25 June 2014 @ FNAL

Implication of 126 GeV Higgs for Planck scale physics and Cosmology

Satoshi Iso (KEK & Sokendai)

based on

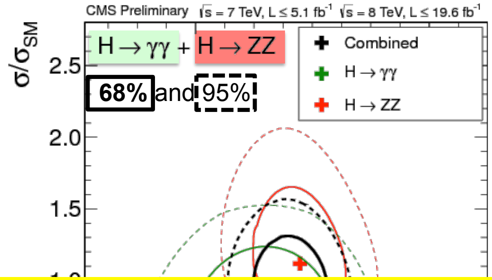
naturalness of Higgs : H.Aoki (Saga), SI Phys.Rev.D86(2012)013001

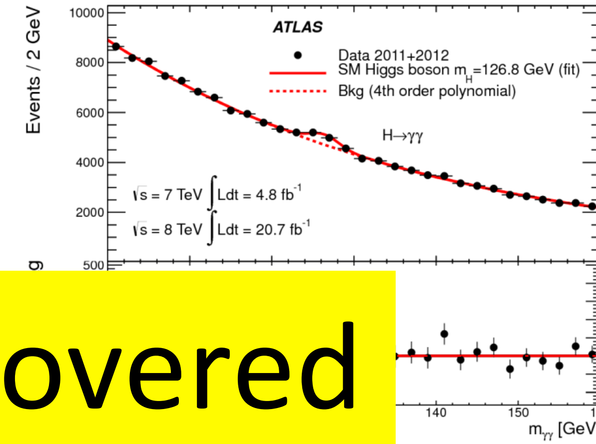
phenomenological models based on this idea

N.Okada (Alabama), Y.Orikasa (Osaka), SI PLB(2009) & PRD(2009)

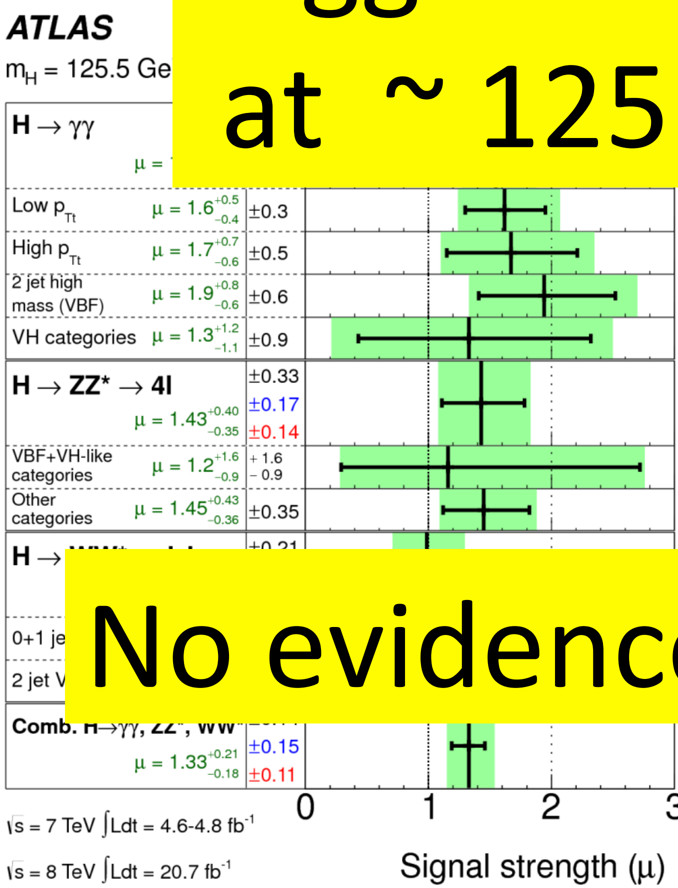
Y.Orikasa (Osaka), SI PTEP(2013) & arXiv:1304.0293

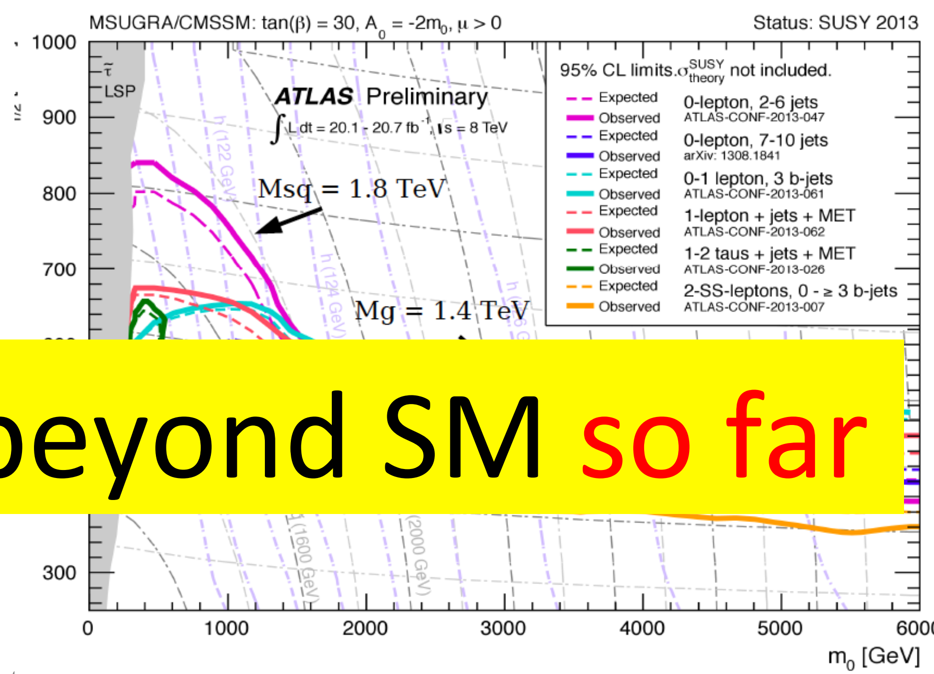
M.Hashimoto (Chubu), Y.Orikasa (Osaka), SI PRD(2013) & PRD(2014)





Higgs boson is discovered at ~ 125.5 GeV





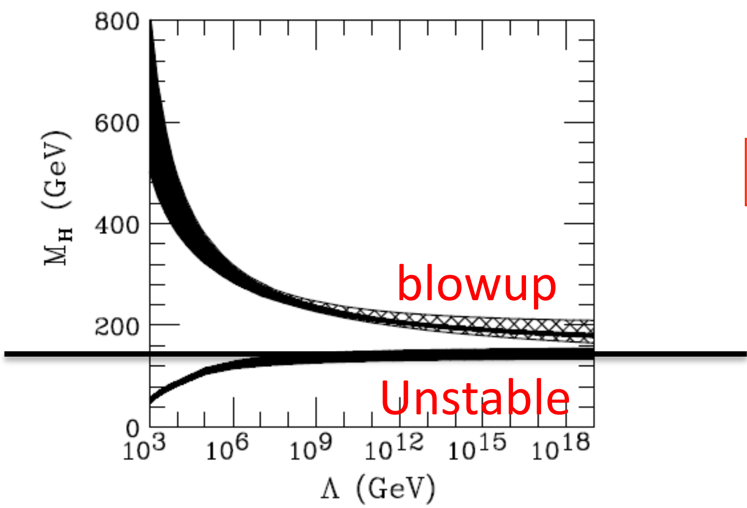
No evidence beyond SM so far

What do the LHC results tell us about Higgs potential ?

