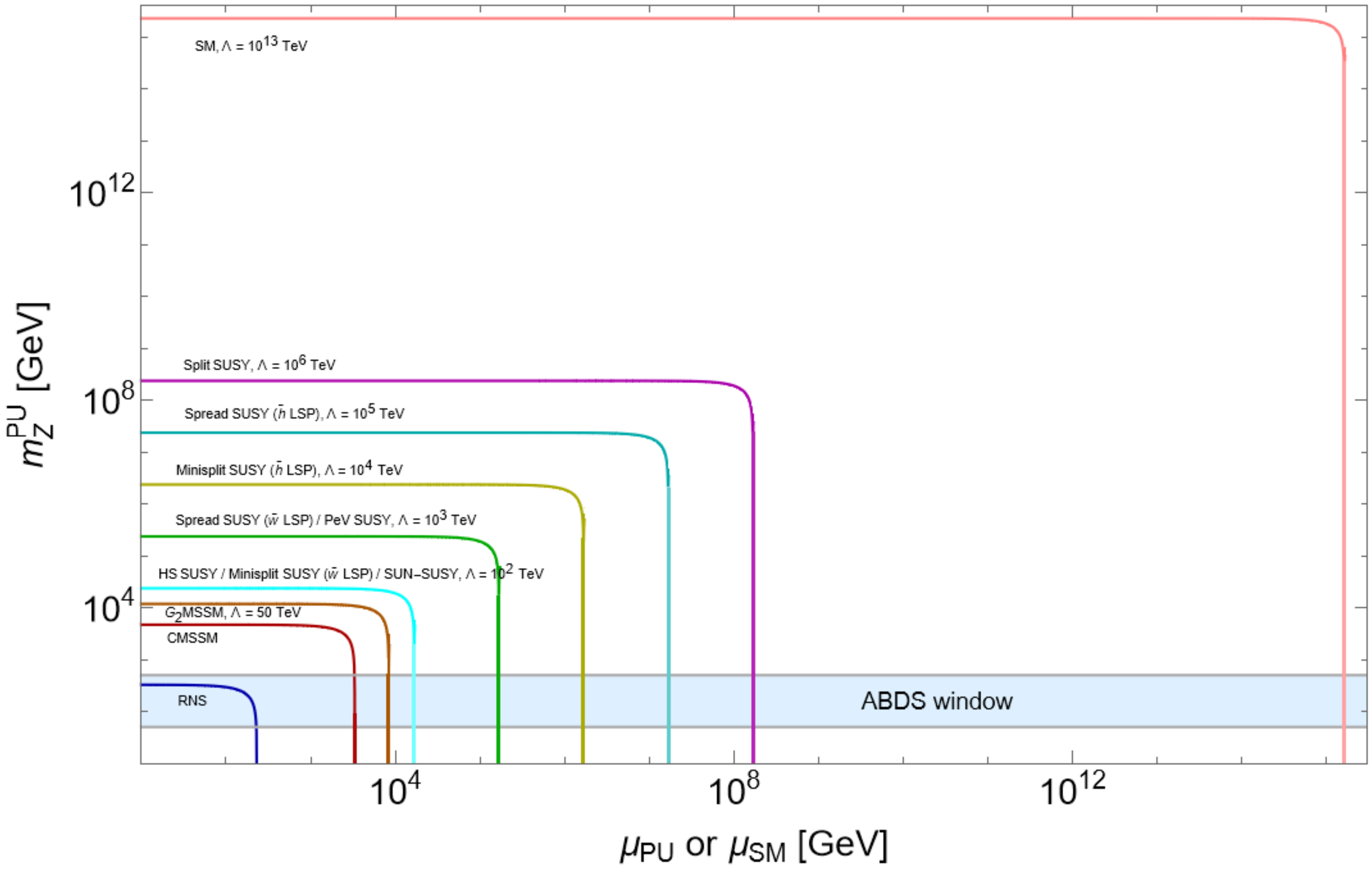
HB, Barger, Martinez, Salam, arXiv:2202.07046

toy multiverse selection shows it is rare to
generate finetuned solutions compared to natural spectra



no mu scale preferred: mu distributed uniformly across the decades

'length' of range of mu s.t. mZ(PU) within ABDS window can be simple measure of probability

