Shift Symmetry

What is the Origin of the Shift. Symm.?

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DESY Theory Workshop : Sep. 26. 2014

SHIFT SYMMETRY:

K. Y. Y. (2000)

Inflaton $\phi \longrightarrow \phi + iC$

$$K = \frac{1}{2}(\phi + \phi^*)^2 + S^\dagger S$$

$$W = m\, S \phi$$

$$\Downarrow$$

$$V = \frac{1}{2} m^2 |\phi|^2$$

Chaotic Inflation

Linde (1983)

Why we have the Shift Symm. ?

Motivated by Particle Physics.

Why do we have three families ?

u, d	$c\ s$	t, b
$\nu\ e$	$\nu\ \mu$	$\nu\ \tau$

$\underline{5}^* + \underline{10}$ $\quad$ $\underline{5}^* + \underline{10}$ $\quad$ $\underline{5}^* + \underline{10}$ $\quad$ of $SU(5)_{GUT}$

$$m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\tau} \quad ?$$

c.f. QCD

$$m_\pi^2 \ll m_{K,\eta}^2 \ll m_N^2$$

π, K, η are Nambu-Goldstone bosons !!

Quarks / Leptons are Nambu-Goldstone chiral multiplets ?

Buchmüller . Peccei . Yanagida (1982)

$$\Phi(x,\theta) = \varphi(x) + \psi(x)\cdot\theta$$

NG boson

quasi NG fermion

$\Downarrow$

Quarks / Leptons

Given G/H, we can determine # of families.

But,

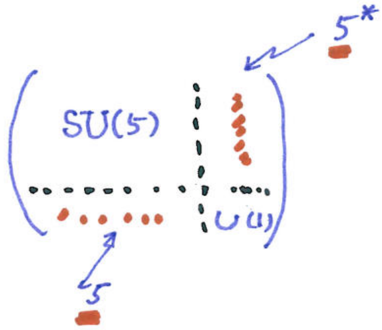
What is G/H ?

$\because$ $G \to H$: NG Φ_s $\Leftarrow$ the Broken Generators

Simple Exercise

- $SU(6)/SU(5)\times U(1)$: Broken generator is $X(5) + X^{\dagger}(5)$

$$\therefore \ \text{NG} \ \phi(x,\theta) \simeq \underline{5^*}$$



- $SO(10)/SU(5)\times U(1)$

$$SO(10) = \underbrace{24}_{SU(5)} + \underbrace{10 + 10^*}_{\text{Broken generator } (10 + 10^*)} + \underbrace{1}_{U(1)}$$

$$\text{NG chiral multiplet } \ \Phi = \underline{10}$$

We need G/H which contains

Both of $\underline{5^*} + \underline{10}$.

$$\Downarrow$$

$$\underline{E_6 \ ?}$$

$\underline{E_6}$

SO(10)

U(1)

Generators $78 = 45 + \underbrace{\underline{16} + \underline{16}^*}_{\text{32 broken generators}} + 1$

$E_6 / SO(10) \times U(1)$:

NG chiral multiplet $\Phi(\underline{16})$

$\underline{16}$ of SO_{10} = $\underline{5}^* + \underline{10} + 1$

right-handed ν

Exceptional Group is also interesting, since it has the maximal Group E_8 !!!

$\Downarrow$

We may have the prediction of # of families.

$E_7 / SU(5) \times U(1)^3$:

(?)

$$NG\ \Phi = \underline{3} \times (\underline{5^*} + \underline{10}) + 5 + 1's$$

three families

Kugo, Yanagida (1983)

$E_8 / SU(5) \times U(1)^4$

$$NG\ \Phi = \underline{3} \times (5^* + 10) + 5 + 1's$$
$$+ \underbrace{(5^* + 10) + (5 + 10^*)}_{\text{Vector-like matters}}$$

$N(\#)$ of Families $\leq \underline{3}$!!!

