Why Do We Have Three Families ?

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---- Cambridge (2018) ----

- We have many particles;
(**5*** + **10** +**1**)x3 + a Higgs + Gauge Fields
48 quarks/leptons

Why do we have so many particles ?

String theories → many many fields
But, we can not explains why we have three families of quarks and leptons

Composite Bound States

~ 1970-1980

If quarks and leptons are composite states, we may explain naturally why we have so many quarks and leptons

Composite quarks and leptons

It is however very difficult to generate massless composite fermions by strong dynamics.

But, we know an example for massless composite states in QCD which are Nambu-Goldstone bosons.

Massless composite bosons are easily generated

Supersymmetry give us a solution !!!

If we have **SUSY**, the NG bosons have always fermion partners which are nothing but massless composite fermions

We may identify those with quarks/ leptons

Buchmuller, Peccei, Love , Yanagida (1982)

A solution to a fundamental problem

Family Problem

- Why the quarks/leptons are **5*** + **10** of SU(5) ?
- Why we have three families ?
- What determines their masses ?

Quasi Nambu-Goldstone Fermions

Buchmuller, Love, Peccei and Yanagida (1982)

- NG bosons are always accompanied by massless fermions in supersymmetric non-linear sigma model ; G → H
- Properties and number of NG bosons are determined by a given G/H
- We identify the quasi NG fermions with the observed quarks and leptons

- NG chiral multiplets are given by G/H and hence for a given G/H we can determine properties and number of quasi NG fermions , that is, quarks and leptons

We can answer to one of the most fundamental questions in particle physics;

Why do we have three families ?

Search for G/H

- G/H must be Kahler manifold in SUSY theories
- SU(6)/SU(5)xU(1) → NG multiplet =**5***
- SO(10)/SU(5)xU(1) → NG multiplet = **10**
- E_6/SO(10)xU(1) → NG multiplet =**16** of SO(10); **16** = **5*** + **10** +**1** (one family)
- Exceptional groups are very interesting to have family structure !

- E_7/SU(5)xU(1)^3→

  NG multiplets = 3x(**5***+**10**+**1**) + **5**

  Three families, Kugo and Yanagida (1983)

E_8/SU(5)xU(1)^4 →

NG multiplets = 4x(**5***+**10**+**1**) + 1x(**5**+**10***+**1**) +…

Three families !

We concluded the maximal number of families is 3 !!!

(E_8 is the maximal exceptional group)

SUSY Non-Linear Sigma Model

- G/H must be a Kahler (complex) manifold

⇓

Nambu-Gldstone multiplets are Chiral

The simplest example is CP^(1) =SU(2)/U(1)

The NG multiplet is phi(+1)

We do not have phi(-1)

SU(2) generators: **T, X^+, X^-**

[T,X^+] = X^+, [T,X^-]=-X^-, [x^+,X^-] =2T

One NG chiral multiplet **; phi(+1)**

[T,phi]=+phi, [X^+, phi]= phixphi, [X^-,phi]=1

SU(2) invariant Kahler potential ;

K= log(1+ phixphi*)

K → K + phi + phi*

Integration of ¥theta shows invariance !

E_7 has 133 generators;

T^i_j (**63**) +E_{ijkl} (**70**) of **SU(8)**

Consider the Kahler manifold E_7/ SU(5)xSU(3)xU(1)

The broken generators are

T^a_i (**5*,3**); E_{abij} (**10, 3***); E_{ijkl} (**5,1**) and their conjugates

NG multiplets are

phi(**5*, 3**, +2) + phi(**10, 3***, +1) + phi(**5,1**,+3)

We should add a **X(5*,1)** multiplet to cancel non-linear sigma model anomalies

We have massless three families of quarks and leptons !!!

