Gauge hierarchy and SUSY: Think again

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Workshop on Connecting Insights in Fundamental Physics:
Standard Model and Beyond
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1. Introduction
2. Gauge hierarchy
3. SQCD before
4. A SGUT solution
5. Quintessential axion

1. Introduction

Chirality is the theme of this talk.

Chirality ensures small scales.

1st BSM

Weak-Interaction Singlet and Strong *CP* Invariance

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(Received 16 February 1979)

Strong *CP* invariance is *automatically* preserved by a spontaneously broken chiral $U(1)_A$ symmetry. A weak-interaction singlet heavy quark Q, a new scalar meson σ^0, and *a very light axion* are predicted. Phenomenological implications are also included.

attempts[1-4] to incorporate the observed made the Lagrangian *CP* invariant. In gen

mplicated and the
ed in the present

he axion properties,
menological impli-
a new scalar σ^0, and

principle, the col-
can be arbitrary.
e the same as light
is $\frac{2}{3}$ or $-\frac{1}{3}$, the
served in high-en-
PEP and PETRA,
arge is 0, there
lor-singlet hadrons
. Hence, the ob-

The new scalar σ^0.—By the spontaneous symmetry breaking of $U(1)_A$, σ will be split into a scalar boson σ^0 of mass $(2\mu_0)^{1/2}$ and an axion a. This σ^0 is *not* a Higgs meson, because it does not break the gauge symmetry, but the phenomenology of it is similar to the Higgs because of its coupling to quark as m_Q/v'. If this scalar mass is $\gtrsim 2m_Q$, we will see spectacular final state of stable particles such as $(Q\bar{u})$ and $(\bar{Q}u)$. If its mass is $\lesssim 2m_Q$, the effective interaction through loops $(c/v')F_{\mu\nu}{}^aF^{a\mu\nu}\sigma^0$, with numerical constant c, will describe the decay $\sigma^0 \to$ ordinary hadrons. The order of magnitude of its lifetime is $\tau(\sigma^0) \approx \tau(\pi^0)(v'/f_\pi)^2(m_{\pi^0}/m_{\sigma^0})^3 \approx 2\times10^{-10}$ sec for $v' \approx 10^5$ GeV and $m_{\sigma^0} \approx 10$ GeV. This kind of particle can be identified as a jet in pp high-energy collisions,

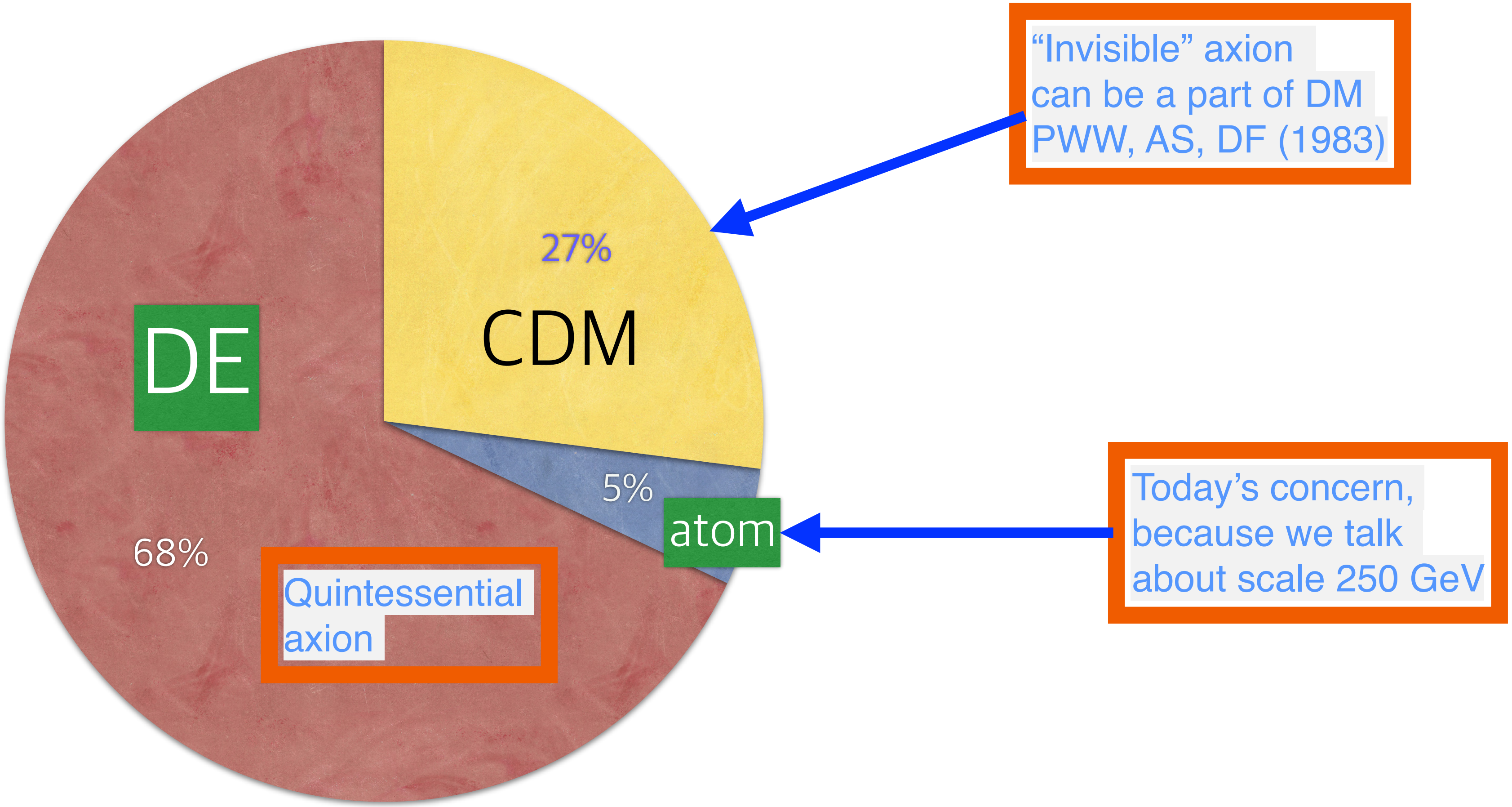
Georgi principle: Only gauge symmetry at the ultraviolet scale: Chirality takes over the role for allowing low energy scales