(1) Naturalness (Hierarchy problem)

Strong constraints on TeV susy suggests that
we need to reconsider the naturalness as the guiding principle
to go beyond the SM.

(2) Stability of the Higgs potential



$$\boxed{124\ \mathrm{GeV} < m_h < 126\ \mathrm{GeV}}$$

indicates vanishing quartic Higgs coupling
at high energy scale (e.g. Planck)

(1) Naturalness problem

$$V = \boxed{-\mu^2|H|^2} + \lambda(|H|^2)^2$$

Naturalness (Hierarchy problem): text book explanation

$$\delta V(\phi) = \frac{1}{2}\int \frac{d^4k}{(2\pi)^4} \,\mathrm{Str}\log(k^2 + M^2(\phi))$$

Quadratic divergence

$$= \frac{\Lambda^2}{32\pi^2}\mathrm{STr}M^2(\phi) + \mathrm{STr}\frac{M^4(\phi)}{64\pi^2}(\ln(M^2/\Lambda^2) - 1/2)$$

$\mathrm{STr}M^2(\phi) \neq 0$ Quadratic divergence in Higgs mass term

$\mathrm{STr}M^2(\phi) = 0$ Cancellation of Quadratic divergence (supersymmetry etc.)

Question: Is quadratic divergence really the issue of the hierarchy problem?

- It can be always subtracted with no effects on physics.
  (subtractive renormalization)

It is different from logarithmic divergences (multiplicative renorm.)

- No quadratic divergences in dimensional regularization.
  (minimal subtraction)

See e.g.
Bardeen (1995)
Hill (2005)
Fujikawa (2011)
Aoki Iso (2012)

Bardeen (1995 @ Ontake summer institute)

Standard model is classically scale invariant if Higgs mass term is absent.

$$T^{\mu}_{\mu} = 0$$

Quantum anomaly breaks the invariance (if not conformal)

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i$$

The common wisdom is that the breaking is not soft and we have

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i + const.\ \Lambda^2 \bar{h}h$$

Bardeen argued that it should be

$$T^{\mu}_{\mu} = \beta(\lambda_i)O_i + \delta m^2 \bar{h}h$$

$$\delta m^2 = const. \times m^2 \neq const. \times \Lambda^2$$

if no intermediate scales exist.

Support for Bardeen by Wilsonian RG

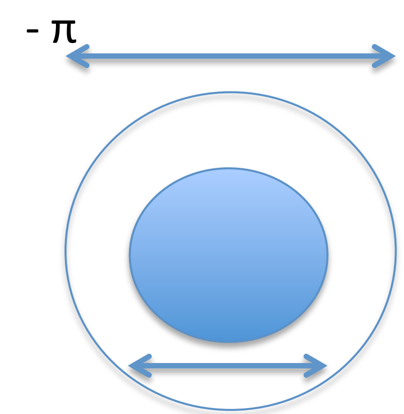
H. Aoki, SI (2012)

Scalar field in d-dim

$$S = \int_{\Lambda^d} \frac{d^d p}{(2\pi)^d} \frac{1}{2}(p^2 + m^2)\phi(p)\phi(-p) + \frac{1}{4!}\lambda \int_{\Lambda^d} \prod_{a=1}^{4} \frac{d^d p_a}{(2\pi)^d} (2\pi)^d \delta^{(d)}(\sum_{a=1}^{4} p_a)\ \phi(p_1)\phi(p_2)\phi(p_3)\phi(p_4)$$

$$\Lambda^d = \{p| -\pi < p^i < \pi,\ \forall i = 1, 2, \cdots, d\}$$ Lattice cutoff

All quantities (mass, field) are dimensionless.
Measured in units of the lattice cut-off.



2 steps of RG transformation

Step 1: Integration over higher momentum modes $|p^i| \geq \frac{\pi}{N}$

Remaining modes $-\frac{\pi}{N} < p^i < \frac{\pi}{N}$

$$-\frac{\pi}{N} < p^i < \frac{\pi}{N}$$

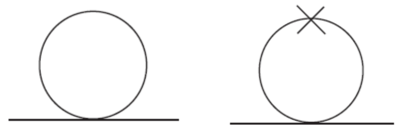
Step 2: Rescaling $p' = Np \qquad \phi'(p') = N^{-\theta}\phi(p)$

θ is chosen so that the kinetic term becomes canonical.

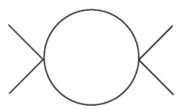
RG transformations

$$\frac{m^2}{\Lambda^2} \ll 1$$

$$m^{2\,\prime} = N^{2\theta-d}(m^2 + c_1\lambda - c_2 m^2\lambda)$$



$$\lambda' = N^{4\theta-3d}(\lambda - 3c_2\lambda^2)$$



$$c_1 = \frac{1}{2}\int_{\Lambda^d_{\rm out}} \frac{d^dq}{(2\pi)^d}\frac{1}{q^2} \longrightarrow \Lambda^2$$

$$c_2 = \frac{1}{2}\int_{\Lambda^d_{\rm out}} \frac{d^dq}{(2\pi)^d}\left(\frac{1}{q^2}\right)^2$$

$$\longrightarrow \Lambda^0 \ln N$$

$$\theta = (d+2)/2$$

Solution

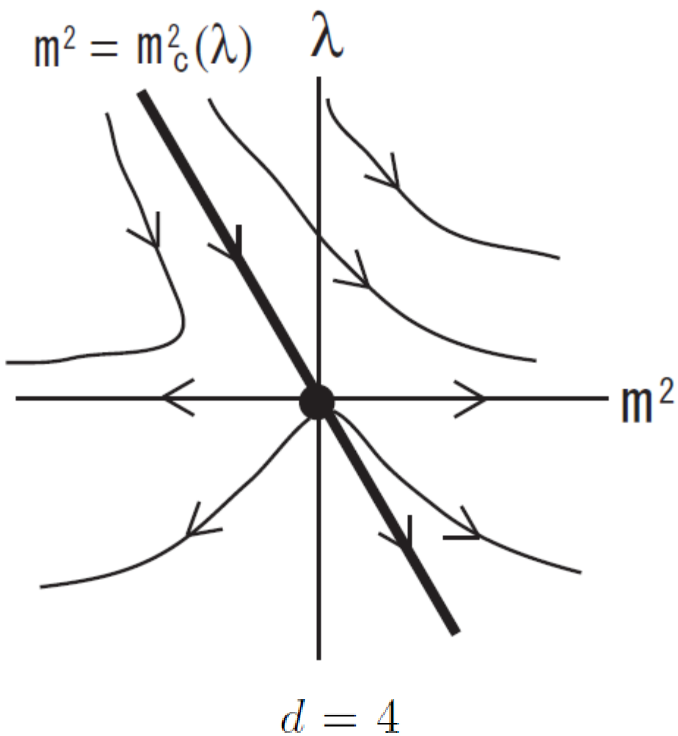
$$d \neq 4 \qquad \frac{1}{\lambda'} - \frac{1}{\lambda^*} = N^{-(4\theta-3d)}\left(\frac{1}{\lambda} - \frac{1}{\lambda^*}\right) + \mathcal{O}(\lambda) \qquad \lambda^* = \frac{N^{4\theta-3d}-1}{3c_2}$$

$$d = 4 \qquad \frac{1}{\lambda_n} = \frac{1}{\lambda_0} + 3c_2 n$$

$$m^{2\,\prime} - m_c^2(\lambda') = N^{2\theta-d}(1 - c_2\lambda)(m^2 - m_c^2(\lambda)) \qquad m_c^2(\lambda) = -\frac{c_1}{1 - N^{2(\theta-d)}}\lambda$$

Quadratic divergence from Wilsonian Renormalization Group

Critical line



critical line Quadratic divergence

$$m_c^2(\lambda) = -\frac{c_1}{1 - N^{2(\theta - d)}}\lambda$$

Quadratic divergence determines the position of critical line.
Scaling behavior of RG flow is determined only by Logarithmic div.