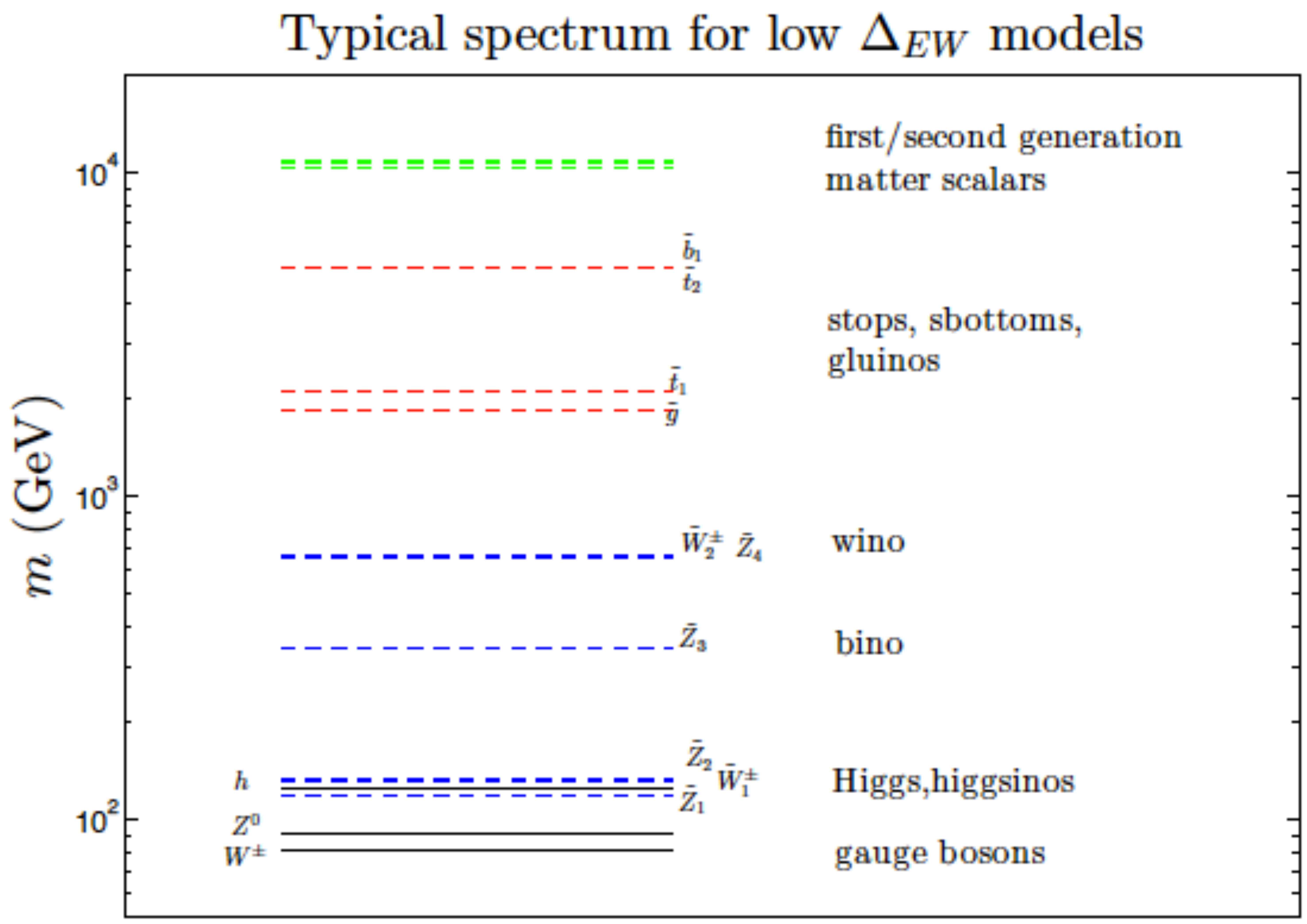


HB, Barger, Martinez, Salam, arXiv:2206.14839

computed relative probabilities for
various natural and unnatural SUSY models

model	$\bar{m}(1,2)$	$\bar{m}(3)$	gauginos	higgsinos	m_h	P_μ
SM	-	-	-	-	-	$7\cdot 10^{-27}$
CMSSM ($\Delta_{EW}=2641$)	~ 1	~ 1	~ 1	~ 1	$0.1-0.13$	$5\cdot 10^{-3}$
PeV SUSY	$\sim 10^3$	$\sim 10^3$	~ 1	$1-10^3$	$0.125-0.155$	$5\cdot 10^{-6}$
Split SUSY	$\sim 10^6$	$\sim 10^6$	~ 1	~ 1	$0.13-0.155$	$7\cdot 10^{-12}$
HS-SUSY	$\gtrsim 10^2$	$\gtrsim 10^2$	$\gtrsim 10^2$	$\gtrsim 10^2$	$0.125-0.16$	$6\cdot 10^{-4}$
Spread ($\tilde{h}$LSP)	10^5	10^5	10^2	~ 1	$0.125-0.15$	$9\cdot 10^{-10}$
Spread ($\tilde{w}$LSP)	10^3	10^3	~ 1	$\sim 10^2$	$0.125-0.14$	$5\cdot 10^{-6}$
Mini-Split ($\tilde{h}$LSP)	$\sim 10^4$	$\sim 10^4$	$\sim 10^2$	~ 1	$0.125-0.14$	$8\cdot 10^{-8}$
Mini-Split ($\tilde{w}$LSP)	$\sim 10^2$	$\sim 10^2$	~ 1	$\sim 10^2$	$0.11-0.13$	$4\cdot 10^{-4}$
SUN-SUSY	$\sim 10^2$	$\sim 10^2$	~ 1	$\sim 10^2$	0.125	$4\cdot 10^{-4}$
G_2MSSM	$30-100$	$30-100$	~ 1	~ 1	$0.11-0.13$	$2\cdot 10^{-3}$
RNS/landscape	$5-40$	$0.5-3$	~ 1	$0.1-0.35$	$0.123-0.126$	1.4

Table 1: A survey of some unnatural and natural SUSY models along with general expectations for sparticle and Higgs mass spectra in TeV units. We also show relative probability measure P_μ for the model to emerge from the landscape. For RNS, we take $\mu_{min}=10$ GeV.



There is a Little Hierarchy, but it is no problem

$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

Conclusions

- 3rd string revolution: the landscape => CC problem, then SUSY?
- rather general arguments for power-law draw to large soft terms for SUSY in landscape
- derived value of weak scale within ABDS window
- predict m(h)~125 GeV with sparticles beyond present LHC reach
- landscape favors EW natural SUSY over finetuned
- stringy naturalness: mgluino~3 TeV more natural than mgl~300 GeV!
- LHC signatures in talk #2

A final takeaway

- ATLAS/CMS have done a good job ruling out much of the 20th century SUSY parameter space
- This has influenced the European strategy and US Snowmass/P5 reports with regard to construction of future facilities
- However, we see that ATLAS/CMS are only beginning to explore the 21st century SUSY parameter space as expected from the string landscape
- Probably need hadron collider with rs~30-50 TeV and e+e- collider with rs>2m(higgsino)