arXiv:1703.10925: PRD96 (2017) 055033

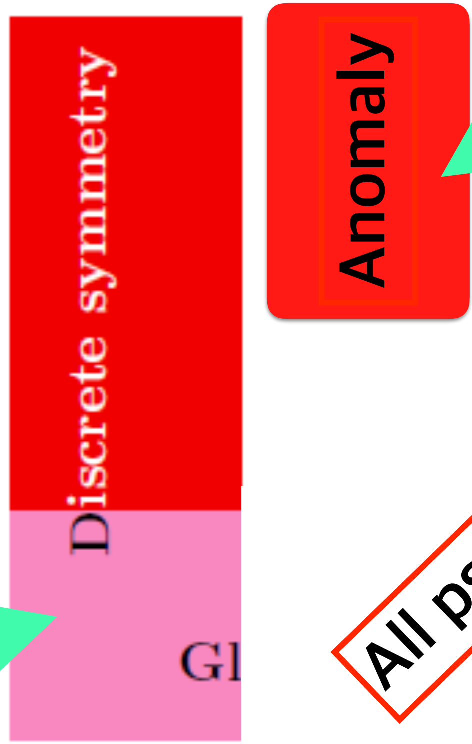
$$Q=\frac{1}{2}:\ \ell_i=\begin{pmatrix}E_i\\ N_i\end{pmatrix}_{\frac{+1}{2}},\qquad \begin{matrix}E^c_{i,-1}\\ N^c_{i,0}\end{matrix}\qquad (i=1,2,3),$$

$$Q=-\frac{3}{2}:\ \mathcal{L}=\begin{pmatrix}\mathcal{E}\\ \mathcal{F}\end{pmatrix}_{\frac{-3}{2}},\qquad \begin{matrix}\mathcal{E}^c_{,+1}\\ \mathcal{F}^c_{,+2}\end{matrix},$$

So, there is a good reason that these particles will be discovered at low energy. First, by kinetic mixing!!


“Invisible” axion
can be a part of DM
PWW, AS, DF (1983)
27%
CDM
DE
5%
atom
68%
Quintessential
axion
Today’s concern,
because we talk
about scale 250 GeV