$E_7 / SU(5) \times U(1)^3$:

Nonlinear Sigma Model Anomaly

But it is canceled by introducing a matter multiplet $\Psi(\underline{5}^*)$.

Yasui (1986)

$$\text{NG } \Phi = 3 \times (\underline{5}^* + \underline{10}) + 1\text{'s} + \underline{5} \oplus \psi(\underline{5}^*)$$

If E_7 is exact, all Yukawa couplings and Masses are zero !!!

Let introduce explicit breakings :

$E_7 \xrightarrow{\text{e.b.}} E_6$: breaking parameter.

- $\underline{5} + \psi(\underline{5}^*)$ has a mass term : $M\, \underline{5} \cdot \psi(\underline{5}^*)$
- t, b, τ get Yukawa Couplings

$$m_t, m_b, m_\tau \neq 0$$

$E_6 \xrightarrow{\text{e.b.}} SO(10)$

- c, s, μ get Yukawa Couplings

$$m_c, m_s, m_\mu \neq 0$$

$SO(10) \xrightarrow{\text{e.b.}} SU(5)$:

- u, d, e get Yukawa Couplings

$m_u, m_d, m_e \neq 0$

Mass hierarchy :

$$\boxed{m_{t,b,\tau} \gg m_{c,s,\mu} \gg m_{u,d,e}}.$$

C.f. QCD

$$\frac{SU(3)_L \times SU(3)_R}{SU(3)_V} : \pi, K, \eta \quad \text{massless NG bosons}$$

Explicit Breaking parameter $m_s \neq 0$

$SU(3)_L \times SU(3)_R \xrightarrow{\text{e.b.}} SU(2)_L \times SU(2)_R$

- K, η get masses.

Explicit Breaking $m_{u,d} \neq 0$

$SU(2)_L \times SU(2)_R \xrightarrow{\text{e.b.}} SU(1)_V$

- π, get masses.

$$\boxed{m_{K,\eta}^2 \gg m_\pi^2}$$

Kähler Potential is given by G/H geometry.

$$K(\Phi_i, \Phi_i^*) = \underbrace{G/H}_{\text{Kähler manifold.}} \text{ Kähler Potential}$$

E_7 transformation

$$K(\Phi_i, \Phi_i^*) \longrightarrow K(\Phi_i, \Phi_i^*) + H(\Phi_i) + H^*(\Phi_i^*)$$

$$\delta \int d^4\theta \, K(\Phi_i, \Phi_i^*) - \int d^4\theta \left[H(\Phi) + H(\Phi^*) \right]$$

$$= 0$$

$K(\Phi, \Phi^*)$ is invariant of E_7.

But.

A Big Problem in Supergravity!!!

In Supergravity : $\int d^4\Theta \, K(\Phi, \Phi^*)$

$$\delta K = \int d^4\Theta \, [H(\Phi) + H^*(\Phi^*)] \neq 0$$

E_7 invariance is maximally broken !!!

Witten, Bagger (1983)

A solution was found !!

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

$$K(\Phi, \Phi^*)_{new} = K(\Phi, \Phi^*) + Z + Z^*$$

$$\{ f_\Phi = M_{pl} = 1 \}$$

$$\begin{cases} K(\Phi, \Phi^*) \xrightarrow{E_7} K(\Phi, \Phi^*) + H(\Phi) + H^*(\Phi^*) \\ Z \xrightarrow[E_7]{} Z - H(\Phi) \end{cases}$$

$K(\Phi, \Phi^*)_{New}$ is completely invariant.

The new field Z has a shift symmetry.

$$Z \to Z + iC \quad !!$$

Z can be the Inflaton ϕ.

