Why Do We Have Three Families ?

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---- TDLI (2019) ----

- 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

NG multiplets are chiral !!!

- SU(6)/SU(5)xU(1) → NG multiplet =**5***
- SO(10)/SU(5)xU(1) → NG multiplet = **10**

E_6 is bigger than SO(10)/SU(5)

How about E_6 ?

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

Number of the broken generators = 133-24-1-1-1 =106

Number of NG bosons = 3x(5+10)x2 + 3(1)x2 +(5)x2 =106 !!!

We can not replace 3x(5* +10) by 3(5+10) !!!

E_7 algebra requires sets of 5* + 10

This is an independent proof why quarks and leptons transform as 5* + 10

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 ?

SUSY Breaking

We introduce a Polonyi field Z whose F term is nonvanishing

But, we have a serious cosmological problem called as "Polonyi Problem" if the Polonyi field Z is neutral

We give a charge of some symmetry for the Z to solve the problem

The anomaly mediation is only way to mediate the SUSY breaking to the SM sector

The anomaly mediation generates the gaugino mass and squark and slepton masses

But, the induced mass^2 for the sleptons are negative !

However, their masses are zero at tree level,
since they are pseud Nambu-Goldstone bosons

Then, the sleptons become tachyonic

Our Vacuum is unstable !!!

We missed an important point

E_7: K(phi, phi*) → K(phi, phi*) + h(phi) + h*(phi)

Lagrangian is E_7 invariant in the global SUSY
But it is NOT invariant in Supergravity

We should introduce a new field S so that h(phi) is cancelled

S → S – h(phi)

Kugo, Yanagida (2010)
Komargodski, Seiberg (2010)

K(phi, phi*) + S + S* is E_7 invariant

The Kahler potential in supergravity is given by

F(K(phi, phi*) + S +S*)

We see an accidental shift symmetry ; S → S + ic

S can be the axion multiplet !

Supergravity requires the Axion !

Once SUSY is broken by the F term of Z, then the SUSY breaking induces the F term of S

$$F_Z = (m_{3/2}) M_{PL}$$

$$F_S = (m_{3/2}) f_a$$

(f_a is the axion decay constant)

S mediation of SUSY breaking occurs,
generating positive mass^2 for sleptons!!!

Our Vacuum becomes Stable !!!

A Miracle Happens

We have anomaly and S mediations and they are not independent

We find

M(bino) ≒ M(wino) within 1 %

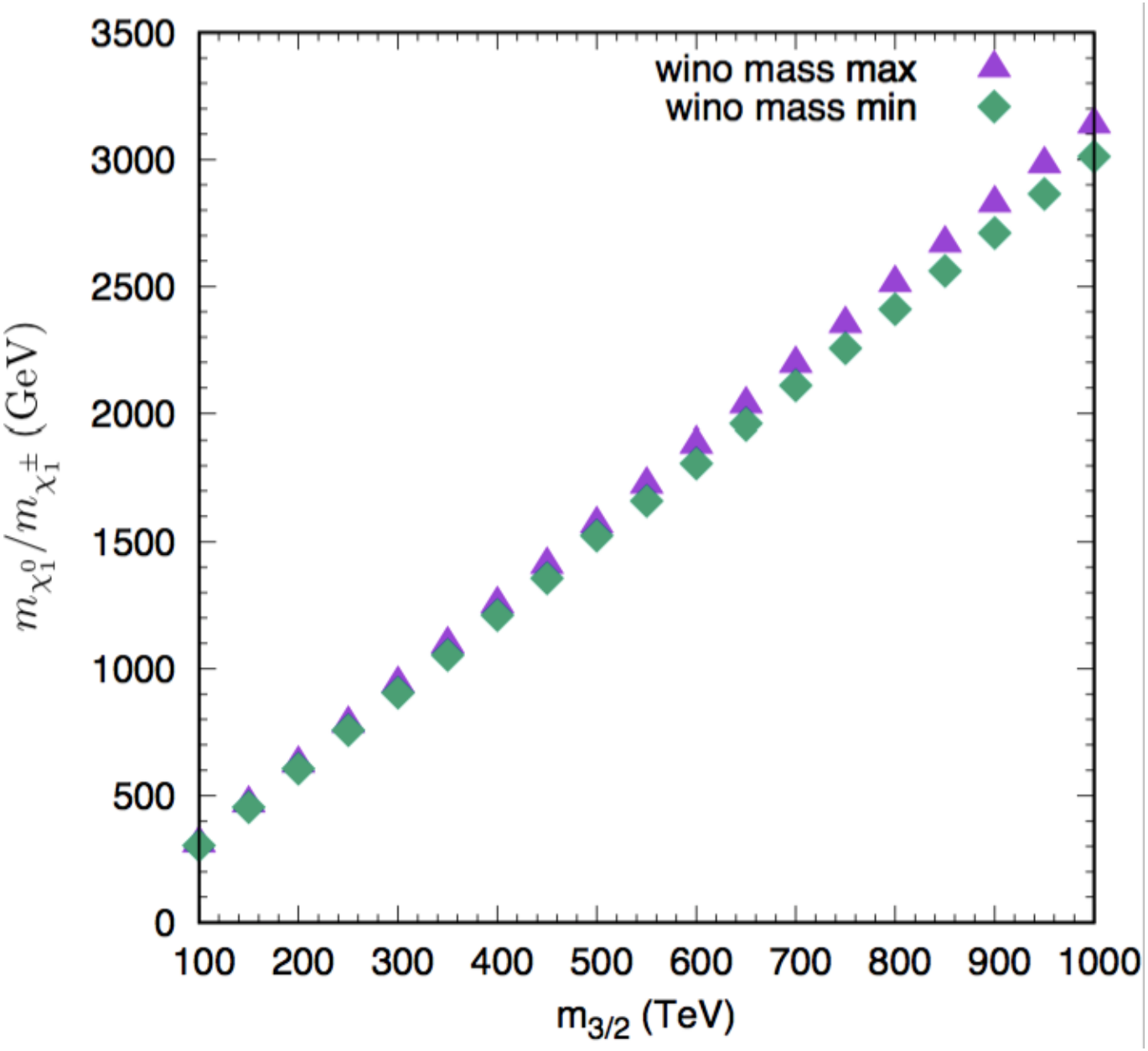
The bino can be the DM due to the bino-wino co-annihilation

