EXPECTATIONS FOR AND INTERPRETATIONS OF LHC SUPERPARTNER AND HIGGS DATA, and OF DARK MATTER

- IN A WORLD WITH AN UNDERLYING UV COMPLETION

GORDY KANE

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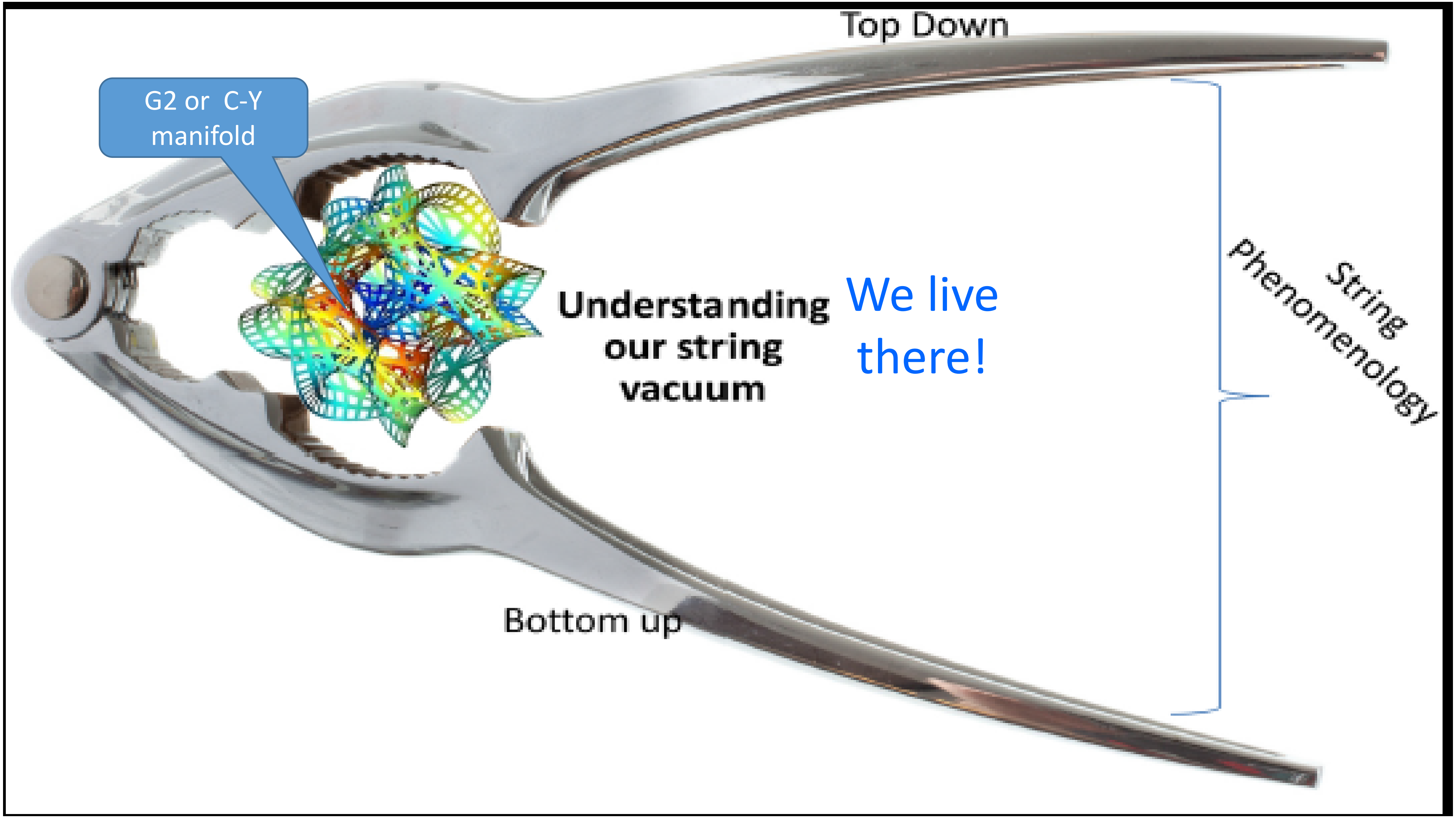
- **Most of us want a comprehensive underlying theory that includes the Standard Models of particle physics and cosmology, and is a quantum theory of GR =UV completion**

- **String theory framework provides that → nine or ten space dimensions**

- **We live in 4D ground state (vacuum)**
- **So must formulate compactified string/M-theory**

- **Significant progress in doing that over past decade**

From that point of view how do we interpret the data, and theoretical approaches???


Top Down
G2 or C-Y
manifold
Understanding
our string
vacuum
We live
there!
String
Phenomenology
Bottom up

- LHC Higgs looks like a Standard Model Higgs boson, mass 125.5 GeV AND Standard Model decays

- Naively the LHC data invites us to consider the possibility that
  the Standard Model is isolated from new physics

- Did not have to be that way!

- No gluinos yet – but predictions for gluino mass? – naïve naturalness → light gluinos – but *opposite of naturalness is having a theory* – before a few years ago no theory predicted gluino mass – now a few examples

- Presumably Higgs sector and the absence of superpartners and dark matter detection are providing major clue(s) to going beyond the Standard Model – how should we interpret them?

- Another Higgs sector clue - there is an interesting implication if you assume the discovered Higgs boson is a Standard Model one, given m_h and m_{top}
- The SM effective potential is $V=\mu^2 h^2 + \lambda h^4$
- $\lambda=0.13$ at the EW scale,
- λ runs, goes negative, well below Planck scale
- Theory unbounded from below, unstable!