The dominant contribution is QCD anomaly term



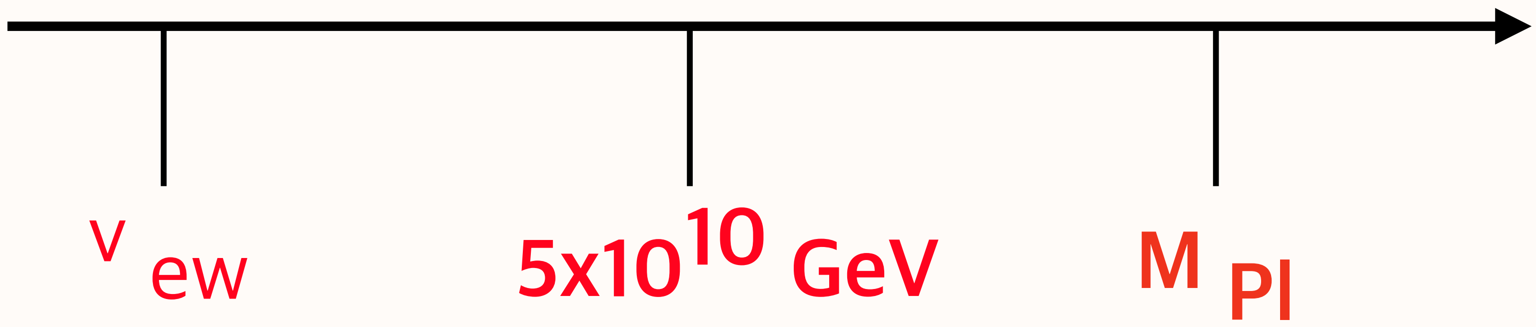
All pseudoscalars are massive

Keep only the leading terms

SUSY mu term: K-Nilles

$$
\begin{array}{lcccc}
PQ: & -1 & -1 & 1 & 1 \\
 & \multicolumn{2}{c}{\dfrac{H_u H_d}{M}} & \sigma & \sigma
\end{array}
$$

How to determine the VEV scale of the singlet?



Common scale for f_a and
source of SUSY breaking

2. Gauge hierarchy

JEK, Kyae, 1904.07371 [hep-th] PLB797, 134807 (2019):
"A model for dynamical SUSY breaking"

Mass scales:

Planck mass 2.44×10^{18} GeV

Next scale defines physics disciplines

Particle physics 246 GeV

Strong Interaction 300 MeV

Nuclear physics 7 MeV

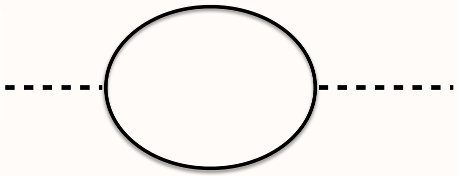
Atomic physics 1 eV

Condensed matter phys 10^{-3} eV

Mass hierarchy:

(Planck mass)/(EW scale) 10^{16}
(GUT mass)/(EW scale) 10^{14}

$$V = -M^2\Sigma^*\Sigma - v_{\rm ew}^2 H^\dagger H + \cdots$$



In the potential V, the scalar $(\text{mass})^2$ parameters have the ratio of 10^{28}.

Why is there such a large ratio of parameters? Including loop corrections?

TeV is the cutoff.

This was pointed out by S.Weinberg after the GUT models were proposed. The GUT models must have parameters such that the Higgs mechanism breaks both SU(5) and SU(2)xU(1) SM.

Anomaly free theories.

fundamentals: [1] one contra-variant index,
[2] two contra-variant index, etc.

SU(3): only quarks or anti-quarks

$$\Phi^{[\alpha]} = \mathbf{3},\ \ \Phi^{[\alpha\beta]} = \overline{\Phi}_{[\gamma]} = \overline{\mathbf{3}},\ \ \Phi^{[\alpha\beta\gamma]} = \mathbf{1},\ \ \text{etc.}$$

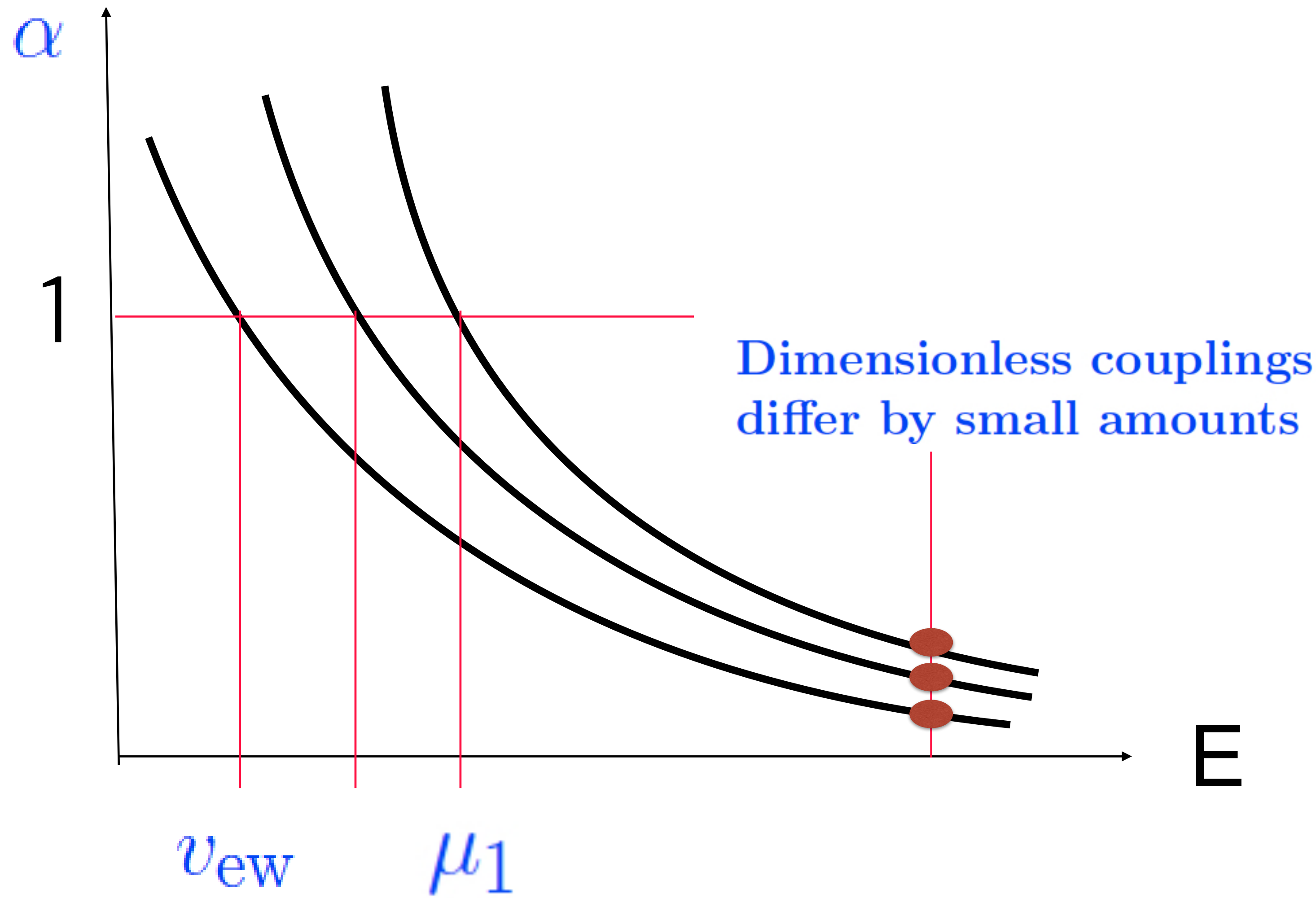
SU(4): only quarks or anti-quarks plus [2]=self-dual (removed)