Yanagida, Yin, Yokozaki (2019)

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)
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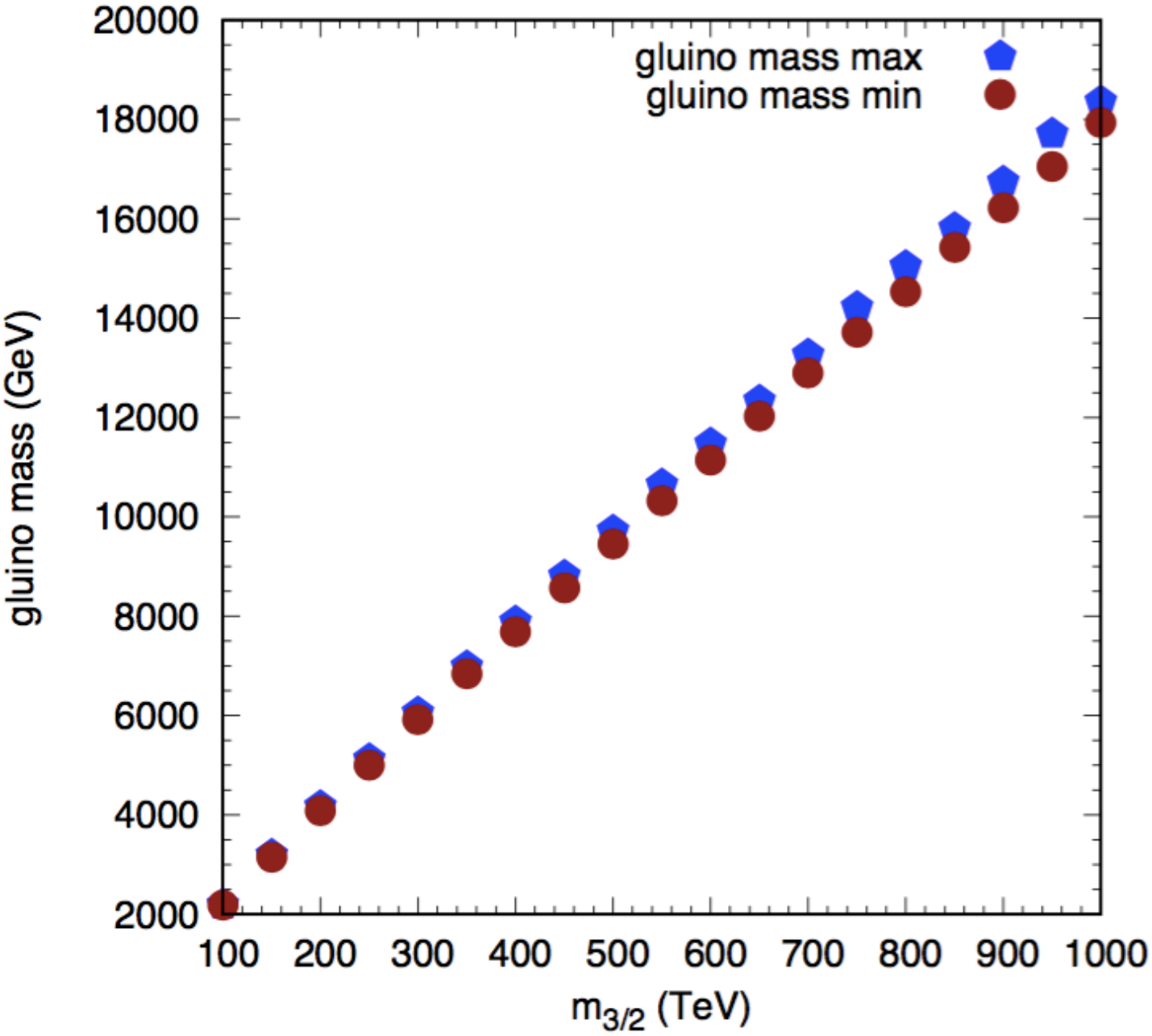