A simple exercise :

Consider $CP^1 \simeq SU(2)/U(1)$: Kähler Manifold.

$$\begin{cases} \text{unbroken generator} & T \\ \text{broken generator} & X,\ X^+ \end{cases}$$

NG multiplet Φ :

$$\begin{cases} [T, \Phi] = +1\, \Phi \\ [X, \Phi] = \Phi^2 \\ [X^+, \Phi] = 1 \end{cases}$$

.. nonlinear realization of $SU(2)$

Kähler Potential

$$K = \log(1 + \Phi\Phi^*)$$

$$\delta K = [X, K] = \frac{\Phi^2\Phi^* + \Phi \cdot 1}{1 + \Phi\Phi^*} = \Phi$$

$$K \to K + \Phi$$

Introduce Z to cancel Φ term.

$$\delta Z = [X, Z] = -\Phi, \quad [X^+, Z] = 0$$

$$[X, \underset{\underset{K_{new}}{\parallel}}{K + Z + Z^*}] = 0$$

$\delta K_{new} = 0$!

c.f. Witten-Bagger Theory

$$\begin{cases} K = f_\phi^2 \left(\log \left(1 + \dfrac{\phi \phi^*}{f_\phi^2} \right) \right) \\ W = 0 \, ! \end{cases}$$

If $f_\phi^2 = 2n M_{pl}^2$, the theory is consistent.

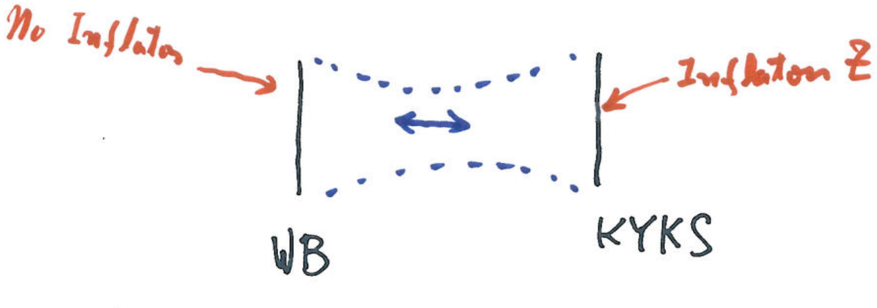
$f_\phi \gg M_{pl}$: $n = 1, 2, 3 \cdots$

May be consistent with $Z_0 \gg M_{pl}$.
the large initial value
for the Chaotic Inflation.

KYKS Model :

$$\begin{cases} K = F(K_{new}) = F\left(f_\phi^2 \log \left(1 + \dfrac{\phi^* \phi}{f_\phi^2} \right) + \dfrac{Z + Z^*}{f_\phi} \right) \\ W \neq 0 \end{cases}$$

f_ϕ is free.



$f_\phi \gg M_{pl}$

Hellerman, Kehagias, Yanagida
(2014)

Explicit Breaking of E_7

$$E_7 \xrightarrow{\text{e.b.}} E_6 \xrightarrow{\text{e.b.}} E_5(SO(10)) \xrightarrow{\text{e.b.}} E_4(SU(5))$$

SO(10) must be a good symmetry.

Let consider $SO(10)/SU(5)\times U(1)$ manifold.

N.G. multiplet $\Phi = \underline{10}$

The up quark mass is given by

$$W = y_u \cdot \underline{10}\cdot\underline{10}\cdot\langle H\rangle$$

If SO(10) is exact symmetry, $y_u = 0 \to m_u = 0$.

$y_u \simeq$ SO(10) explicit breaking parameter

$\simeq 10^{-5}$ for $m_u \simeq$ a few MeV.