So we have four clues from Higgs physics:

- Value of m_h ;
- h decay BR SM-like;
- λ_{SM} runs negative;
- Hierarchy problem

- The likely **solution** has been known for decades → **supersymmetry, 2 doublet decoupling sector with EWSB**

  [Haber and Nir 1990; Gunion and Haber 2003]

- 2 doublets tells us $m_h^{tree} \leq M_Z$

- Other four Higgs masses heavy $\sim$ multi TeV – one doublet effectively decouples – light Higgs boson has SM-like BR – one loop top-stop corrections raise mass few tens of GeV

- λ is positive definite for supersymmetry so no vacuum instability

- Usual hierarchy problem solution via superpartners

We want an underlying theory with such a Higgs sector

Some are known from string/M-theory

- For example, consider 11 D M-theory (Witten, 1995), compactified near Planck scale

  - my work focused there

- Compactify on 7D manifold having holonomy G_2 – then automatically N=1 supersymmetric 4D quantum field theory (Papadoupoulos, Townsend 1995)

11-7=4

I'll show some technical aspects quickly – enough to see real calculations were done

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS

Earlier work 1995-2004 (stringy, mathematical) ; Witten 1995

- Papadopoulos, Townsend th/9506150, compactification on 7D manifold with G_2 holonomy → resulting quantum field theory has N=1 supersymmetry!!!
- Acharya, hep-th/9812205, non-abelian gauge fields localized on singular 3 cycles
- Acharya and Witten, hep-th/0109152, chiral fermions supported at points with conical singularities (massless quarks and leptons)
- Beasley and Witten, hep-th/0203061, generic Kahler form
- Lukas, Morris hep-th/0305078, generic gauge kinetic function

Particles and forces!

- Basic framework established – powerful, rather complete

We started in 2005 – since LHC coming, focused on moduli stabilization, supersymmetry breaking, etc → LHC physics, Higgs physics, dark matter etc

[**Bobby Acharya (Professor, King's College London)**, Bobkov, Piyush Kumar, Kuflik, Shao, Watson, Lu, Zheng, S.Ellis, Perry – over 20 papers, over 500 arXiv pages]

All moduli stabilized in fluxless sector (Acharya), de Sitter vacuum – fluxes (like EM fields in extra dimensions) have mass dimensions, so $\sim$ compactification scale – so hard to get TeV physics

Soft supersymmetry breaking from RGE running, simultaneously generates potential for moduli

Calculated the full high scale supersymmetry soft-breaking Lagrangian → radiative electroweak symmetry breaking,

→ precise ratio of M_h/M_Z , and Higgs decay predictions (in decoupling sector) – 2011, before data

No adjustable parameters since using generic needed functions, Kahler potential and gauge kinetic function

A set of Kahler potentials, consistent with G_2 holonomy and known to describe some explicit examples, was given by Beasley-Witten th/0203061; Acharya, Denef, Valandro th/0502060, with

$$K = -3\ln(4\pi^{1/3} V_X)$$

$$V_X = \prod_{i=1}^{N} s_i^{a_i}, \quad \text{with} \quad \sum_{i=1}^{N} a_i = 7/3$$

The gauge kinetic functions here are integer linear combinations of all the moduli (Lukas, Morris th/0305078),

$$f_k = \sum_{i=1}^{N} N_i^k \, z_i \, .$$

gauge kinetic function

SUPERPOTENTIAL

Complex moduli

$$W = \sum_{k=1}^{M} A_k e^{ib_k f_k} \sim \sum_k e^{ib_k \sum N_i^k z_i}$$

Keep two terms – enough to find solutions with good properties such as being in supergravity regime, simple enough to do most calculations semi-analytically (as well as numerically) – check some things with more terms numerically

Imagine expanding exponential – all terms get interactions

DE SITTER VACUUM, GAUGINO MASSES ALWAYS SUPRESSED

Standard Model gauge kinetic function

$$M_{1/2} \sim \Sigma\, K_{mn}\, F_m\, \partial_n\, f_{SM}$$

-- f_{SM} doesn't depend on chiral fermions, whose F-term gives the largest contribution to supersymmetry breaking (2006)

-- $F_{\text{chiral fermion}} \sim V_7$ but $F_{\text{moduli}} \sim V_{3,}$ $V_7 >> V_3$

-- matter Kahler potential does not enter, so results more reliable

-- moduli dependence is entirely in volume factors, so same for all G2 manifolds for tree level gaugino masses

Scalar masses – squarks and M_{Hu}, M_{Hd} and trilinears

$m^2_{scalar} \approx M^2_{3/2} + V_0$ + small corrections calculable from W,K,f

V_0 is value of potential at minimum≈cosmological constant, set it to be ≈0 for any particular vacuum

***So scalar masses essentially equal to gravitino mass ~40 TeV, too heavy to see at LHC** (prediction)*

❑ From Planck scale to 50 TeV "dimensional transmutation"

Scale of gaugino condensation $\Lambda \approx M_{pl} \exp(-8\pi^2/3Qg^2) \approx \exp(2\pi \mathrm{Im}f/3Q)$

where $\mathrm{Im}f = \sum N_i s_i$

Q is rank of condensing gauge group

With Q-P=3, $\mathrm{Im}f = 14Q/\pi \rightarrow \Lambda \approx M_{pl}\, e^{-28/3} \approx 2\times10^{14}$ GeV, so

$\Lambda \approx 10^{-4} M_{pl} \approx$ *scale at which supersymmetry broken*

Then $W \sim \Lambda^3 \sim 10^{-12} M_{pl} \sim 2\times10^6$ GeV = 2×10^3 TeV. Also expect inverse volume factor $1/V_7$ from $e^{K/2}$ so

$$M_{3/2} \approx e^{K/2}\, W \sim 40\ \text{TeV}$$

Note Imf/Q not explicitly dependent on Q – still dependent because of V_7 and P_{eff}, but weakly – so Λ rather well determined