Such property does hold at all orders of perturbations.

Continuum Limit

$$m_0^2 - m_c^2(\lambda_0) = N^{-2} e^{c_2 \sum \lambda_i} (m_R^2 - m_c^2(\lambda_R))$$

In terms of the **dimensionless** parameter m,
we need to fine-tune the bare mass close to the critical line.

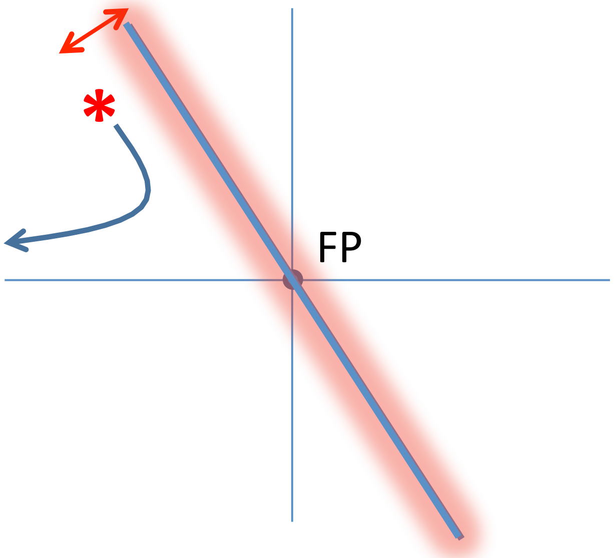
In terms of **dimensionful** parameter,

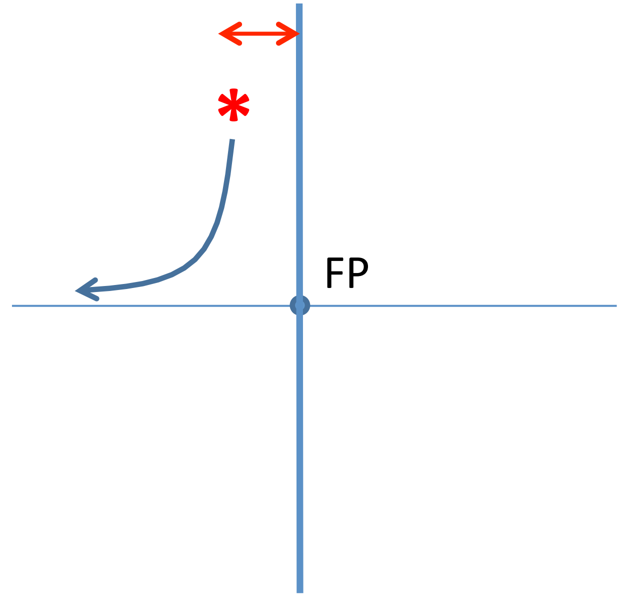
$$\tilde{\Lambda}_0 = N^n \tilde{\Lambda}_n = N^n M \qquad \tilde{m}_k^2 = \left(\frac{\tilde{\Lambda}_k}{\Lambda}\right)^2 m^2$$

$$\boxed{\tilde{m}_0^2 - \tilde{m}_c^2(\lambda_0) = e^{c_2 \sum \lambda_i} (\tilde{m}_R^2 - \tilde{m}_c^2(\lambda_R))}$$

Log scaling of mass term

This type of tuning has nothing to do with quadratic divergences.





With quadratic div.

$$\Lambda^2 \neq 0$$

No quadratic div.

$$\Lambda^2 = 0$$

Fine - tuning of the **distance from the critical line** = **Low energy mass scale**

This fine-tuning always occurs for both non-susy and susy.
i.e. It has nothing to do with quadratic divergences.
Most natural possibility is to put the theory on the critical line.

What is the real issue of the Hierarchy problem?

1. Initial boundary condition at UV

   the same for both susy and non-susy

2. Mixing of multiple relevant operators

   TeV susy can avoid this problem.

Mixing of multiple relevant operators by Logarithmic div.

$$S = \int_{\Lambda^d} \left[\sum_{\alpha=1}^{S} \left(\frac{1}{2}(p^2 + m_\alpha^2)\phi_\alpha^2 + \frac{1}{4!}\lambda_{\alpha\alpha}\phi_\alpha^4 \right) + \sum_{\alpha\neq\beta} \frac{1}{8}\lambda_{\alpha\beta}\phi_\alpha^2\phi_\beta^2 \right]$$

Solution → $\tilde{m}^2_{\alpha(0)} - \tilde{m}^2_{c\alpha}(\lambda_{(0)}) = \sum_\beta \left(M^{-1}\right)_{\alpha\beta} \left(\tilde{m}^2_{\beta(n)} - \tilde{m}^2_{c\beta}(\lambda_{(n)})\right)$

Critical line $m^2_{c\alpha}(\lambda) = -\frac{c_1}{1 - N^{2(\theta-d)}} \sum_\beta \lambda_{\alpha\beta} + \mathcal{O}(\lambda^2)$

Example:

$$\begin{aligned} \tilde{m}^2_{1(n)} - \tilde{m}^2_{c1}(\lambda_{(n)}) &= m^2_{\mathrm{W}} \\ \tilde{m}^2_{2(n)} - \tilde{m}^2_{c2}(\lambda_{(n)}) &= m^2_{\mathrm{GUT}} \end{aligned}$$

Mixing of weak scale with Gut scale

$$m^2_{\mathrm{W}} \simeq \frac{1}{(M^{-1})_{11}}(\tilde{m}^2_{1,0} - \tilde{m}^2_{c1}(\lambda_0)) - \frac{(M^{-1})_{12}}{(M^{-1})_{11}}\, m^2_{\mathrm{GUT}}$$

Classification of divergences

1. Power divergences Λ^2

It can be simply subtracted at UV scale = boundary condition at UV

Once subtracted, no longer appears in IR.