gluino mass max
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gluino mass (GeV)
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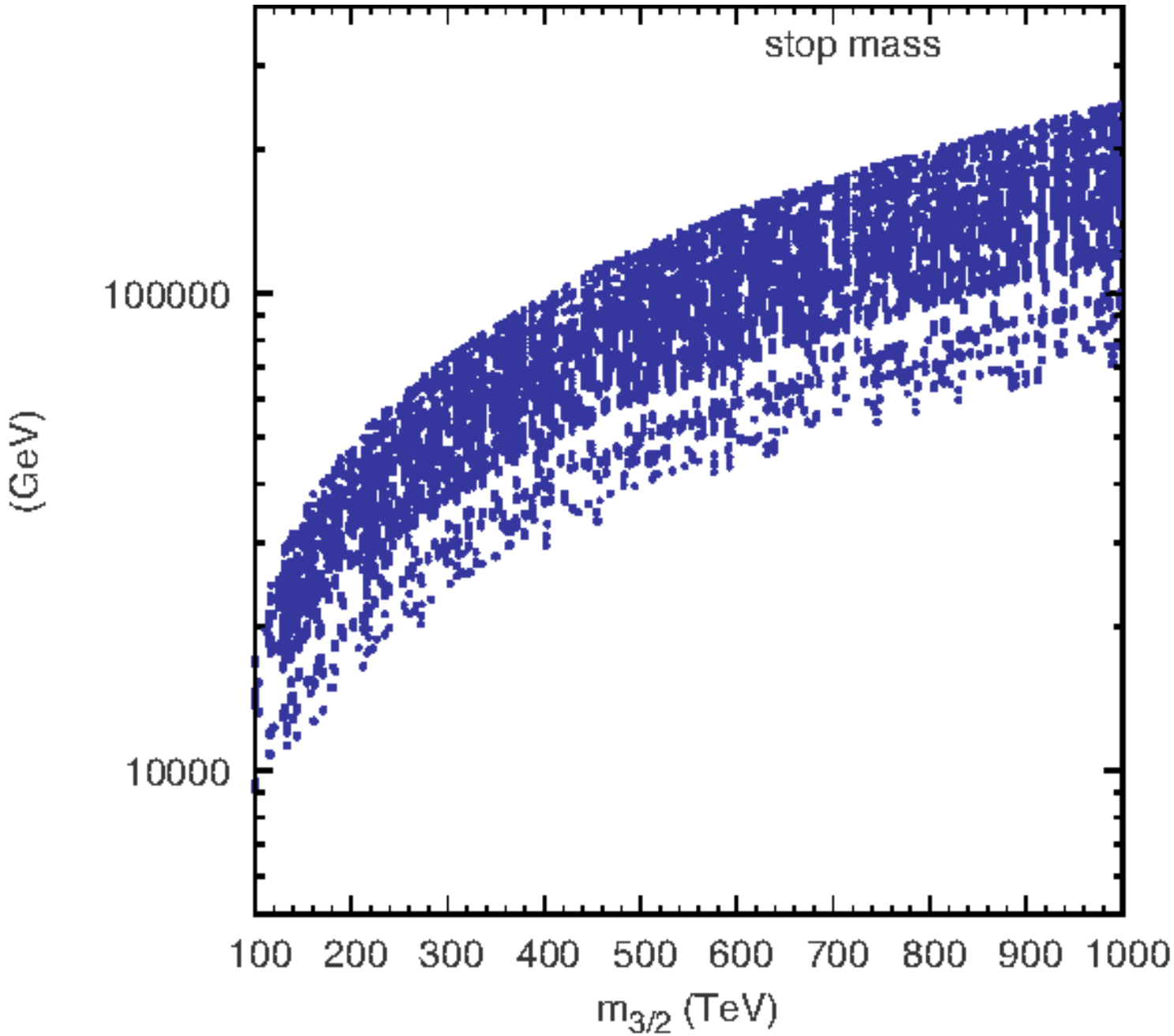
m3/2 (TeV)