A larger manifold E_7/SU(5)xU(1)xU(1)xU(1)

E_7/E_6xU(1) → NG multiplets = 5* + 5* + 10 + 1 + 1 + 5

E_6/SO(10)xU(1) → NG multiplets = 5* + 10 +1

SO(10)/SU(5)xU(1) → NG multiplets = 10

We have three families of **5*** + **10** + **1 !!!**

1 is the right-handed neutrino

Mass hierarchy

Explicit breaking of E_7 gives Yukawa couplings;

Suppose hierarchy in the explicit breaking as
E_7→E_6→SO(10) → SU(5)

We obtain the mass hierarchy as

m_t : m_c : m_u = 1 : epsilon^2 : epsilon^4
m_b : m_s : m_d = 1 : epsilon : epsilon^3

We have a large neutrino mixing !

Is the NG hypothesis consistent ?

Why E_7 ?

Is the NG hypothesis consistent ?

- The squarks and sleptons are all massless at the GUT scale
- The Higgs multiplets are NOT NG multiplets and they have soft SUSY breaking masses of the order of m_3/2 ~ 100 TeV
- Higgs loop diagrams give negative soft masses^2 for squarks and sleptons (tachyonic)
- ***Our vacuum is no longer stable !!***

If the soft SUSY breaking masses^2 of Higgs bosons are negative, the masses^2 of squarks and sleptons are positive !!!

Yin, Yokozaki (2016)