----

2. Logarithmic divergences $m^2 \log(\Lambda/m)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right)$$

scalar mass within SM

3. Large Logarithmic divergences: $M^2 \log(\Lambda/M)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right) + \boxed{\frac{M^2}{8\pi^2}\lambda_{mix}}$$

$$\delta m^2 = \frac{\lambda_{mix} M^2}{16\pi^2}\log(\Lambda^2/M^2)$$

Heavy particles beyond SM

m	<<	M
Low energy physics		High energy physics

In order to solve the "naturalness problem",
of IR theory embedded in UV completion theory, we need to control

(a) " M_{PL}^2 term" → correct boundary condition at Planck

The most natural b.c. is NO MASS TERMS at Planck

(= classical conformal)

$$V = \cancel{-\mu^2|H|^2} + \lambda(|H|^2)^2$$

(b) "large logarithmic divergence" by mixing with a large mass M

No large intermediate scales beyond EW up to Planck

"Classical conformal theory with no intermediate scale"

can be an alternative solution to the naturalness problem.

(2) Stability of Vacuum

a hint for Planck scale physics

from M_H=126 GeV

$$V = -\mu^2|H|^2 + \lambda(|H|^2)^2$$

$$m_h^2 = 2|\mu^2| = \boxed{2\lambda\langle h\rangle^2}$$

m_H determines λ.

$\langle h\rangle$ = 246 GeV

RGE improved effective potential for large field (h >> v) $$V_{\text{eff}}(h) = \frac{\lambda_{\text{eff}}(h)}{4} h^4$$

RGE @1-loop $$\frac{d\lambda_H}{dt} = \frac{1}{16\pi}\left(24\lambda^2 \boxed{- 6Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g_1^4 + \cdots}\right)$$

Already known

It is related to Higgs mass as $M_h^2 = 2\lambda v^2$

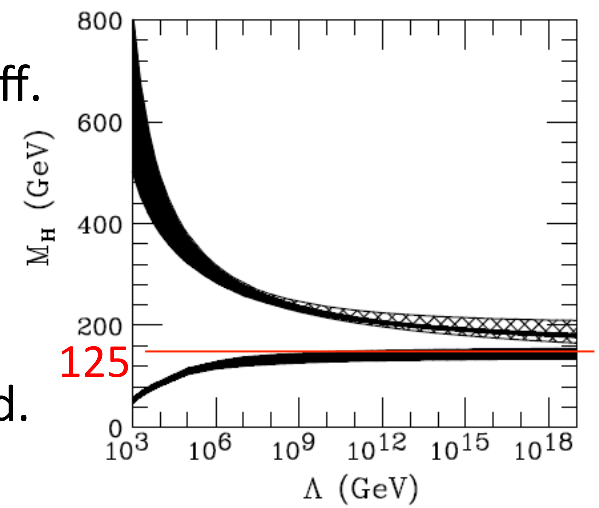
Higgs mass controls the behavior of Higgs potential at large values of h.

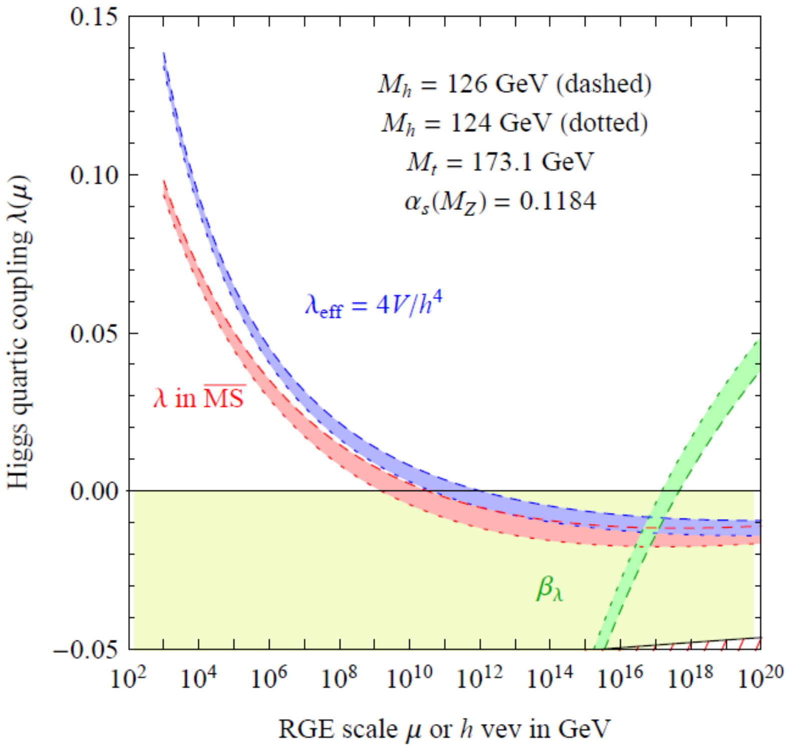
This gives two bounds for Higgs mass

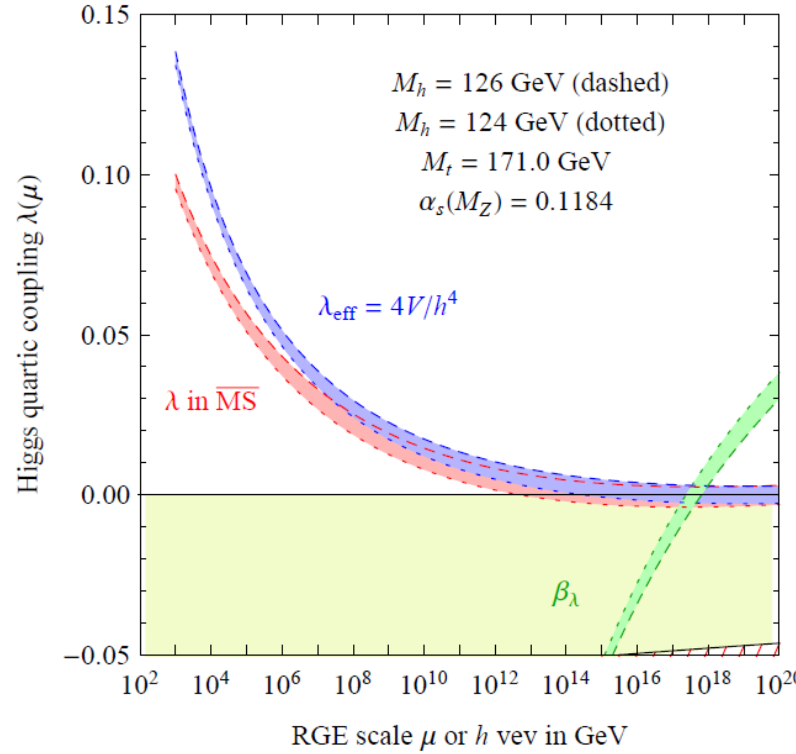
(1) The quartic coupling does not blow up until UV cut-off.
M < 180 GeV (triviality bound)

(2) The quartic coupling does not become negative until UV cut-off. (Stability bound)

M = 125 GeV Higgs is very close to the stability bound.