Now,

$G/H = SO(10)/SU(5)\times U(1)$

$$K_{new} = K(\phi, \phi^*) + Z + Z^*$$

Introduce the explicit breaking of SO(10)

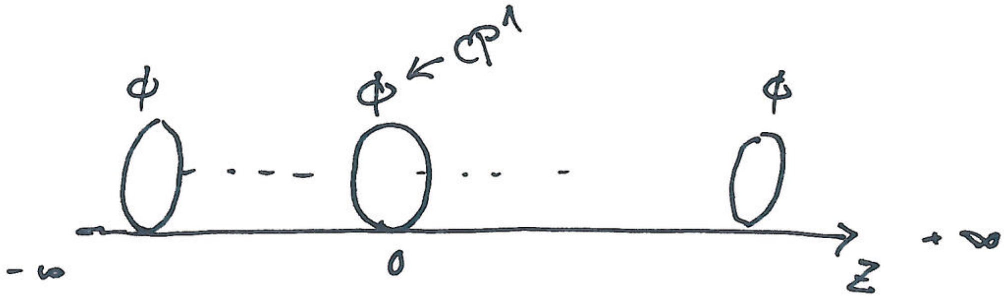
$$W = y_u\, 10\cdot 10\cdot\langle H\rangle + m S Z$$

10^{-5}

$10^{-5} = 10^{13}$ GeV !!!

Good for Inflaton mass.

Now Our Manifold is <u>Non compact</u> !!!



$\mathrm{Im}\, Z$ can be $-\infty \longleftrightarrow +\infty$.

$$|Z_0| \gg M_{pl}$$

We may have naturally the large initial value for the Inflaton Z.

What is the Prediction ?

$$\begin{cases} m_{3/2} \simeq m_{\text{squark}} \simeq 100\ \text{TeV} & ! \\ m_H \simeq 125\ \text{GeV} & !! \end{cases}$$

Consider CP^1 as an example :

$$K = K\left(\log(1+\phi^\dagger\phi) + z^\dagger + z \right)$$

$$= \log(1+\phi^\dagger\phi) + z + z^\dagger$$

$$+ \frac{1}{2}\left[\log(1+\phi^\dagger\phi) + z + z^* \right]^2 + \cdots\cdots$$

needed for the Kinetic term of ϕ

needed for the Kinetic term of Z

$$K_{\text{inflaton}} = z + z^* + \frac{1}{2}(z+z^*)^2 + \cdots$$

$$e^{z} W$$

$$K_{\text{inflaton}} = \frac{1}{2}(z+z^*)^2$$

$$\tilde{W} = e^{z} W$$

$$W = y \, \mathrm{tr}\, q_L H + \cdots + \frac{1}{2} M N N + \cdots$$

$$Z \xrightarrow[\text{decay}]{} N + N \ : \ q t H \ : \ \cdots$$

$$T_R \simeq 10^{9} - 10^{10}\ \mathrm{GeV}$$

Good for thermal leptogenesis.

Let consider Dynamial SUSY. Breaking.

Dynamical Scale Λ

Composite hadrons mass $\sim \Lambda$

Susy breaking $F \simeq \alpha \cdot \frac{\Lambda^2}{4\pi}$ $\alpha \simeq 1 \sim 0.1$

$$W = W_{\text{standard model}} + W_{\text{hidden}}$$

$$W_{\text{hidden}} = M_{\text{composite}} \cdot \Psi \bar{\Psi} + \cdots$$

$$M_{\text{composit}} \simeq \Lambda$$

If $\Lambda \lesssim \frac{1}{2} m_{\text{inflaton}} \simeq \frac{1}{2} \cdot 10^{13}\,\text{GeV}$,

The inflaton decays mainly to Hidden hadrons.

Hidden hadrons $\xrightarrow{\text{decays}}$ gravitinos

LSP $\xleftarrow{\text{decay}}$

If $\Lambda \lesssim \frac{1}{2} m_{\text{inflaton}} \simeq \frac{1}{2} \cdot 10^{13}\,\text{GeV}$,

The inflaton decay produces too many LSP !!