stop mass
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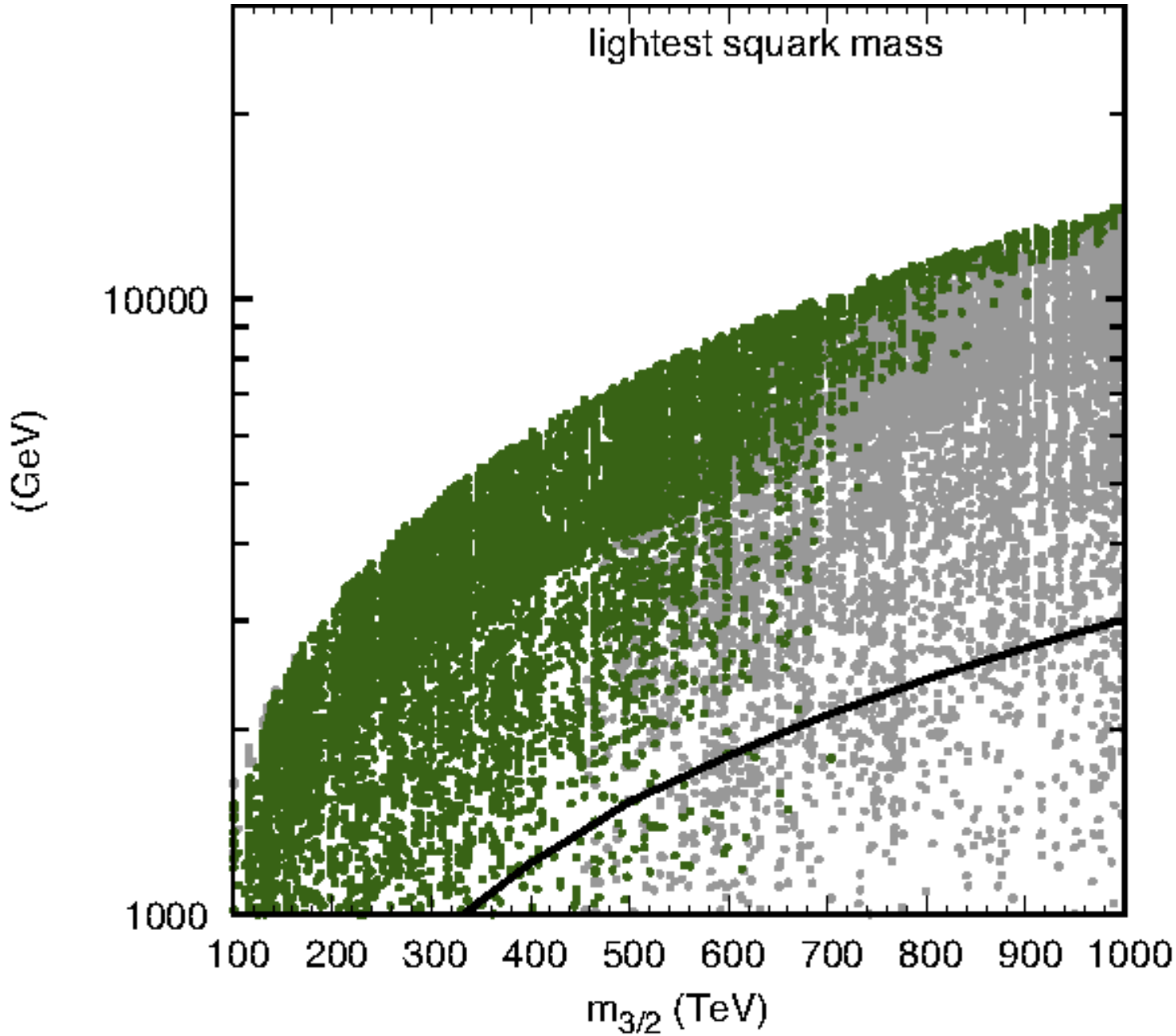
$m_{3/2}$ (TeV)