Higgs bosons have positive masses^2

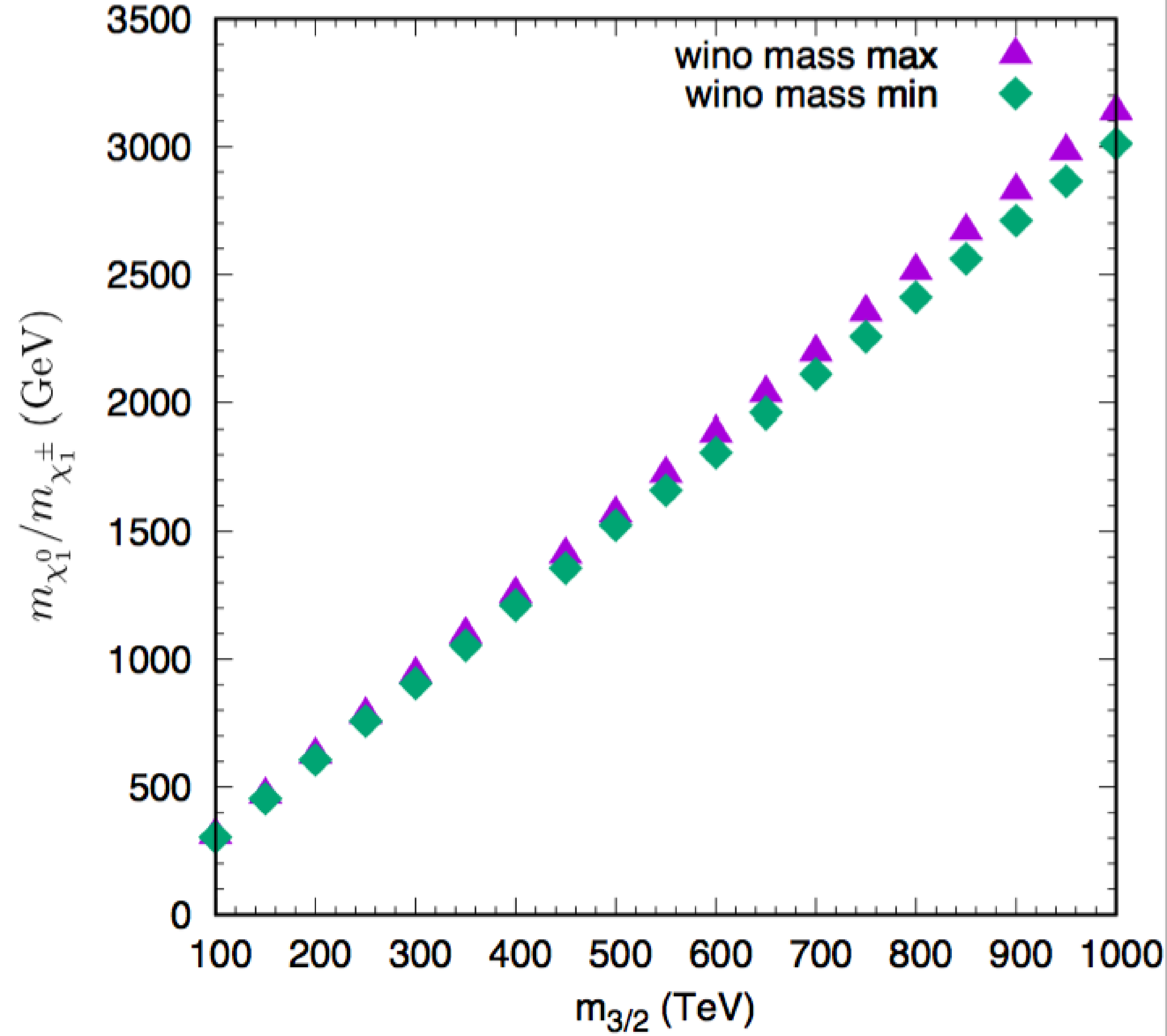
=|¥mu|^2 +m^2(soft) >0

Our Vacuum is Stable !!!

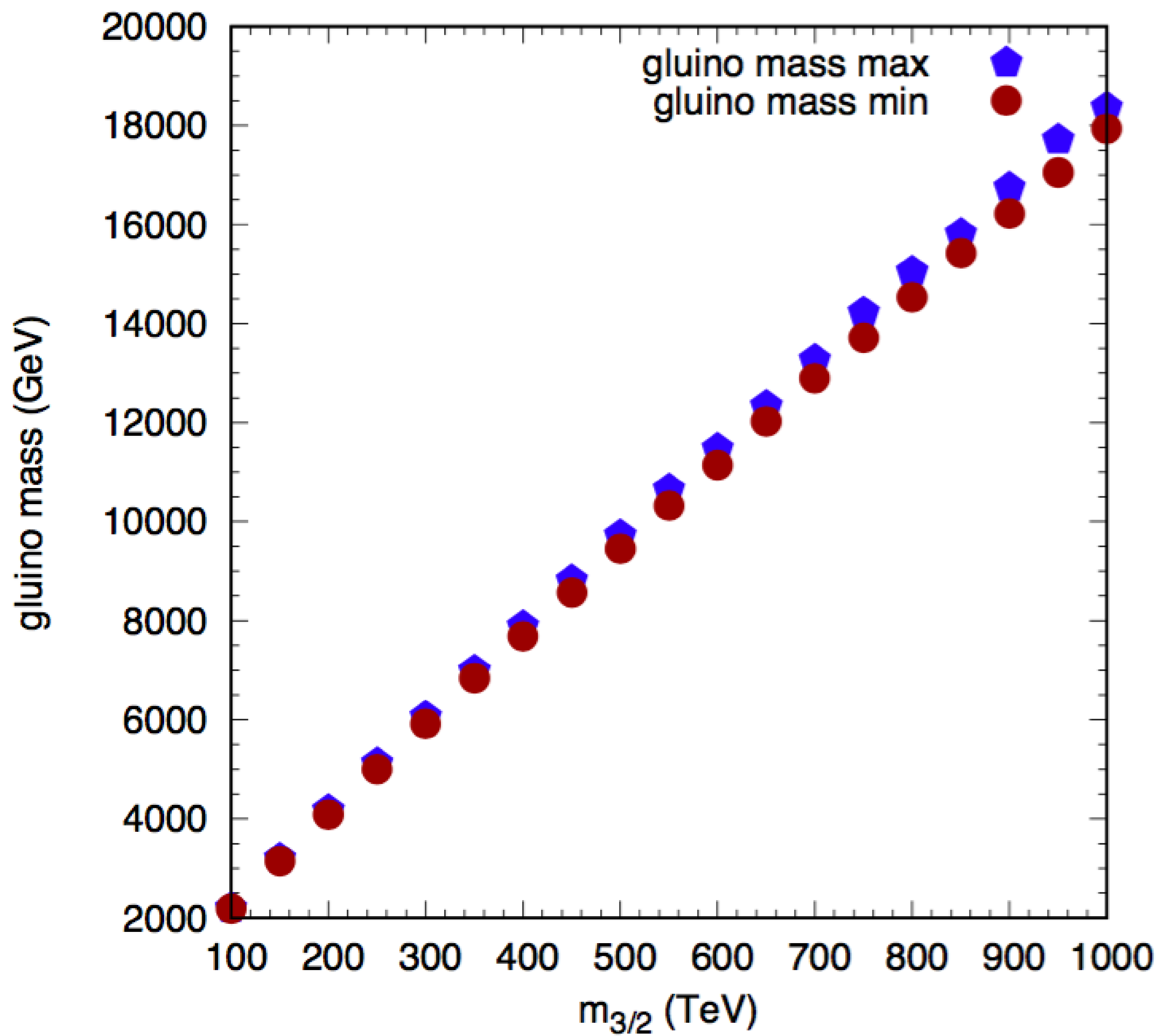
Stop mass = O(10) TeV explaining the Higgs boson mass =125 GeV