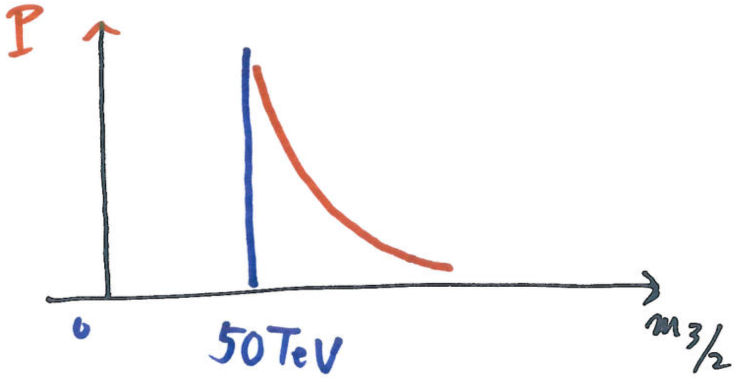
$$\Omega_{LSP} \ggg \Omega_{\text{observation}}$$

$$\Downarrow$$

$$\Lambda \gtrsim \frac{1}{2}\, 10^{13}\,\text{GeV}$$

$$F \gtrsim 0.25 \times 10^{25}\,\text{GeV} \times (\alpha)$$

$$m_{3/2} \gtrsim \alpha \cdot 500\,\text{TeV} \qquad \alpha(1-0.1)$$



Harigaya, T.T.Y.
(2014)

If SUSY breaking is low-energy biased,

$$m_{3/2} \simeq 100\ \mathrm{TeV}\ !!!$$

m_H is predicted as $m_H \simeq \underline{125\ \mathrm{GeV}}$.

Okada, Yamaguchi, Yanagida
(1992).

Conclusions

We have a very serious problem in Particle Physics.

$$\begin{cases} \text{LHC found Higgs boson of mass} \sim 125\,\text{GeV}. \\ \text{LHC found no SUSY particle} \lesssim 1\,\text{TeV} \end{cases}$$

These observations suggest the high scale SUSY

$$m_0 \gtrsim 10\,\text{TeV} \;!!!$$

Why so high ?

If SUSY is the solution to the naturalness problem, we expect

$$m_0 \lesssim 1\,\text{TeV}.$$

Without a convincing answer to the question I can not believe SUSY.

Now, the Chaotic Inflation gives us an answer!

$$\Lambda_{dyn} \geq \frac{1}{2} m_{inflaton} \simeq \frac{1}{2} \cdot 10^{13} \, \text{GeV}$$

$$\downarrow$$

$$m_{3/2} \gtrsim 100 \, \text{TeV}$$

If $m_{inf} \simeq 10^{12}$ GeV, we get

$$m_{3/2} \gtrsim 500 \, \text{GeV}. \qquad F \propto \Lambda^2 \simeq m^2$$

$m_{inf} \simeq 10^{13}$ GeV is crucial!!!

The pure gravity mediation predicts

Ibe, Yanagida (2011)

$$\begin{cases} m_{gluino} \gtrsim 3 \, \text{TeV} \\ m_{wino} \lesssim \text{a few TeV} \end{cases}$$

Wino is the DM.

Ibe, Matsumoto, Yanagida (2012)

If R parity is broken, Wino can decay through

$$W_{\not R} = \lambda L L E$$

$$\lambda \lll 1 . \quad (\lambda \doteqdot 10^{-19})$$

The wino decay explains the recent observation of the cosmic positron anomaly by AMS02-2014.