SU(5): the smallest gauge group to have a chiral representation,
[2] + [4] which is anomaly free.

$$\Phi^{[\alpha]} = \mathbf{5},$$
$$\Phi^{[\alpha\beta]} = \mathbf{10},$$
$$\Phi^{[\alpha\beta\gamma]} = \overline{\Phi}_{[\delta\epsilon]} = \overline{\mathbf{10}},$$
$$\Phi^{[\alpha\beta\gamma\delta]} = \overline{\Phi}_{[\epsilon]} = \overline{\mathbf{5}}$$

$$V = -M^2\Sigma^*\Sigma - v_{\rm ew}^2 H^\dagger H + \cdots$$

An exponential hierarchy obtained by dimensional transmutation.



α
1
Dimensionless couplings
differ by small amounts
E
$v_{\rm ew}$
μ_1

1st confining force:

Technicolor confines at 3 TeV: Susskind and Weinberg 1979.

exponential 3 TeV= $M_{GUT} \times e^{-40}$.

Dimensional transmutation, e.g. 300 MeV

But it failed in flavor physics, by extended technicolor, through S and T parameter constraints.

Yukawa couplings are definitely needed: scalars are needed definitely.

SUSY idea: 1981~
Supergravity phenomenology: 1983~
Supersymmetry: LSP added for DM candidate: 1984~

SUSY breaking needed: Needed for SM partners ~$(\mathrm{TeV})^2$,

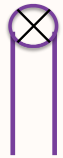
Source of SUSY breaking: 10^{13} GeV, by Gaugino condensation

L = SUSY terms + SUSY breaking soft terms of $O(\mathrm{TeV}^2)$

Gaugino condensation by R=0 singlet:
Nilles(1982),
Derendinger-Ibanes-Nilles(85),
Dine-Rohm-Seiberg-Witten(85)

Condensation of q and anti-q in QCD:

$(300\ \mathrm{MeV})^3$



Similarly, gauginos in SUSY theory may condense: Gaugino condensation.

$(10^{13}\mathrm{GeV})^3$

Then, scalar $(\mathrm{mass})^2$ parameters in the SM feel this breaking by gravity effects: $(10^{13}\mathrm{GeV})^3$ / $(\text{Planck mass})^2$ ~ TeV

How come, “Is there such source of 10^{13}GeV confining force?
Is there really “gaugino condensation”?
DIN, DRSW.

Two problems:

(1) scale problem.

(2) stability problem.

$$\delta m_h^2 = \frac{3G_F^2}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2$$

Remove quadratic divergence. —> SUSY

$$PQ: \quad -1 -1 \quad 1 \; 1$$

$$\frac{H_u H_d}{M} \quad \sigma \; \sigma$$

Planck scale

Intermediate scale

μ-term

3. SQCD before.

SUSY SU(N) gauge theory with L-handed q and R-handed q.

$SU(N_c)$ gauge group

$SU(N_f) \times SU(N_f)$ flavor group (global)

Introducing a vector-like representation.

Studied extensively by Seiberg and his collaborators, and many more. These focussed on duality and not obtained SUSY breaking from the gauge theory.