Squark (u,d,s,c) and slepton masses = O(1) TeV, since their Yukawa couplings are small

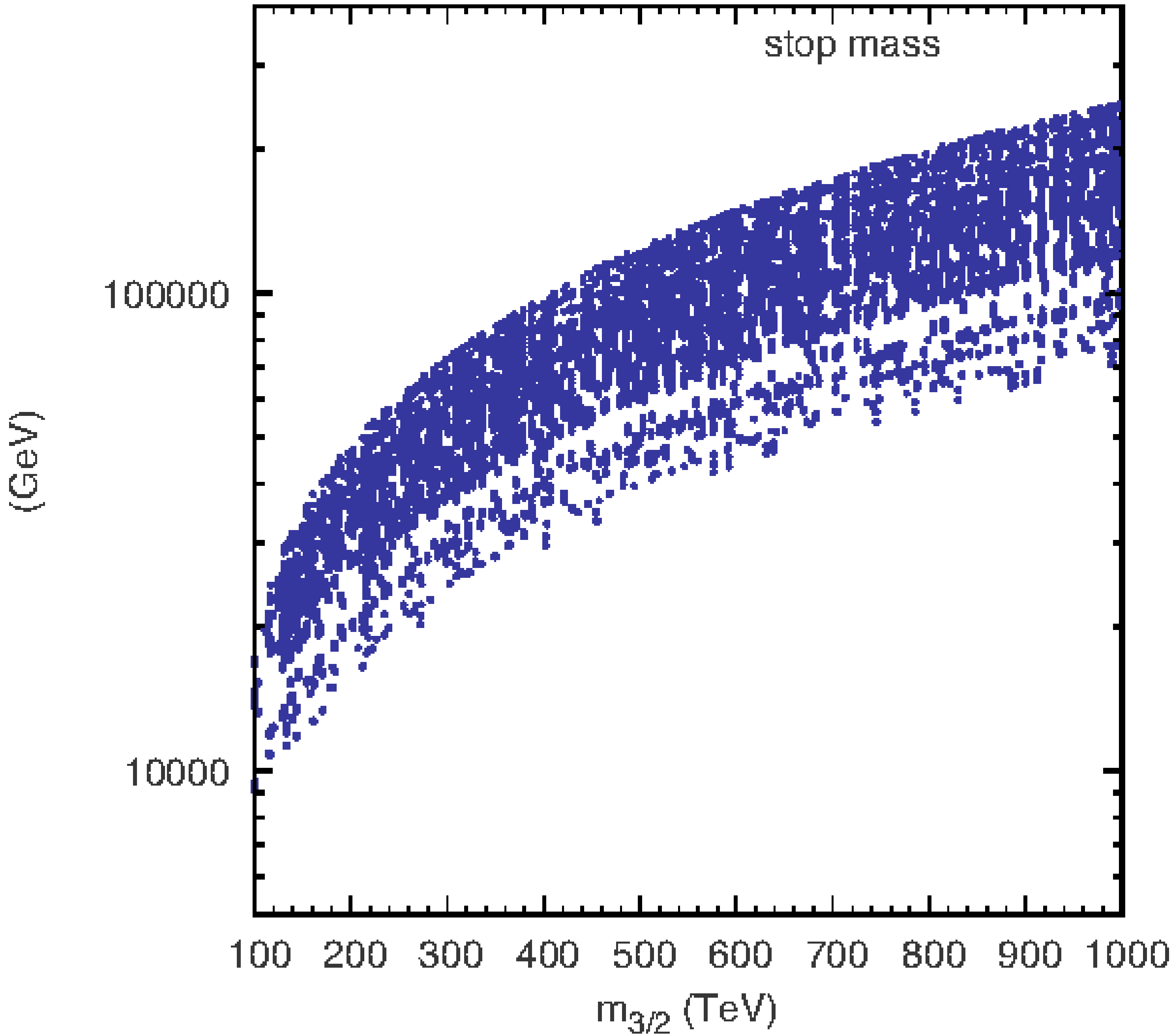
There is a parameter region where we can explain the muon g-2 anomaly