New physics at 10^{12} GeV
is necessary to stabilize the vacuum

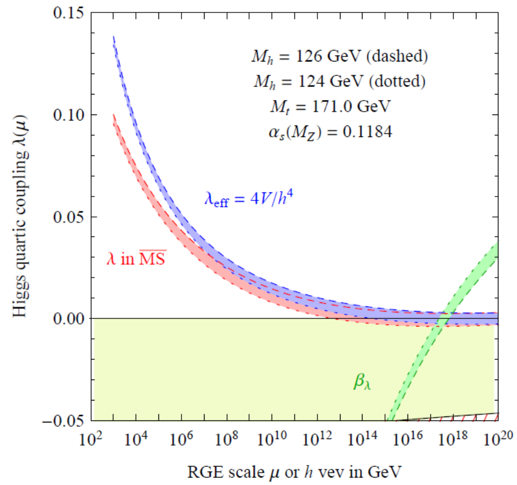
Flat Higgs potential
at Planck scale

$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2\ {\rm GeV}}{0.9\ {\rm GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\ {\rm GeV}.$$

Elias-Miro et.al.(12)
Alkhin, Djouadi, Moch (12)

very sensitive to top quark mass

(Also sensitive to higher dim op. and nonperturbative behavior of RG)

If this  is the case ?

$$\lambda(\Lambda_0) = \beta_\lambda(\Lambda_0) = 0$$

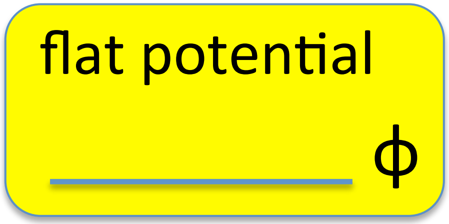
$$V = -\mu^2|H|^2 + \cancel{\lambda(|H|^2)^2}$$

Direct window to Planck scale

Froggatt Nielsen (96)
M.Shaposhnikov (07)

Indication to the Higgs potential

$$V = -\cancel{\mu^2|H|^2} + \cancel{\lambda(|H|^2)^2}$$

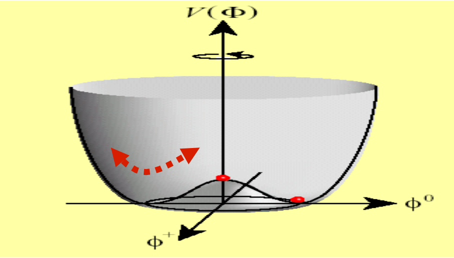


flat potential V(H)=0 at Planck.

M_{PL}

Radiatively generate

Coleman-Weinberg mechanism



EWSB @ M_{EW}

But CW does not work in SM.

the **large top Yukawa** coupling **invalidates the CW** mechanism

Extension of SM is necessary !

Meissner Nicolai (07)
Foot et al (07)

(B-L) extension of SM with flat Higgs potential at Planck

SM + B-L sector

- $U(1)_{B-L}$ gauge
- SM singlet scalar ϕ
- Right-handed ν

N Okada, Y Orikasa,
M. Hashimoto & SI
0902.4050 (PLB)
0909.0128 (PRD)

"Occam's razor" scenario

that can explain

- 126 GeV Higgs
- Naturalness problem
- ν oscillation, baryon asymmetry

B-L symmetry is radiatively broken via CW mechanism.
How does the EWSB occur ?

Flat potential is suggested by LHC

$$V(H) = 0 \quad @M_{PL}$$

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2}\Phi^2$$

classically conformal

126 GeV

key to relate EW and B-L @TeV

The coefficient must be small and negative.

$$\langle H \rangle = \sqrt{\frac{-\lambda_{H\Phi}}{\lambda_H}} M_{B-L}$$

Can the small scalar mixing be realized naturally?

→ Yes (Orikasa, SI 2012) : 1210.2848(PTEP)

Scalar mixing can be generated via gauge mixing of $U(1)_Y$ and $U(1)_{B\text{-}L}$

- U(1) mixing is radiatively generated

- Then a small negative scalar mixing is radiatively generated

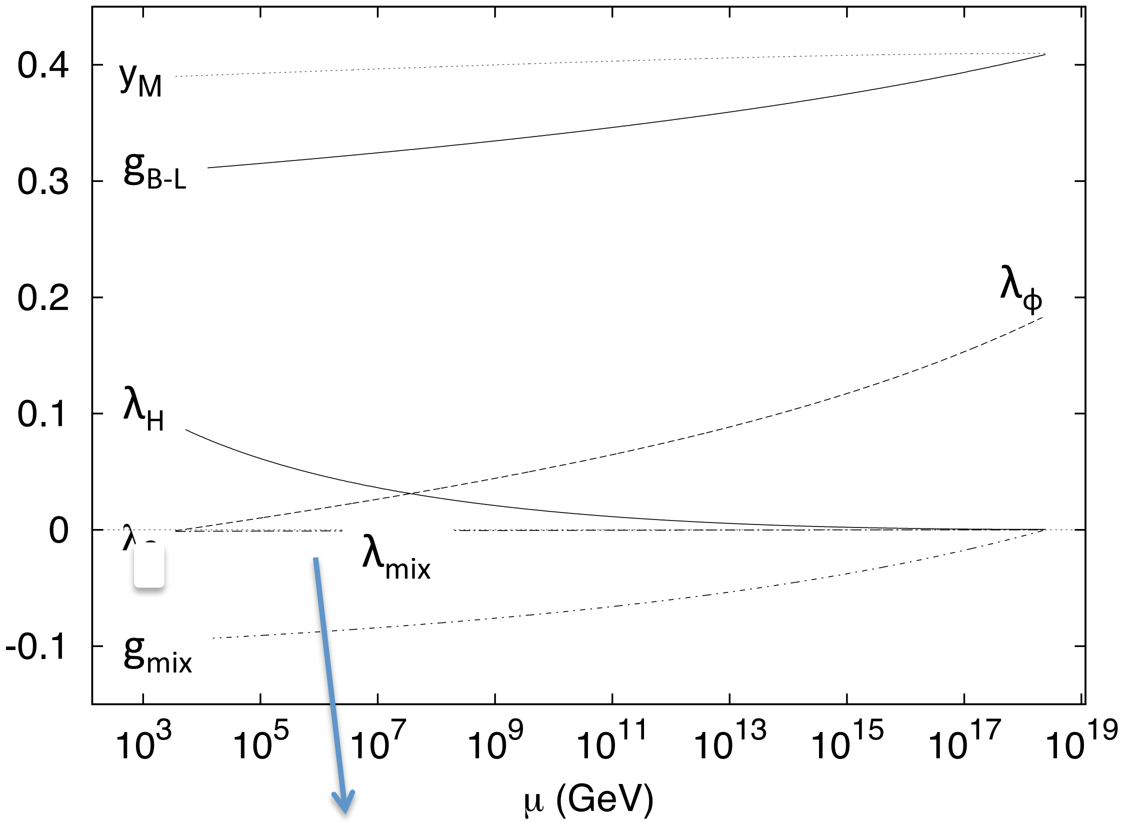
$$\frac{d\lambda_{H\Phi}}{dt} = \frac{1}{16\pi^2}\left(\boxed{6g_{B-L}^2 g_{mix}^2} + \lambda_{H\Phi}\times(\cdots)\right) \longrightarrow \lambda_{H\Phi} \sim -g_{B-L}^2 g_{mix}^2$$

The scalar mixing triggers EWSB.

The scalar mixing is very small and negative.
This triggers the EWSB.
→ small hierarchy between B-L scale and EW scale.