EWSB depends on μ parameter too

- Witten gave solution to μ problem in compactified M theory – showed there was a generic matter symmetry that gave $\mu=0$
  - Hep-ph/0201018
- His argument fails when moduli stabilized since moduli are matter too
- We cannot calculate μ after moduli stabilized, but if moduli vev's vanish get back $\mu=0$, and expect $\mu \approx M_{3/2}$ from supersymmetry breaking, so expect

$$\mu \approx \langle \text{mod vev} \rangle M_{3/2}$$

- Typical moduli vevs $\sim M_{pl}/20$, so finally expect $\mu \approx 2$ TeV
- M_{hu} runs down fast so it is also $\sim$ TeV
- Quality of calculations not good enough to prove no little hierarchy problem, but maybe

COMPACTIFIED M-THEORY RESULTS – ALL SIMULTANEOUS

- Moduli are stabilized

- Supersymmetry breaking is automatic, and gravity-mediated

- The gravitino mass approximately calculated, from Planck scale input. It is about 40 TeV

- Scalars of order the gravitino mass (squarks, Higgs soft terms, etc) – so no squarks at LHC. An early prediction (2006).

- Gaugino masses are suppressed (by volume ratios), a factor of order 40, for general reasons – 2006

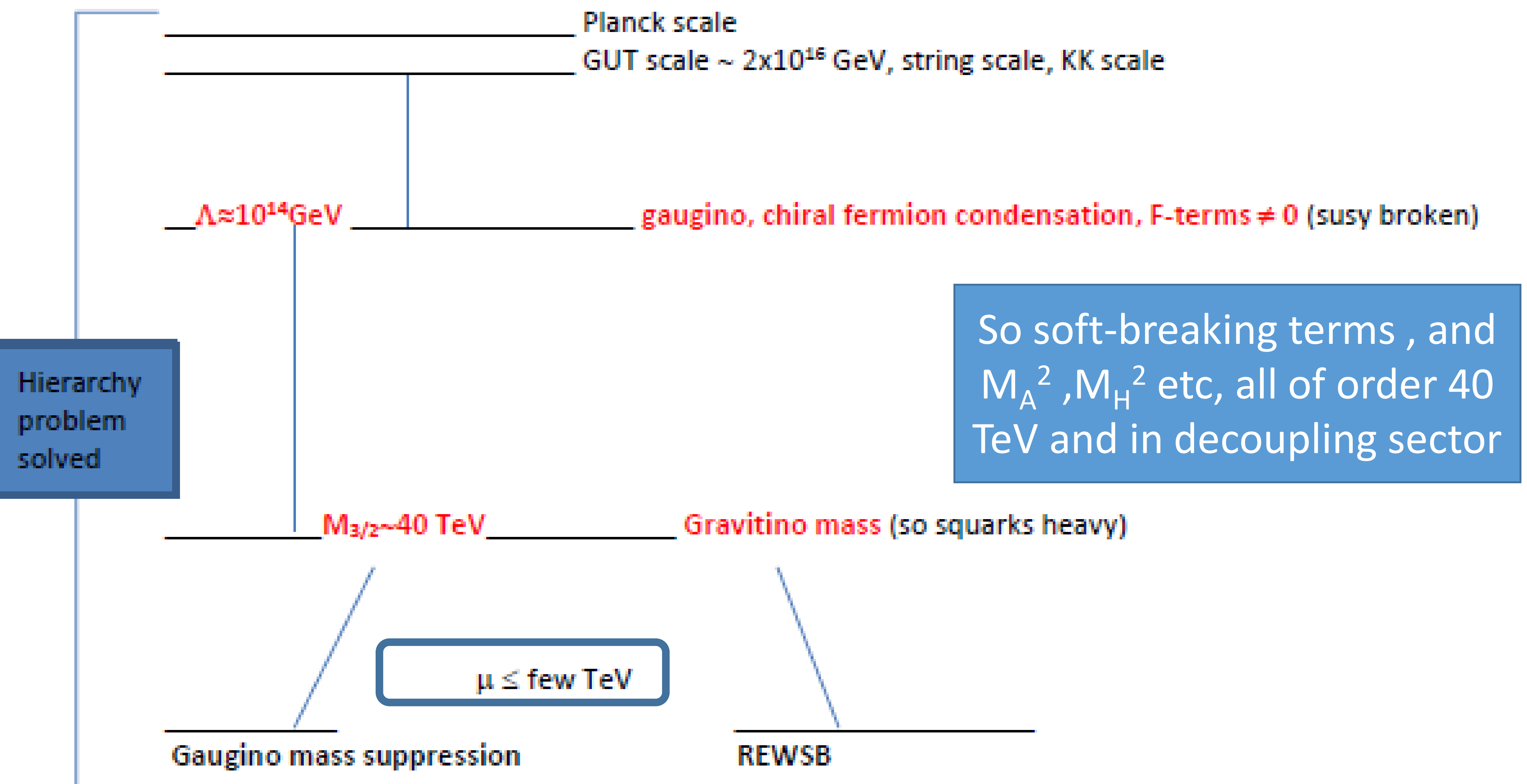
- The Higgs boson mass *and* decay BR were anticipated before the data.