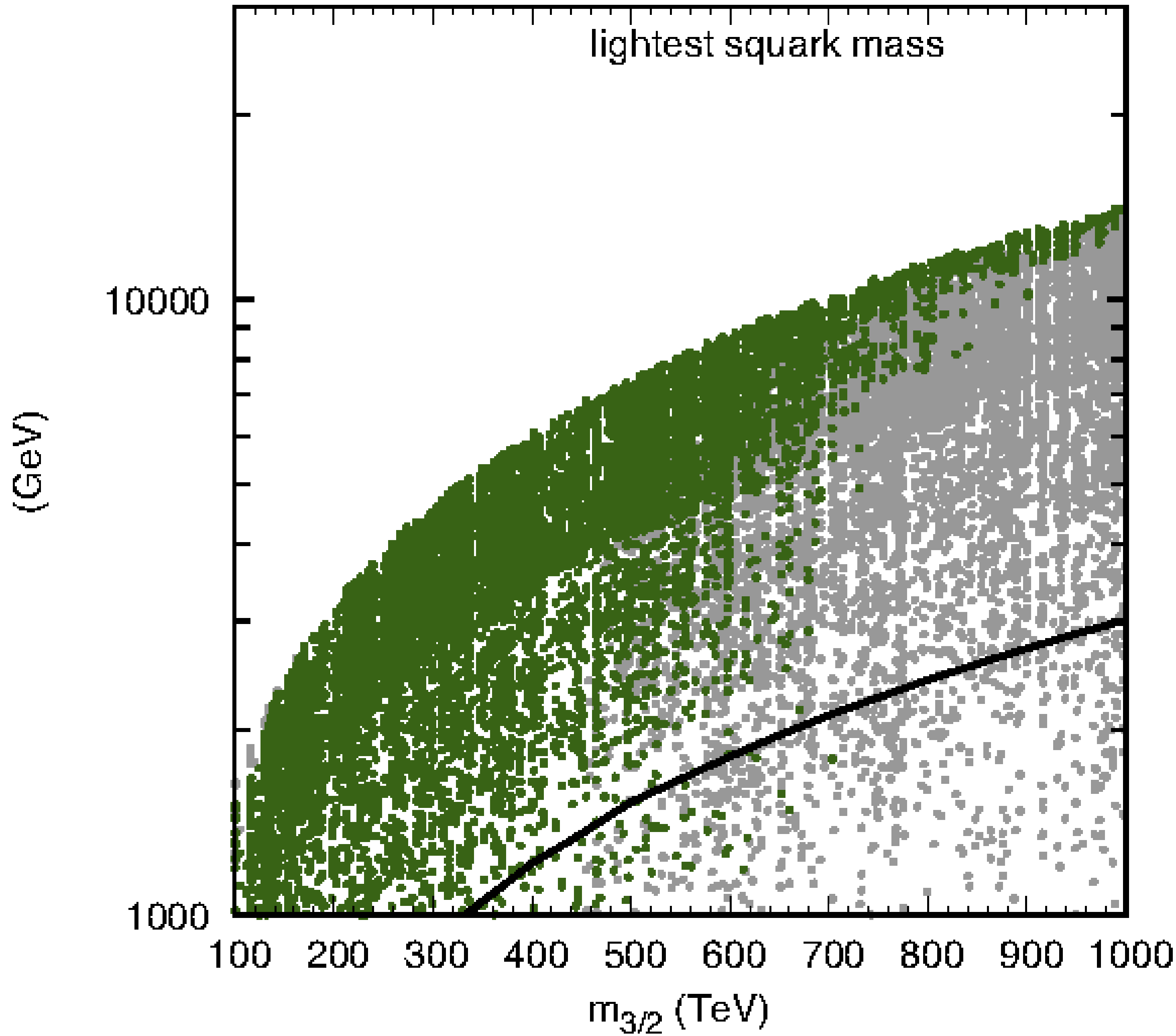
wino mass max
wino mass min
$m_{\chi_1^0}/m_{\chi_1^\pm}$ (GeV)
$m_{3/2}$ (TeV)
0
500
1000
1500
2000
2500
3000
3500
100
200
300
400
500
600
700
800
900
1000