4. A SGUT now

SUSY GUT is defined by not introducing a vector-like representation.

SU(5) GG model is a minimal chiral example.

Anomaly free theories.

fundamentals: [1] one contra-variant index,
[2] two contra-variant index, etc.

SU(3): only quarks or anti-quarks
SU(4): only quarks or anti-quarks plus [2]=self-dual (removed)

SU(5): the smallest gauge group to have a chiral representation,
[2] + [4] which is anomaly free. Due to Georgi's criteria,
this is the simplest example.

$$[2] = \Psi^{\alpha\beta} \; : \; \Psi^{\alpha\beta} = -\Psi^{\beta\alpha}$$

$[4] = \psi$

$\Psi^{\alpha\beta} \oplus$

Meurice-Ver

suggested a

nd

In conclusion, we have found that in theories with chiral fermions the presence of several currents which do not fall into a vector/axial vector classification brings about strong constraints on SUSY vacua. These constraints, once coupled to reliable small-size instanton effects, lead in certain cases to a contradiction. Even the SQCD way out of a vacuum at infinity appears to be blocked leaving us with the only possibility of a non-supersymmetric ground state.

In the near future further calculations should not fail to provide a complete systematics of the circumstances under which spontaneous SUSY breaking take place.

Standard model (observed):

All participating here, I guess, worked on standard-like models. Not worrying about gauge symmetry breaking at the GUT scale.

Flipped SU(5) from string:

(1) Simple enough for studying flavors in detail
(2) GUTs
(3) $\sin^2$(weak mixing angle)=3/8

Anomaly free theories.

fundamentals: [1] one contra-variant index,
[2] two contra-variant index, etc.

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Meurice-Ver ... nd

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In conclusion, we have found that in theories with chiral fermions the presence of several currents which do not fall into a vector/axial vector classification brings about strong constraints on SUSY vacua. These constraints, once coupled to reliable small-size instanton effects, lead in certain cases to a contradiction. Even the SQCD way out of a vacuum at infinity appears to be blocked leaving us with the only possibility of a non-supersymmetric ground state.

In the near future further calculations should not fail to provide a complete systematics of the circumstances under which spontaneous SUSY breaking take place.

Our model (took 46 years):

JEK+Kyae: 1904.07371 “A model for dynamical SUSY breaking ”

SU(5) representation:

[2] + [1] + 2[4] which is anomaly free.

$$\bar{\Psi}^{\alpha\beta} \oplus \bar{\psi}_1^{\alpha} \oplus 2\cdot\psi_{2\alpha}$$

$$(\overline{\mathbf{10}},\mathbf{1}) \oplus (\overline{\mathbf{5}},\mathbf{1}) \oplus (\mathbf{5},\mathbf{2})$$

$$(\mathrm{SU}(5)_{\rm gauge},\mathrm{SU}(2)_{\rm global})$$

Now we can construct superpotential terms,

$$W_0 \ni \frac{1}{4}\bar{\Psi}^{\alpha\beta}\psi^i_{2\alpha}\psi^j_{2\beta}\epsilon_{ij},\ \ \bar{\psi}^{\alpha}_1\psi^i_{2\alpha}D_{1i},\ \ \frac{1}{5!}\bar{\Psi}^{\alpha\beta}\bar{\Psi}^{\gamma\delta}\bar{\psi}^{\epsilon}_1\,\epsilon_{\alpha\beta\gamma\delta\epsilon},$$

This is not possible with Meurice-Veneziano. In ours, one U(1) remaining.

$$\begin{aligned} &U(1)_{\bar{\Psi}} + 2U(1)_{\psi_2} = 0, \\ &U(1)_{\bar{\psi}_1} + U(1)_{\psi_2} + U(1)_{D_1} = 0, \\ &2U(1)_{\bar{\Psi}} + U(1)_{\bar{\psi}_1} = 0. \end{aligned}$$

$\mathrm{SU}(5)_{\mathrm{gauge}}$−singlet chial fields,

$$\phi = \frac{1}{5!}\bar{\Psi}^{\alpha\beta}\bar{\Psi}^{\gamma\delta}\bar{\psi}^{\epsilon}_1\,\epsilon_{\alpha\beta\gamma\delta\epsilon},\ \ \Phi_i = \bar{\psi}^{\alpha}_1\psi_{2\,\alpha\,i}.$$

$U(1)_{global}$-$SU(2)_{gauge}$-$SU(2)_{gauge}$ anomaly below conf. scale

As in axion physics theta term is considered by triangle loops.

$$\sim \frac{\theta}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu}$$

Confinement of SU(2) leads to this anomaly, due to instanton calculus, even if we integrate out the SU(2) charged fermions. If we consider infinite spacetime, gauged SU(2) is like global SU(2). So, we satisfy