- The hierarchy problem is solved as usual via supersymmetry – little hierarchy problem similar to usual one,

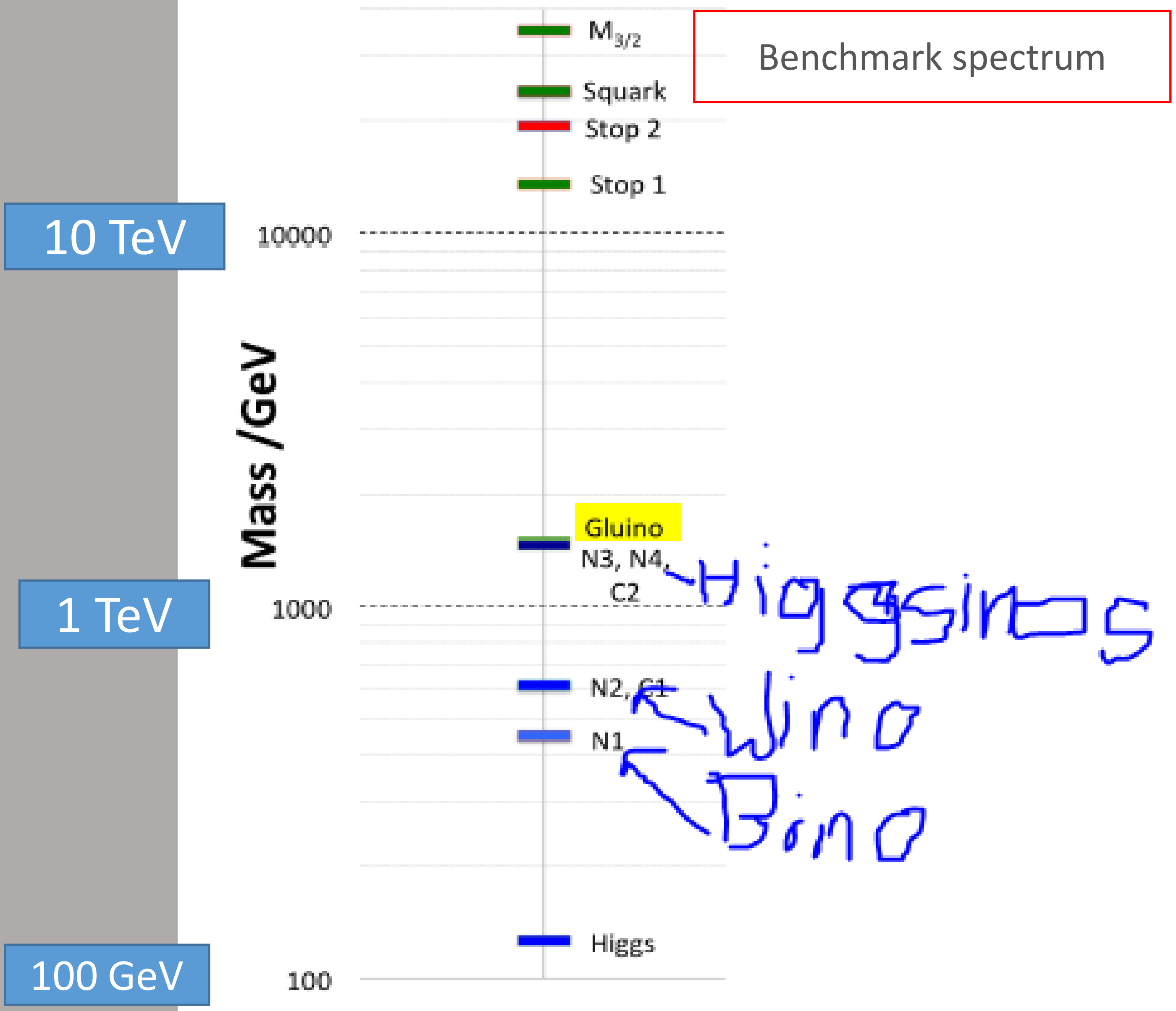
  -- not worse because of 40 TeV – possibly solved but can't tell because of sensitivity

- The dark matter, and axions, come from decay of the lightest modulus.
- Non-thermal cosmological history via moduli decay shortly before BBN.
- Axions are stabilized, and provide a solution to the strong CP problem.
- Standard Model is not yet embedded, but masses are hierarchical so encouraging
- Gauge coupling unification and proton decay are all right
- There are no flavor problem, and weak CP violation is ok.
- EDMs are calculable. Their smallness is explained (could have been wrong), an important result.
- $\mu \approx$ few TeV – included in theory and approximately calculable.