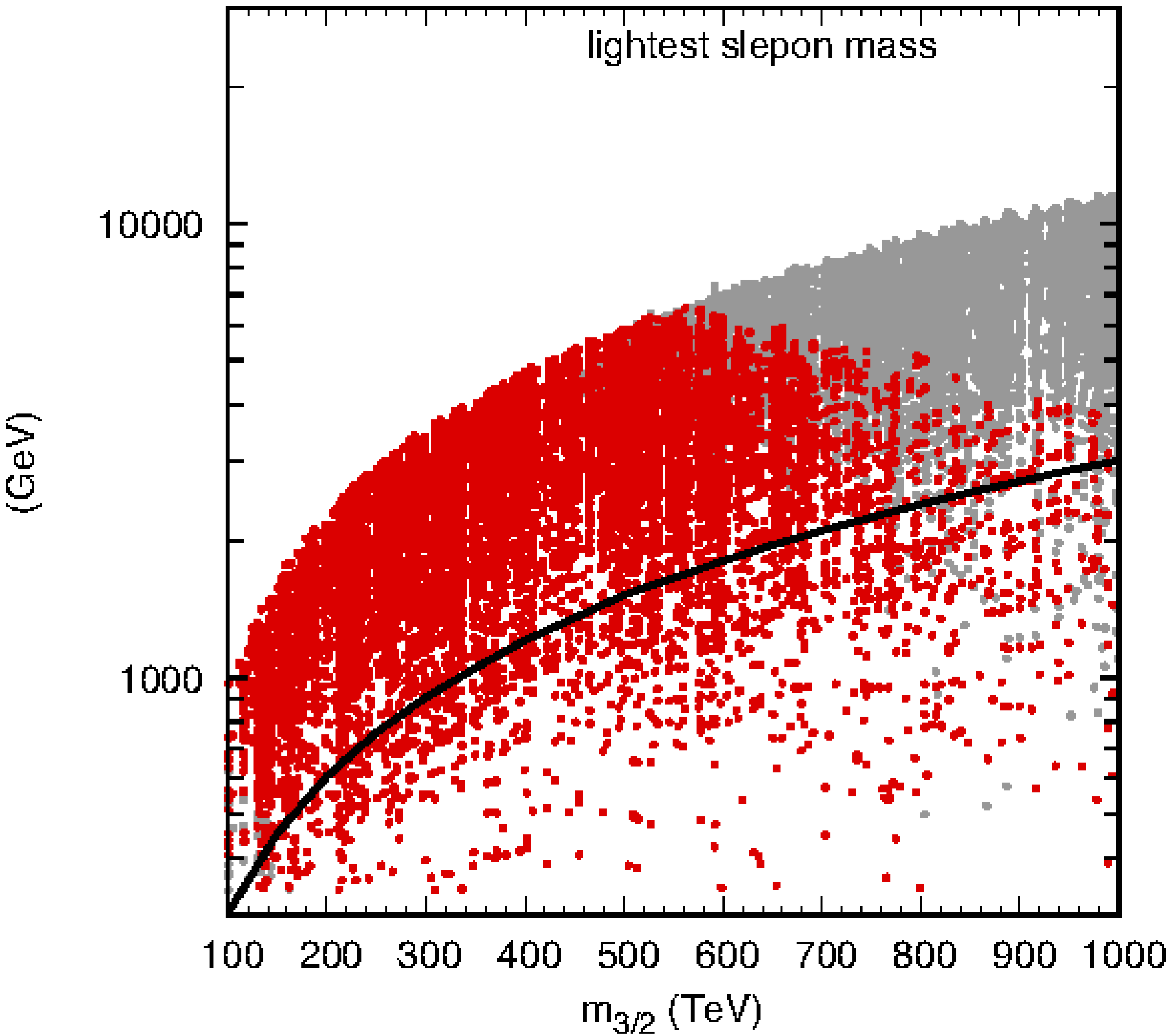
gluino mass max
gluino mass min
gluino mass (GeV)
m3/2 (TeV)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
100
200
300
400
500
600
700
800
900
1000