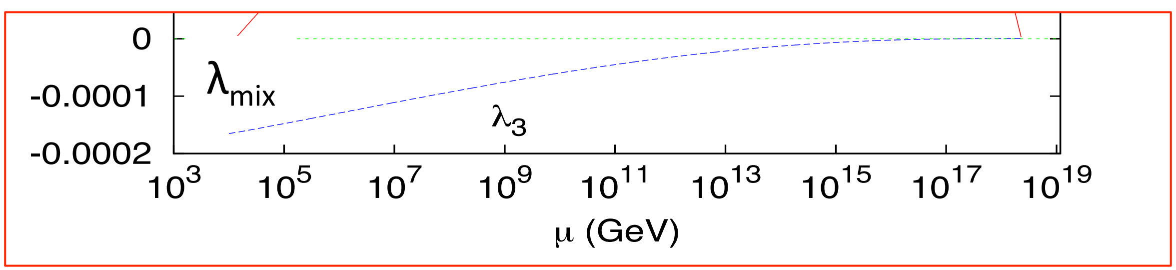
$$\langle H\rangle = \sqrt{\frac{-\lambda_{mix}}{\lambda_H}} M_{B-L} \sim c\frac{\alpha_{B-L}\alpha_Y}{\sqrt{\lambda_H}} M_{B-L}$$

A typical behavior of RGE



M_{B-L} = 3.55 TeV,
m_ϕ = 200 GeV,
m_N= 2.8 TeV

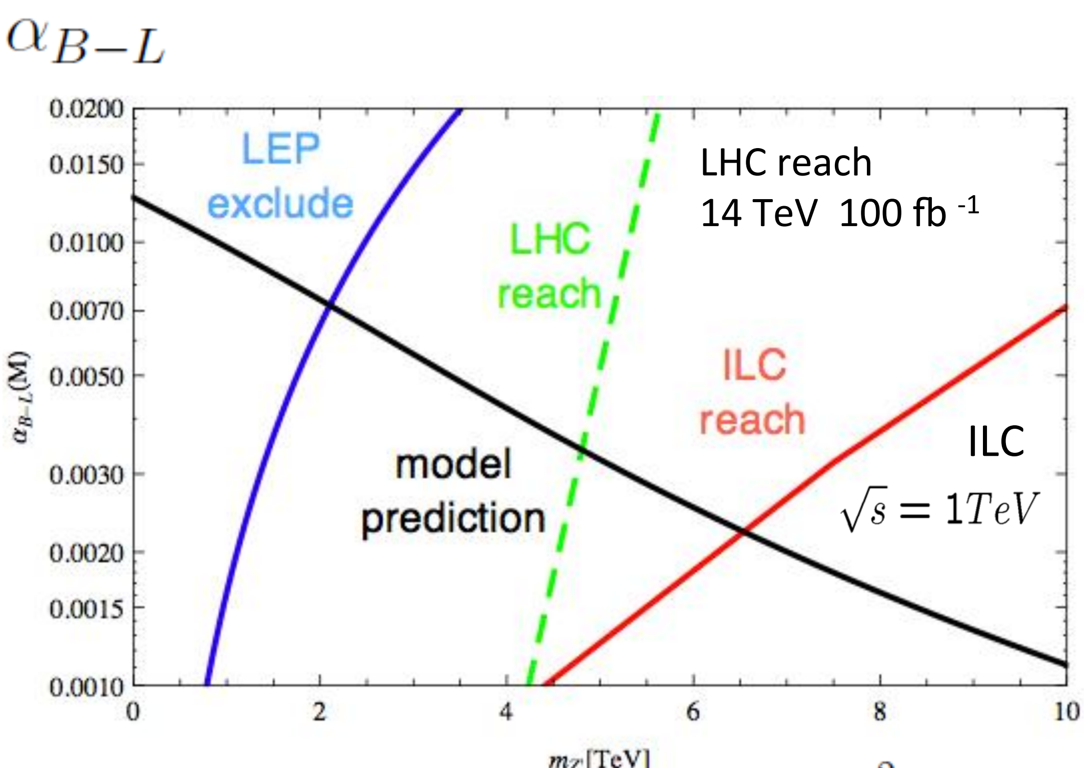
M_{EWSB} = 246 GeV,
m_H = 126 GeV



A small negative scalar mixing is generated !!

Prediction of the model

In order to realize EWSB at 246 GeV,
B-L scale must be around TeV (for a typical value of $\alpha_{B\text{-}L}$).



$$M_{B-L} \sim \frac{1}{\alpha_{B-L}} \times 35 \text{ GeV}$$

$$m_{Z'} \sim \frac{1}{\sqrt{\alpha_{B-L}}} \times 250 \text{ GeV}$$

$$\boxed{m_\phi \lesssim 0.1\ m_{Z'}}$$

$$m_{Z'}^2 = 16\pi\alpha_{B-L}(0)M_{B-L}^2$$

Y Orikasa, SI; 1210.2848(PTEP)

Flatland model

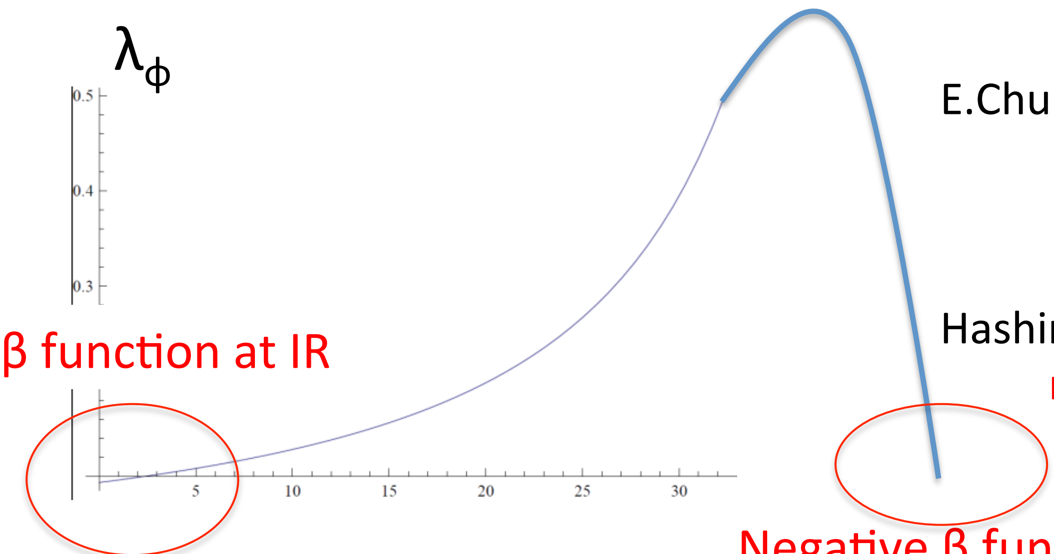
M. Hashimoto, Y.Orikasa, SI
arXiv/1310.4304 PRD
1401.5944 PRD

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2 \Phi^2} + \cancel{m_\phi^2 \phi^2} + \boxed{\lambda_\phi \phi^4}$$

Can we further throw away the last term ?

Radiative generation of
scalar potential from nothing !!