SCALES DERIVED FROM M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM

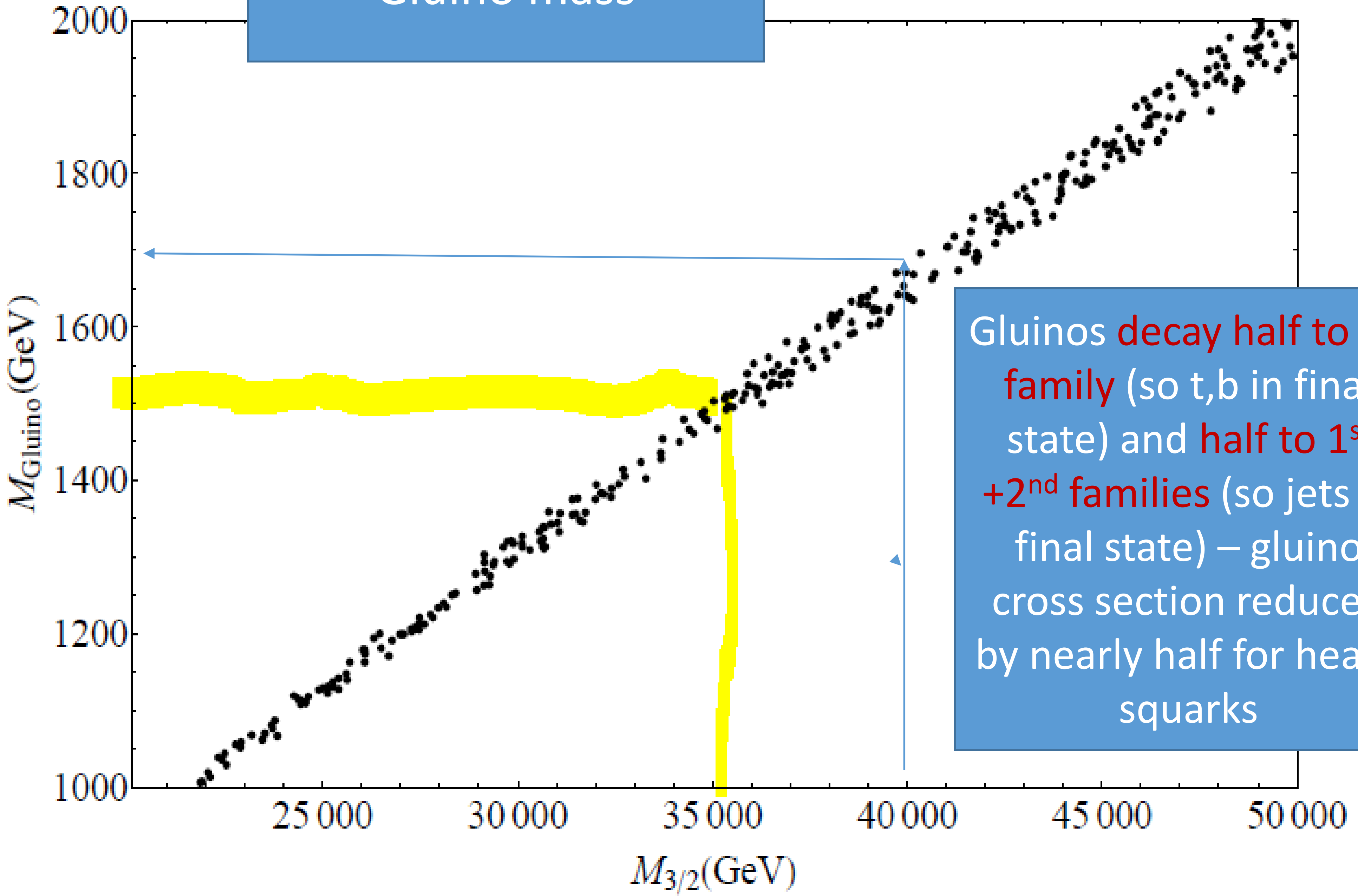


Benchmark spectrum

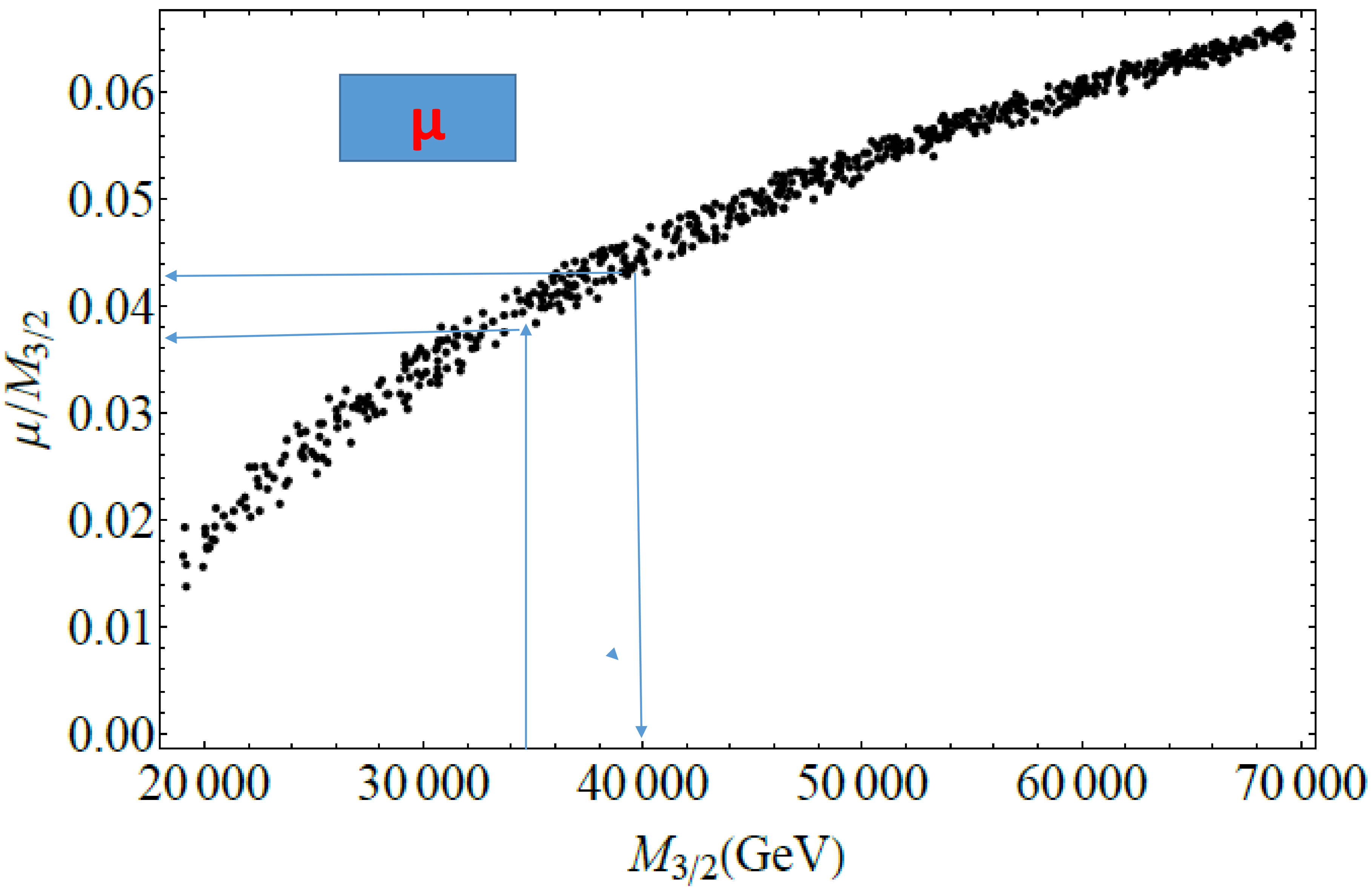


Particle	Mass (GeV)
m_0	24200
$M_{3/2}$	35000
$\tilde{q}_{L,R}$	24000
$\tilde{t}_2$	19300
$\tilde{t}_1$	13500
$\tilde{b}_2$	23900
$\tilde{b}_1$	19300
$\tilde{g}$	1500
χ_1^0	450
χ_2^0	614
χ_3^0	1460
χ_4^0	1460
$\chi_1^\pm$	614
$\chi_2^\pm$	1460
h	125.2[2]