stop mass
100000
10000
(GeV)
100 200 300 400 500 600 700 800 900 1000
$m_{3/2}$ (TeV)



lightest squark mass
10000
1000
(GeV)
100
200
300
400
500
600
700
800
900
1000
m3/2 (TeV)



lightest slepon mass
10000
1000
(GeV)
100
200
300
400
500
600
700
800
900
1000
m3/2 (TeV)

The Nambu-Goldstone hypothesis for squarks and sleptons is consistent with all observations so far

Yanagida, Yin, Yokozaki (2016)

Why Does Nature Choose E_7 ?

N=8 Supergravity

Gravity multiplet; one graviton (2), 8 gravitinos (3/2), 28 vector bosons (1)
56 Majorana spinors (1/2), 70 real scalar boson (0)

70 scalar boson = Nambu-Goldston bosons on E_{7,7}/SU(8)

Cremmer, Julia (1978)
De Wit, Nicolai (1981)

The maximal subgroup of E_7 is SU(8) :

E_7 generators (133) = **T^i_j** (63) **+ E_{I,j,k,l}** (70)

SU(8) generators (i,j=1-8)

E_7/SU(8) has 70 NG bosons !!

This hidden E_{7,7} may be the origin of our effective E_7 ?

When N=8 → N=1 SUSY , G/H must be a Kahler manifold
But, E_7/SU(8) is NOT a Kahler manifold

We need rethinking

N=8 supergravity has a local SO(8) symmetry
and a hidden local SU(8) symmetry Nicolai (1982)

Let us assume some of the symmetries survive the breaking of the N=8 supergravity down to N=1 supergravity

Assume [SU(2)x SU(2)] x SU(8)

A subgroup of SO(8)

Preon Model

Consider eight SU(2)-doublet preons Q^i_a, ; i=1-8 and a=1,2
and eight SU(2)'-doublet preons Q'^j_b ; J=1-8 and b=1,2

Here we have a global SU(8) x SU(8)'

Consider Mesons; M^{ij} = Q^iQ^j and M'_{ij} =Q'_iQ'_j
and superpotential W=M^{ij}M'_{ij}

We have a global SU(8)

Consider the strong coupling limit of the SU(2)xSU(2) gauge theory which has infrared fixed points

Seiberg (1996)

On the fixed point we have an enhanced global symmetry that is E_7 !!!

Dimofte, Gaiotto (2012)

This may be the origin of our E_7

8 fundamental preons Q and {¥bar Q}

The theory has an IR fixed point, on which we have an enhanced symmetry E_7

Quarks and Leptons can be identified with massless quasi-NG fermions, which are bound states of the preons

The presence of SU(8) may be a crucial in N=8 Supergravity

conclusion

- The higgs mass 125 GeV suggests high scale SUSY…….. m_3/2=100-300 TeV, m_sq=O(100) TeV and m_gluino=2-6 TeV
- But, NG hypothesis for squarks and sleptons still survive from all experimental data
- This suggests that m_sq in the 1st and 2d generations = 1-4 TeV and m_gluino=2-6 TeV which may be tested in future LHC