If SSB occurs in Flatland, we need a behavior like



Positive β function at IR

E.Chun, S.Jung, H.Lee (2013)

Hashimoto, Orikasa, SI (2013)

necessary condition

for flatland scenario

Negative β function at UV

$$\frac{d\lambda_\Phi}{dt} = \frac{1}{16\pi^2}\left(20\lambda_\Phi^2 + 2\lambda_{mix}^2 - Tr\left[Y_N^4\right] + 96 g_{B-L}^4 + \lambda_\Phi\left(2Tr\left[Y_N^2\right] - 48 g_{B-L}^2\right)\right)$$

Balance between Y_N and $g_{B\text{-}L}$ is necessary

K

A necessary and (almost) sufficient condition for both CW mechanism at IR and Flatland at UV to occur

Gauge-Yukawa-Higgs system
(abelian gauge theory with a scalar ϕ and a fermion)

g: gauge coupling
y: Yukawa coupling
λ: quartic self-coupling of scalar $\lambda \phi^4$

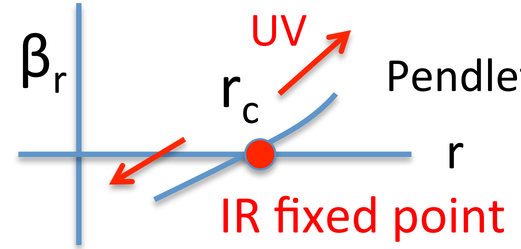
$$\beta_g \equiv \mu \frac{\partial}{\partial \mu} g = \frac{a}{16\pi^2} g^3,$$

$$\beta_y \equiv \mu \frac{\partial}{\partial \mu} y = \frac{y}{16\pi^2} \left[b y^2 - c g^2 \right],$$

$$\beta_\lambda \equiv \mu \frac{\partial}{\partial \mu} \lambda = \frac{1}{16\pi^2} \left[- d y^4 + f g^4 + \cdots \right]$$

a, b, c, d >0

$$16\pi^2 \mu \frac{\partial}{\partial \mu} = \frac{\partial}{\partial t} \qquad r = y/g$$

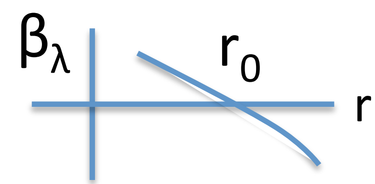


Pendleton,Ross (81)

$$\begin{aligned} \dot{g} &= a g^3 \\ \dot{y} &= y(b y^2 - c g^2) \\ \boxed{\dot{\lambda} = -d y^4 + f g^4.} \end{aligned}$$

$$\longrightarrow \boxed{\dot{r} = bgy(r^2 - r_c^2),}$$

$$\boxed{r_c = \sqrt{\frac{a+c}{b}}.}$$



If CW occurs at IR (t=0) → $\beta_\lambda > 0$ → $r(t=0) < r_0.$

increase

If Flatland at UV($t=t_{UV}$) → $\beta_\lambda < 0$ → $r(t = t_{UV}) > r_0$

$$\boxed{r_0 = \left(\frac{f}{d}\right)^{1/4}.}$$

$$r_c < r(t=0) < r_0 < r(t_{UV})$$

$$K = \left(\frac{r_c}{r_0}\right)^2 = \frac{a+c}{b}\sqrt{\frac{d}{f}} < 1.$$

$$K = \left(\frac{r_c}{r_0}\right)^2 = \frac{a+c}{b}\sqrt{\frac{d}{f}} < 1.$$

M.Hashimoto, Y.Orikasa, SI
1310.4304 (PRD)

In the B-L model with (N_g, N_ϕ, N)

- N_g : # of generations coupled with the B-L gauge
- N_ϕ : # of SM singlet scalars
- N : # of right-handed neutrinos with large Yukawa coupling

$$(3,1,1) = 1.22, \quad (3,1,2) = 1.3, \quad (3,1,3) = 1.27,$$
$$(2,1,1) = 0.982, \quad (2,1,2) = 1.04, \quad (1,1,1) = 0.74$$

Gauging (B-L)+ α Y → K can be smaller than (but close to) 1
various other models for N_g =3

M.Hashimoto, Y.Orikasa, SI
1401.5944 (PRD)

back

If K is close to 1, the scalar mass m_ϕ becomes very light.

$$m_\phi^2 = \beta_\lambda(0) M^2 = \frac{M^2}{16\pi^2}\left(-d y^4(M) + f g^4(M)\right) > 0.$$

Mass of the scalar is proportional to the β function

$\boxed{K \sim 1 \rightarrow \ r(M) \sim r_c \ \rightarrow \ m_\phi \ll M}$

$\rightarrow \ M\nu_R \sim M_{Z'}$

$$\frac{m_\phi^2}{M_{Z'}^2} + N_\nu \frac{g_{B-L}^2}{\pi^2}\frac{M_{\nu_R}^4}{M_{Z'}^4} \simeq \frac{3 g_{B-L}^2}{2\pi^2}$$

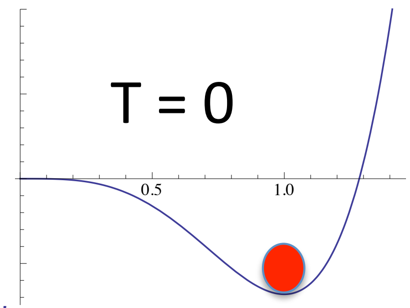
In the flatland scenario, SM singlet Higgs becomes very light.

Cosmological implication

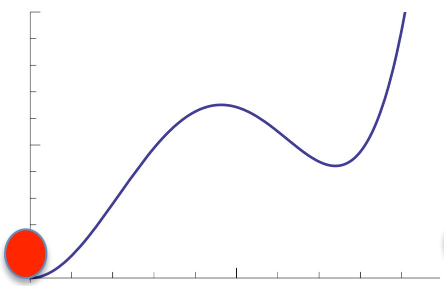
K.Kohri, K.Shimada, SI
to appear

Classical conformal models generically have very flat potential, and suitable for cosmological applications (inflaton).

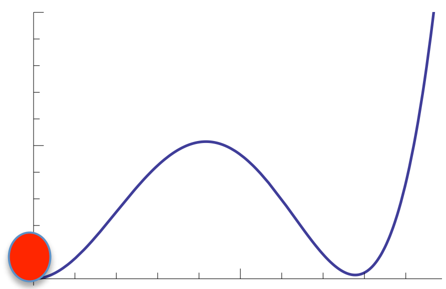
A common issue in classical conformal models is
supercooling of the false vacuum