Gluino mass

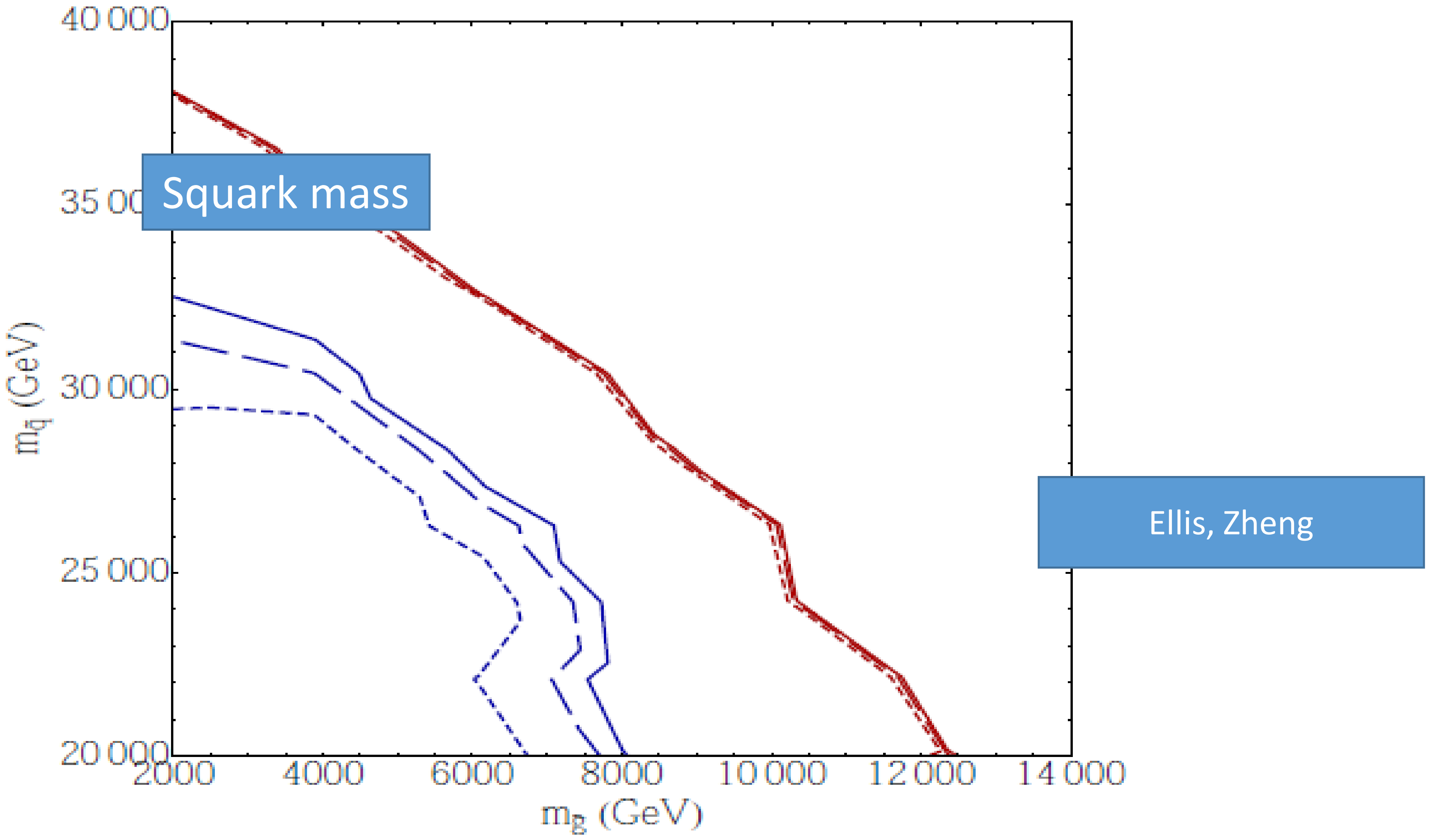


Gluinos decay half to 3rd family (so t,b in final state) and half to 1st +2nd families (so jets in final state) – gluino cross section reduced by nearly half for heavy squarks



μ
0.06
0.05
0.04
0.03
0.02
0.01
0.00
$\mu/M_{3/2}$
20 000
30 000
40 000
50 000
60 000
70 000
$M_{3/2}$(GeV)

Squark-gluino associated production at "100 TeV"



“Recent” result – LSP not stable in string/M-theories!