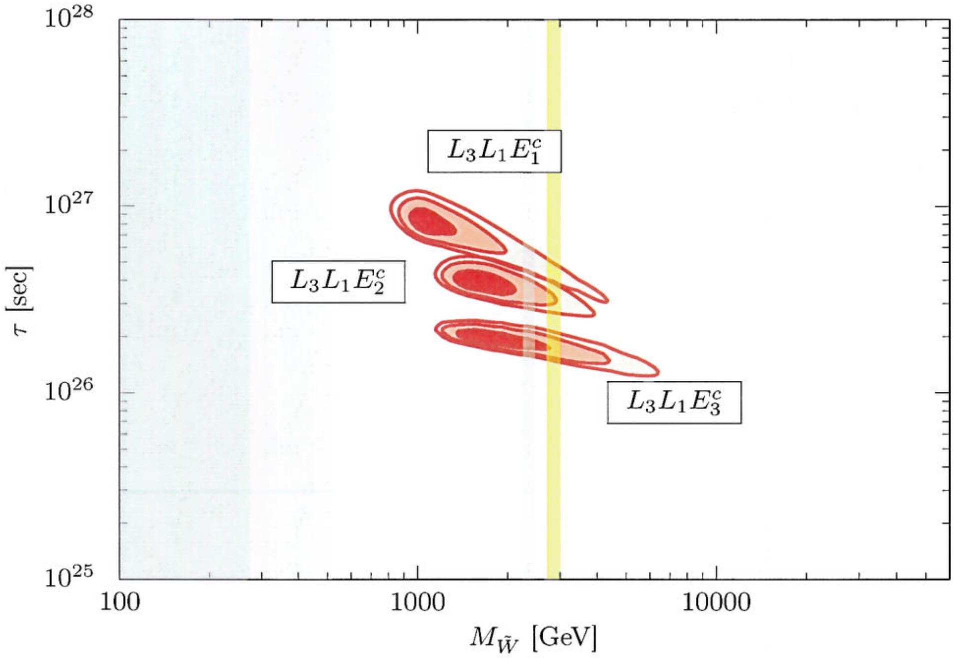
We derive the mass of the Wino :

$$\underline{m_W \simeq 1 - 3 \text{ TeV}} \ !!!$$

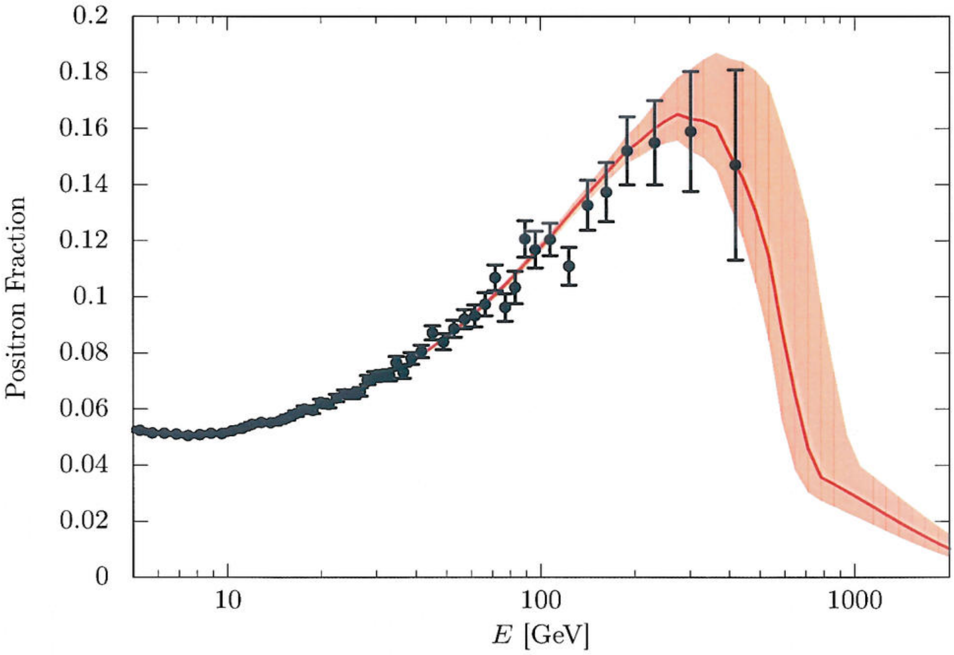
See figures

Ibe, Matsumoto, Shirai (now)

Consistent with the prediction of the "pure gravity mediation".



(a) $L_3L_1E_k$



(b) $L_3L_1E_2$ positron fraction