$U(1)_{global}$-$SU(2)_{global}$-$SU(2)_{global}$ anomaly

For U(1), we do not have the instanton argument, and there is no need to match

$U(1)_{global}$-$U(1)_{global}$-$U(1)_{global}$ anomaly

$\boxed{U(1)_{gauge}}$ $\boxed{U(1)_{gauge}}$

$$\sim \frac{\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Even if we consider it, we know that it is a total derivative.

$$\begin{aligned}
&\propto \theta \frac{1}{4}\epsilon_{\mu\nu\rho\sigma}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial_\rho A_\sigma - \partial_\sigma A_\rho) = \theta\epsilon_{\mu\nu\rho\sigma}(\partial_\mu A_\nu)(\partial_\rho A_\sigma)\\
&= \partial_\rho[\theta\epsilon_{\mu\nu\rho\sigma}(\partial_\mu A_\nu)(A_\sigma)] - [\partial_\rho(\theta\epsilon_{\mu\nu\rho\sigma}\partial_\mu A_\nu)](A_\sigma)\\
&= \partial_\rho[\theta\epsilon_{\mu\nu\rho\sigma}(\partial_\mu A_\nu)(A_\sigma)] - [\theta\epsilon_{\mu\nu\rho\sigma}\partial_\rho\partial_\mu A_\nu](A_\sigma)\\
&= \partial_\rho[\theta\epsilon_{\mu\nu\rho\sigma}(\partial_\mu A_\nu)(A_\sigma)]
\end{aligned}$$

For anomaly, it is a short distance contribution. It has been used in axion physics in calculating axion-photon-photon coupling, considering the PQ charges of quarks even above the confinement scale. We did not calculate just by considering what are the composite fermions. If so, we should have done it with p and n PQ charges.

	$2\ell(R_{SU(5)})$	$SU(2)$	$U(1)_{\bar\Psi}$	$U(1)_{\bar\psi_1}$	$U(1)_{\psi_2}$	$U(1)_{D_1}$	$U(1)_{AF}$	$U(1)_R$	dimension
ϑ	0	0	0	0	0	0	0	$+1$	$\frac{1}{2}$
$\bar\Psi \sim (\overline{\mathbf{10}}, \mathbf{1})$	–	$\mathbf{1}$	$+1$	0	0	0	-1	$+1$	1
fermion	$+3$	$\mathbf{1}$	$+1$	0	0	0	-1	0	–
$\bar\psi_1 \sim (\overline{\mathbf{5}}, \mathbf{1})$	–	$\mathbf{1}$	0	$+1$	0	0	$+2$	0	1
fermion	$+1$	$\mathbf{1}$	0	$+1$	0	0	$+2$	-1	–
$\psi_2 \sim (\mathbf{5}, \mathbf{2})$	–	$\mathbf{2}$	0	0	$+1$	0	$+\frac{1}{2}$	$+\frac{1}{2}$	1
fermion	$+1\times 2$	$\mathbf{2}$	0	0	$+1$	0	$+\frac{1}{2}$	$-\frac{1}{2}$	–
$D \sim (\mathbf{1}, \mathbf{2})$	–	$\mathbf{2}$	0	0	0	$+1$	$-\frac{5}{2}$	$+\frac{3}{2}$	1
fermion	$+1\times 2$	$\mathbf{2}$	0	0	0	$+1$	$-\frac{5}{2}$	$+\frac{1}{2}$	–
$W^a \sim \lambda^a$	0	–	0	0	0	0	0	$+1$	$\frac{3}{2}$
Λ^b		–	–	–	–	–	–	$\frac{2b}{3}$	b
ϕ	–	$\mathbf{1}$	–	–	–	–	-5	$+2$	1
fermion	–	$\mathbf{1}$	–	–	–	–	-5	$+1$	–
Φ_i	–	$\mathbf{2}$	–	–	–	–	$+\frac{5}{2}$	$+\frac{1}{2}$	1
fermion	–	$\mathbf{2}$	–	–	–	–	$+\frac{5}{2}$	$-\frac{1}{2}$	–
S	–	$\mathbf{1}$	0	0	0	0	0	$+2$	1
fermion	–	$\mathbf{1}$	0	0	0	0	0	$+1$	–
$D^i \sim (\mathbf{1}, \mathbf{2})$	–	$\mathbf{2}$	–	–	–	$+1$	$-\frac{5}{2}$	$+\frac{3}{2}$	1
fermion	–	$\mathbf{2}$	–	–	–	$+1$	$-\frac{5}{2}$	$+\frac{1}{2}$	–