B. Acharya, S. Ellis, G. Kane, B.Nelson, M. Perry, arxiv:1604.05320, PRL 117

- WIMP paradigm wrong!
- Basically - compactified string/M-theories have hidden sectors
  - some hidden sector(s) have light stable matter (e.g. as ours does)
  - lots of U(1)’s on hidden sectors
  - so kinetic mixing common, not suppressed by large masses
  - SOME hidden sector out of many will have both light matter and U(1)

→LSP generically unstable on cosmological time scales

- holds in M-theory and more generally in string theories

THIS IS FIRST TESTABLE PREDICTION OF STRING THEORY

Final remarks -1

So – LHC Higgs data behaves just as it should in world with M-theory compactified on G_2 manifold

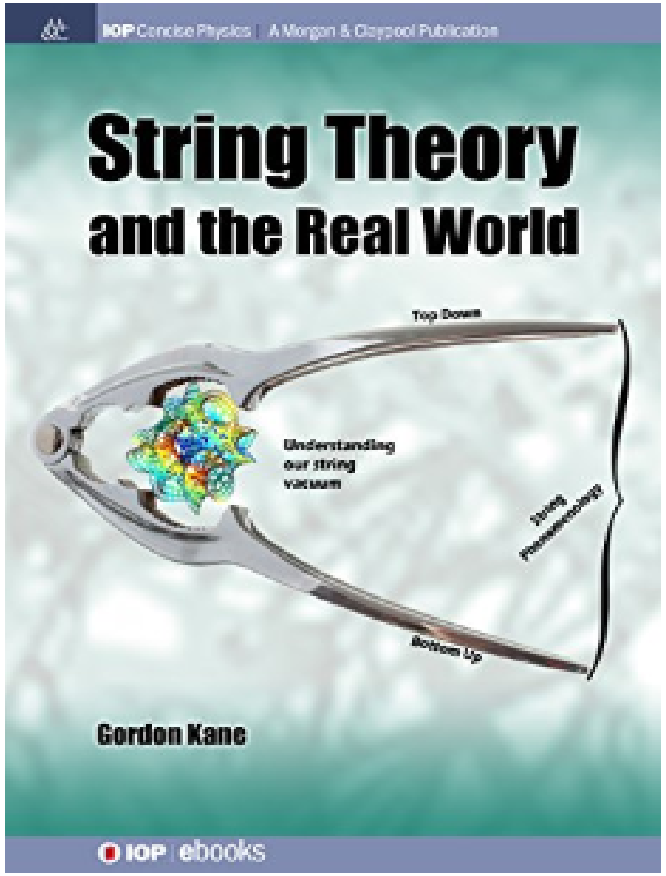
(or perhaps other string theory as well?)

- Predicts squarks, heavier Higgs states won't be seen at LHC
- Predicts h decay BR within few per cent of SM ones
- Since squarks heavy, predicts g_μ-2 data will change
- Predicts gluinos, winos will be seen at LHC in current run – need upgrades to see Higgsinos, squarks, sleptons
- Predicts DM hard to see in direct and indirect detection
- Explains and predicts much more – very testable

Final Remarks -2

- String theorists mostly study theories, not the real world
- String theory is too important to leave to string theorists
- Making a quantum theory of GR changes how we think about our world (even if we don’t care much about quantum gravity)
- Compactified string/M-theories testable, in the normal way

Look inside



String Theory and the Real World (IOP Concise Physics) Kindle Edition

by Gordon Kane (Author)

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The aim of this book is to explain why "string theory" may provide the comprehensive underlying theory that describes and explains our world, perhaps fairly soon. Although such a claim might seem controversial to many, I hope to convince the reader that after progress in recent years this is now a defendable goal, and one deserving of broad

Qualitative gravitino and gluino masses

$$W \sim \Lambda^3$$

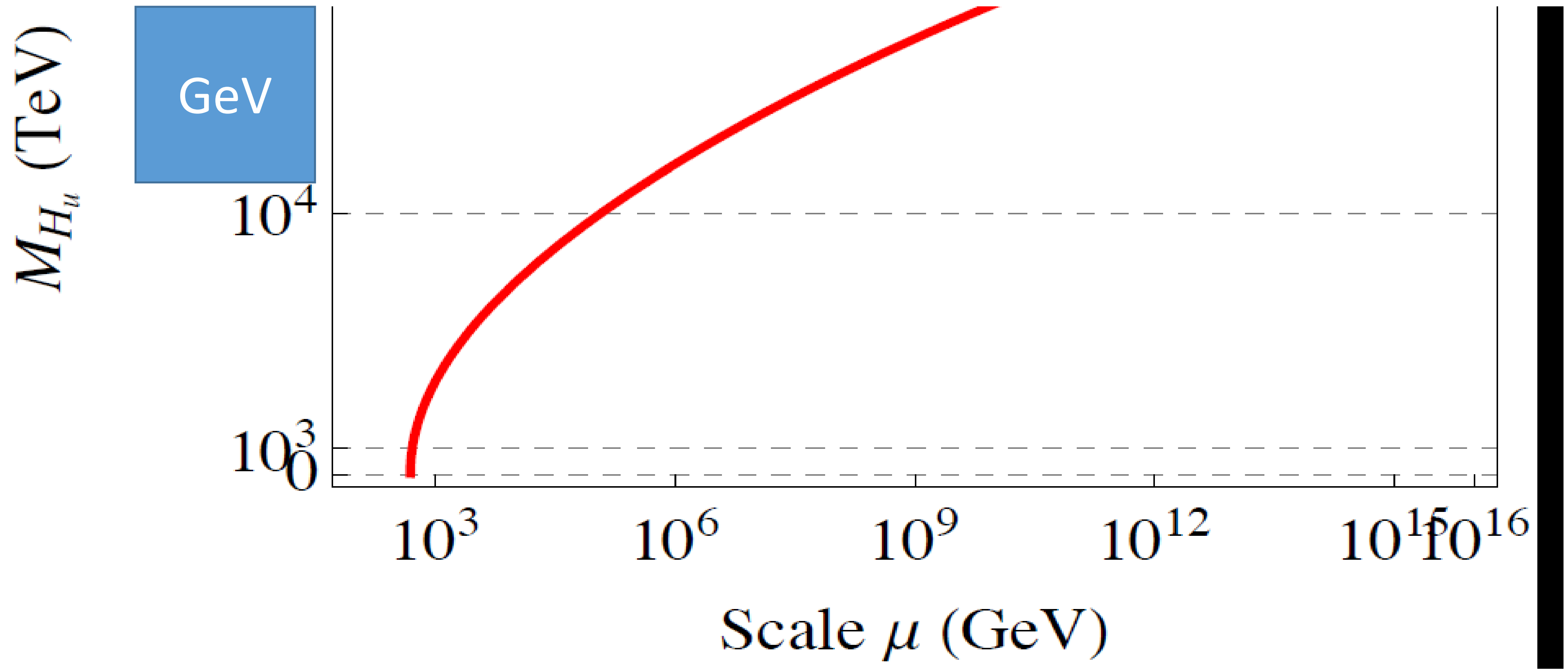
$$M_{3/2} = \frac{e^{K/2} W}{M_{Pl}{}^2} \approx \left(\frac{\Lambda}{M_{Pl}}\right)^3 \frac{1}{V_3} M_{Pl}$$