lightest squark mass
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(GeV)
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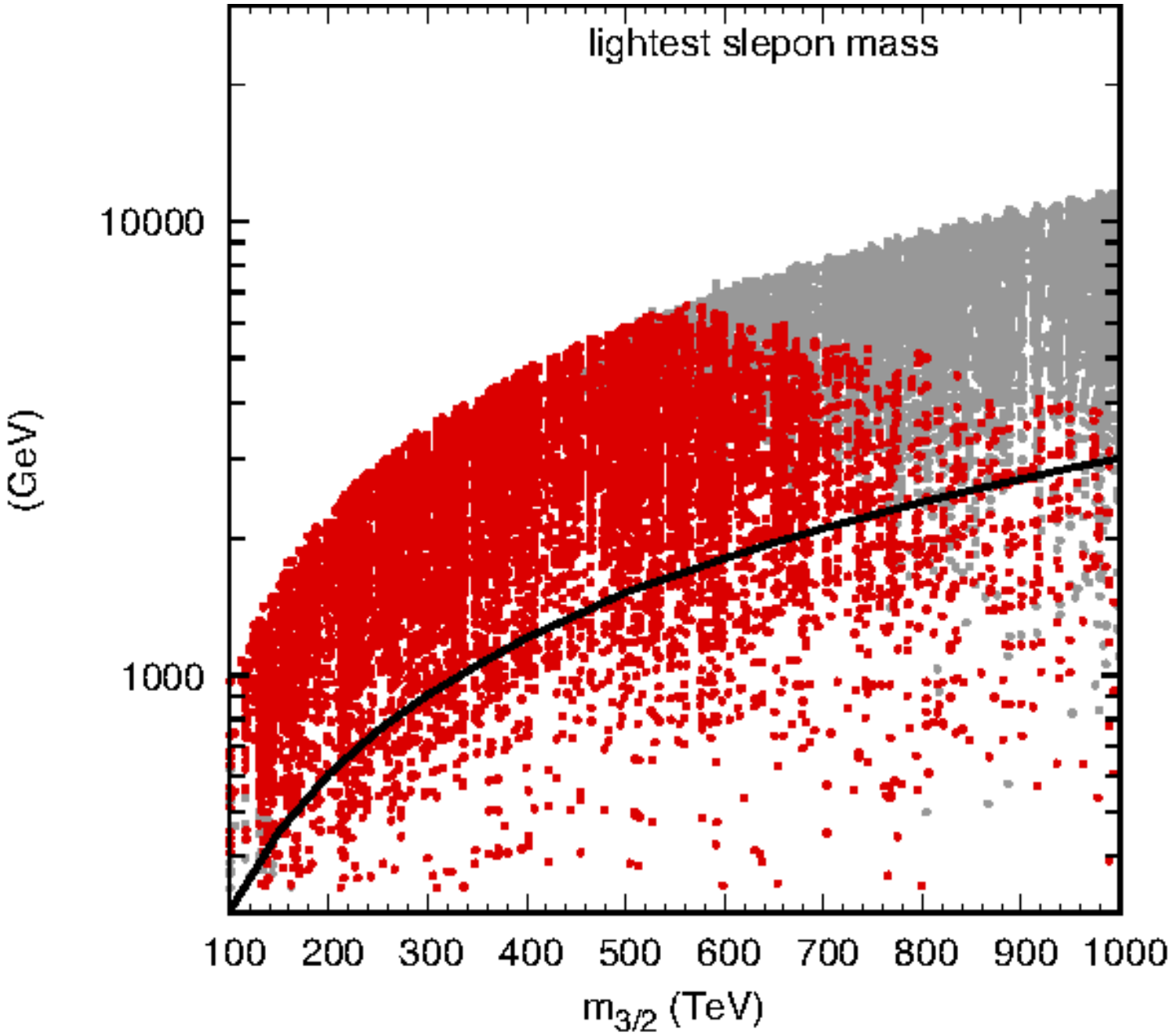
$m_{3/2}$ (TeV)


lightest slepon mass
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$m_{3/2}$ (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 ?

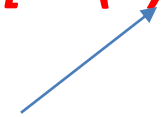
When N=8 → N=1 SUSY , G/H must be a Kahler manifold
But, E_7/SU(8) is NOT a Kahler manifold

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

- Supergravity requires an Axion multiplet
- Anomaly and Axion mediation predicts the bino-wino co-annihilation; bino DM
- NG hypothesis for squarks and sleptons still survives 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