	$2\ell(R_{SU(5)})$	$SU(2)$	$U(1)_{\bar\Psi}$	$U(1)_{\bar\psi_1}$	$U(1)_{\psi_2}$	$U(1)_{D_1}$	$U(1)_{AF}$	$U(1)_R$	dimension
ϑ	0	0	0	0	0	0	0	$+1$	$\frac{1}{2}$
$\bar\Psi \sim (\overline{\mathbf{10}}, \mathbf{1})$	–	$\mathbf{1}$	$+1$	0	0	0	-1	$+\frac{1}{2}$	1
fermion	$+3$	$\mathbf{1}$	$+1$	0	0	0	-1	$-\frac{1}{2}$	–
$\bar\psi_1 \sim (\overline{\mathbf{5}}, \mathbf{1})$	–	$\mathbf{1}$	0	$+1$	0	0	$+2$	$+1$	1
fermion	$+1$	$\mathbf{1}$	0	$+1$	0	0	$+2$	0	–
$\psi_2 \sim (\mathbf{5}, \mathbf{2})$	–	$\mathbf{2}$	0	0	$+1$	0	$+\frac{1}{2}$	$+1$	1
fermion	$+1 \times 2$	$\mathbf{2}$	0	0	$+1$	0	$+\frac{1}{2}$	0	–
$D \sim (\mathbf{1}, \mathbf{2})$	–	$\mathbf{2}$	0	0	0	$+1$	$-\frac{5}{2}$	0	1
fermion	$+1 \times 2$	$\mathbf{2}$	0	0	0	$+1$	$-\frac{5}{2}$	-1	–
$W^a \sim \lambda^a$	0	–	0	0	0	0	0	$+1$	$\frac{3}{2}$
Λ^b		–	–	–	–	–	–	$\frac{2b}{3}$	b
ϕ	–	$\mathbf{1}$	–	–	–	–	-5	$+2$	1
fermion	–	$\mathbf{1}$	–	–	–	–	-5	$+1$	–
Φ_i	–	$\mathbf{2}$	–	–	–	–	$+\frac{5}{2}$	$+2$	1
fermion	–	$\mathbf{2}$	–	–	–	–	$+\frac{5}{2}$	$+1$	–
S	–	$\mathbf{1}$	0	0	0	0	0	$+2$	1
fermion	–	$\mathbf{1}$	0	0	0	0	0	$+1$	–
$D^i \sim (\mathbf{1}, \mathbf{2})$	–	$\mathbf{2}$	–	–	–	$+1$	$-\frac{5}{2}$	0	1
fermion	–	$\mathbf{2}$	–	–	–	$+1$	$-\frac{5}{2}$	-1	–

$U(1)_A$-$SU(2)_{global}$-$SU(2)_{global}$ anomalies above and below are matched,

Above (+1)x5 = 5 from (5,2)
Below 5 from $\Phi_i = \bar{\psi}_1^{\alpha} \psi_{2\,\alpha\, i}$

Now, consider composites below the confinement scale.

$\mathrm{SU}(5)_{\mathrm{gauge}}$−singlet chial fields,

$$\phi = \frac{1}{5!} \bar{\Psi}^{\alpha\beta} \bar{\Psi}^{\gamma\delta} \bar{\psi}_1^{\epsilon} \, \epsilon_{\alpha\beta\gamma\delta\epsilon}, \ \ \Phi_i = \bar{\psi}_1^{\alpha} \psi_{2\,\alpha\, i}.$$

$U(1)_A$-$SU(2)_{global}$-$SU(2)_{global}$ anomalies above and below are matched,

Now, consider composites below the confinement scale.

The superpotential consistent with $SU(2)_{global}$ x $U(1)_{global}$ is

$$W = M^2\phi + \frac{N_c(N_c^2-1)}{32\pi^2}\mu_0^2 S\left(1 - a\log\frac{\Lambda^3}{S\mu_0^2}\right) + bM\Phi_i D^i,$$

$$\frac{\partial W}{\partial \phi} = 0: \ M^2 = 0,$$

$$\frac{\partial W}{\partial \Phi_i} = 0: \ D^i = 0,$$

$$\frac{\partial W}{\partial D^i} = 0: \ \Phi_i = 0,$$

$$\frac{\partial W}{\partial S} = 0: \ \mu_0^2\left(1 + a - a\log\frac{\Lambda^3}{S\mu_0^2}\right) = 0,$$

Gaugino condensation

SUSY is broken by the 'O Raifeartaigh mechanism!!!

This is shown here for the first time.

So, we have a solution for the gauge hierarchy problem.

$$\frac{\lambda_0}{5!}\,\bar{\Psi}^{\alpha\beta}\,\bar{\Psi}^{\gamma\delta}\,\bar{\psi}_1^{\epsilon}\,\epsilon_{\alpha\beta\gamma\delta\epsilon} \to \lambda_0\mu_0^2\,\phi$$

At SU(5)' level

M^2

If lambda0 is nonzero, M^2 is nonzero

Common scale for SUSY breaking and f_a

So, if the hidden SU(5)' confines at 10^{13} GeV - $5\mathrm{x}10^{10}$ GeV, the SUSY breaking scale for SM partners is above 1 TeV.

In particular, the lower end $5\mathrm{x}10^{10}$ - 10^{11} GeV is particularly interesting because it is the anticipated axion scale, which is the most difficult region for axion search.