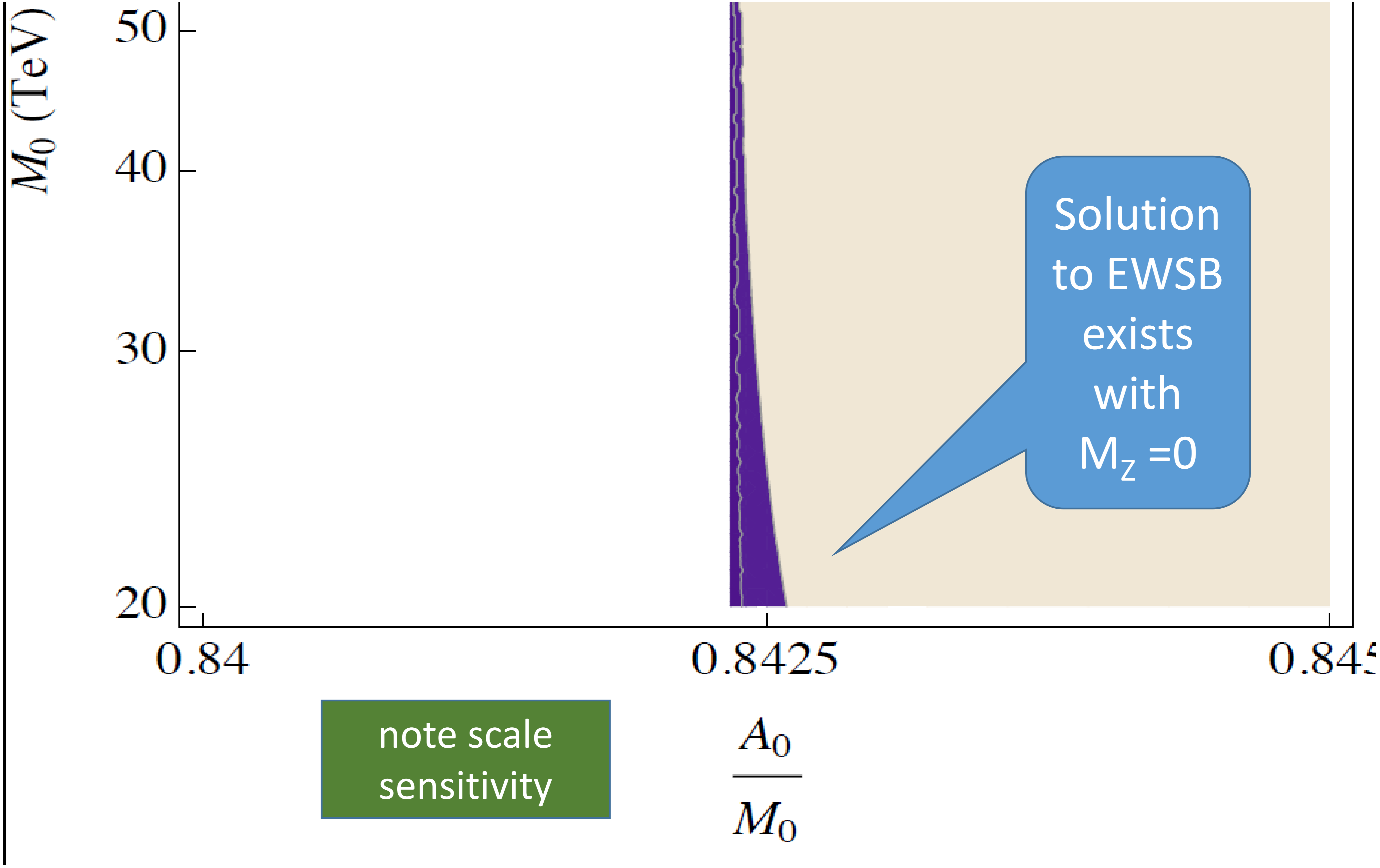
Squarks, higgs soft masses ~ 40 TeV

$$M_{gluino} \approx \left(\frac{\Lambda}{M_{Pl}}\right)^3 \frac{1}{V_3} \frac{V_3}{V_7} M_{Pl}$$

Gaugino masses ~ 1 TeV

+ anomaly mediation terms


GeV
M_{H_u} (TeV)
10^4
10^3
0
10^3
10^6
10^9
10^{12}
10^{15}
10^{16}
Scale μ (GeV)



M_0 (TeV)
50
40
30
20
0.84
0.8425
0.845
Solution to EWSB exists with M_Z =0
note scale sensitivity
$\frac{A_0}{M_0}$

Explicit string calculations demonstrating non-zero kinetic mmixing in TypeIIB compactifications, Heterotic M-theory, C-Y compactifications, heterotic orbifold models. Massive open strings stretching between D-branes give massive bi-fundamental fieldsin all supersymmetric TypeI, Type IIA, Type IIB, and generalizations to heterotic string theory, M-theory, and F-theory.

Need kinetic mixing to be generated by a Wilson line breaking. Generically expect at least one hidden sector with a GUT gauge group broken via a Wilson line.