The SU(5)' confinement provides this region because of the scalar condensation, rather than gaugino condensation.

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$

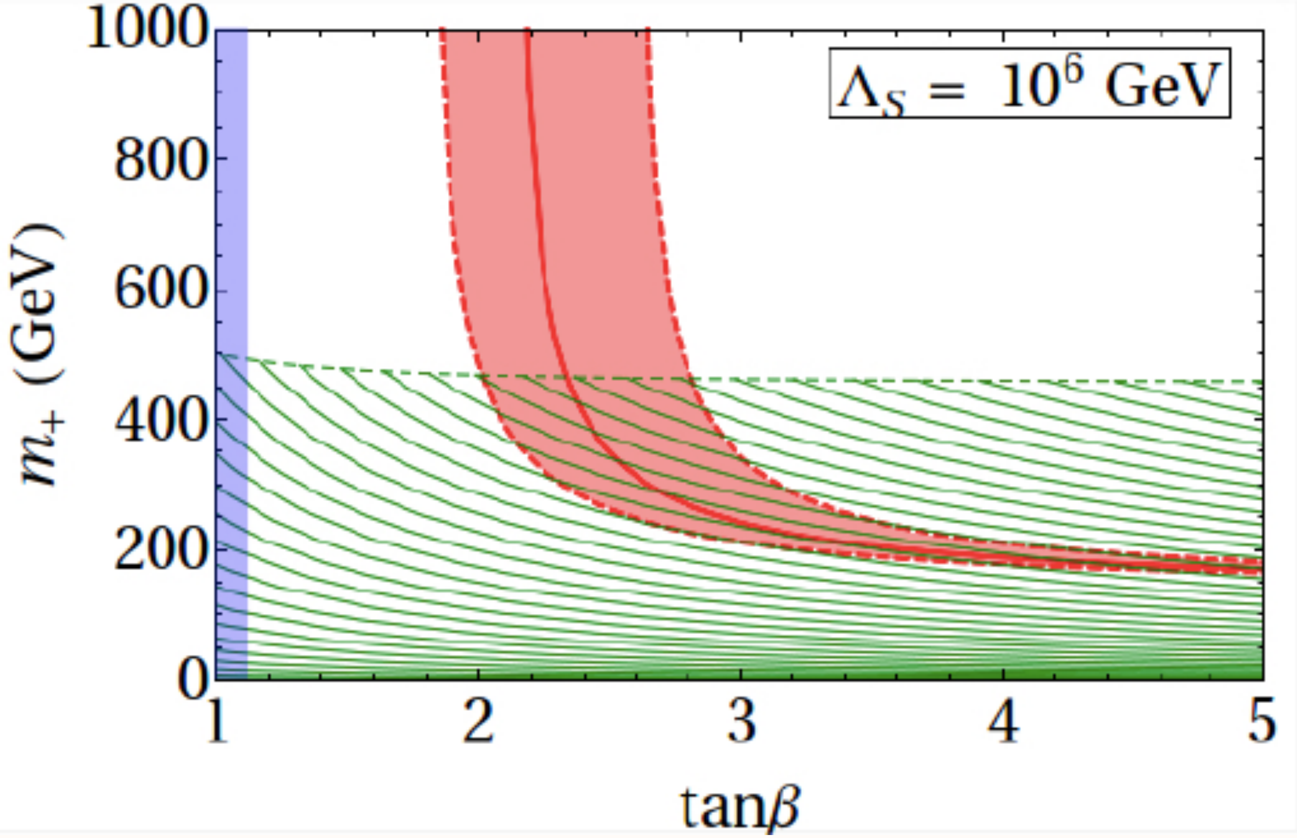
TeV scale

A common view on the SUSY solution of the GHP.

With gauging condensation at 10^{13} GeV

In our case, the confinement scale by singlet composite scalar is somewhere between 5×10^{10} GeV—10^{12} GeV. Not at 10^{13} GeV.

With this, M_{SUSY} can be raised to the scale of the little hierarchy. The super partner scale at a TeV needs $a^{1/2}\times5\times10^{10}$ GeV for the confinement scale. 6 TeV needs 10^{11} GeV confinement scale.



Saha, Friday:
Reasonable fit of Higgs mass

’t Hooft global-anomaly matching (1979)

QCD example for global symmetry matching

Interpretation: Anomaly is related to gauge bosons. “Anomaly” is the anomaly in the process of gauge theory renormalization. How global anomaly results from this? In the confinement process?

Choose SU(2) gauge bosons with a global U(1).

5. Conclusion

1. Chirality: Low mass particles and dynamical SUSY breaking.
2. It can solve the difficult problem of gauge hierarchy
3. A guess on it came from the hidden sector of a working model of flipped SU(5) from string

Randall: To discover one, one should be an expert in model building [APS Denver, April, 2019]