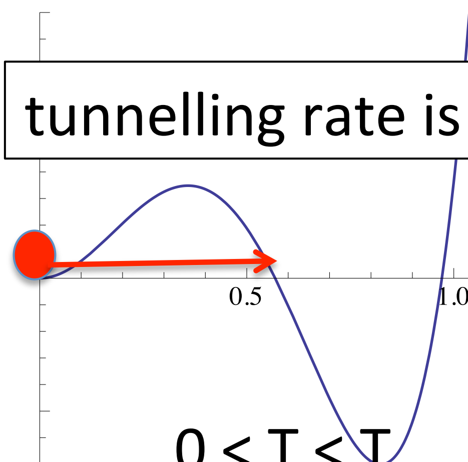
$T = 0$



$T > T_c$



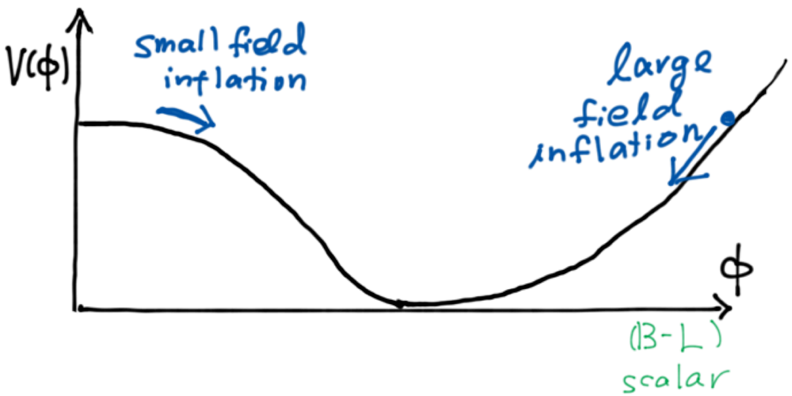
$T = T_c = O(m_\phi)$



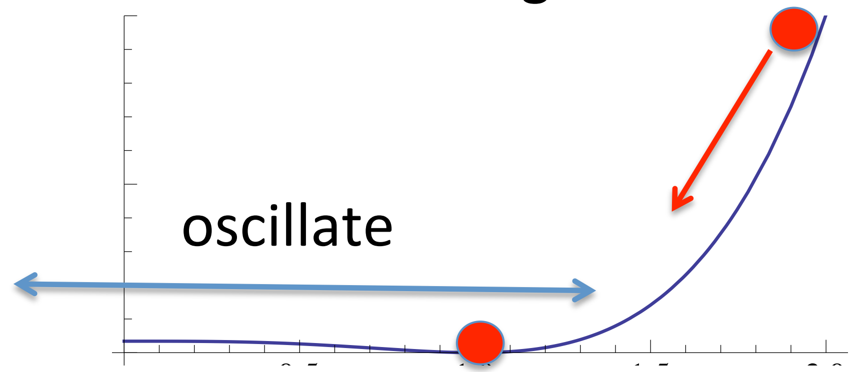
tunnelling rate is very small.

$0 < T < T_c$

Possible cosmic scenarios



Large field inflation



(1) Large field inflation (chaotic inflation) with $\boxed{T_{RH} < T_c = O(M_\phi)}$

State falls in the true vacuum.

Fluctuations of CMB are generated during the LFI.

$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \approx 8\left(\frac{M_{\rm Pl}}{\phi}\right)^2$$

$$\eta = M_{\rm Pl}\left(\frac{V''}{V}\right) \approx 12\left(\frac{M_{\rm Pl}}{\phi}\right)^2$$

$$n_s = 1 - 6\epsilon + 2\eta = 1 - 3\epsilon = 0.9603 \pm 0.0073$$

$$\rightarrow \quad r = 16\epsilon \sim 0.208$$

$$N = \int_t^{t_{end}} H dt = \frac{1}{8M_{\rm Pl}^2}(\phi^2 - \phi_{end}^2) \sim \frac{1}{\epsilon} - \frac{1}{8}$$

$$\Delta_R^2 = \frac{V}{24\pi^4 M_{\rm Pl}^2 \epsilon} = \frac{\lambda_0}{44\pi^2}\left(\frac{\phi}{M_{\rm Pl}}\right)^2 \ln\frac{\phi^2}{M^2} = \frac{2\lambda_0}{11\pi^2\epsilon}\ln\frac{\phi^2}{M^2}$$
$$= \frac{2\lambda_0}{11\pi^2}\frac{\ln(8M_{\rm Pl}^2/M^2) - \ln(\epsilon)}{\epsilon} = 2.215\times 10^{-9}.$$

→ $\lambda_0 \sim 10^{-7}\times\epsilon/\log\text{ factor} \sim 10^{-10}$ very small quartic coupling

λ_0 is the physical quartic coupling at $M_{B\text{-}L}$ $\beta_\lambda = 3\lambda_0/11$

$$M_\phi \sim 10^{-5} M_{B\text{-}L}$$

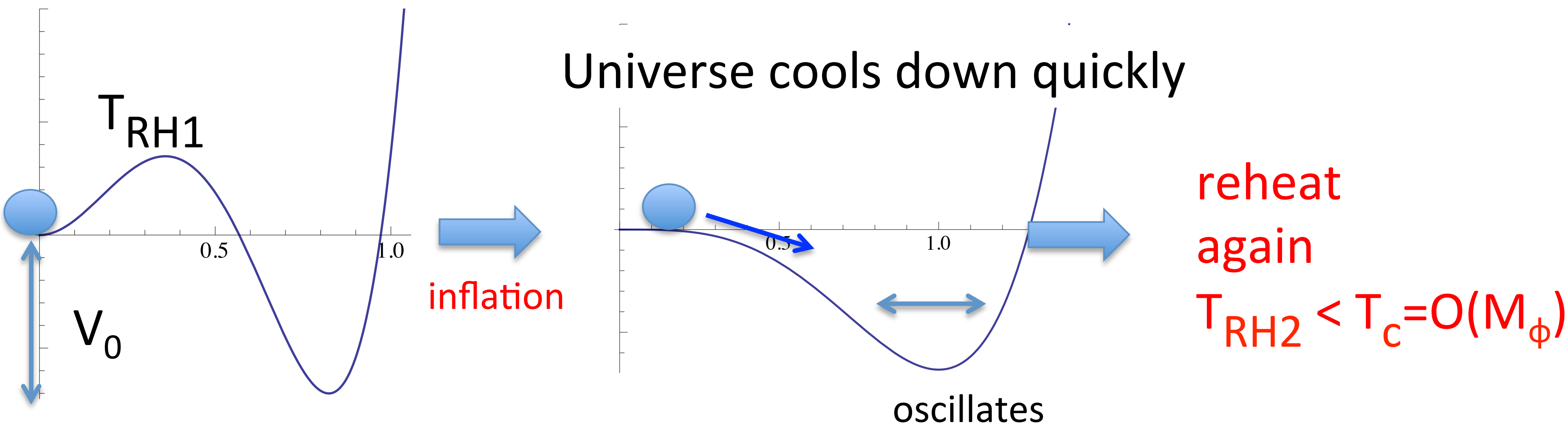
scalar is very light compared to $M_{B\text{-}L}$

$T_{EW} < M_{N1} < T_{RH} < M_\phi \sim T_c \ll M_{Z'} \sim M_{N2} \sim M_{B\text{-}L}$

e.g. 500 GeV $5 * 10^4$ TeV

(2) After LFI, $\boxed{T_{RH1} > T_c}$ → state falls in the false vacuum.

Second inflation occurs due to $V_0 > 0$



In this scenario, fluctuations of CMB are generated during the second inflation (new inflation).

$$\epsilon \approx 32 \left(\frac{M_{\rm Pl}}{M}\right)^2 \left(\frac{\phi}{M}\right)^6 \left(\ln \frac{\phi^2}{M^2}\right)^2$$
$$\eta \approx 24 \left(\frac{M_{\rm Pl}}{M}\right)^2 \left(\frac{\phi}{M}\right)^2 \ln \frac{\phi^2}{M^2}.$$

Since $\phi \ll M$

$$\epsilon \ll |\eta|$$

$\longrightarrow$ $n_s \approx 1 + 2\eta$ $\boxed{r \sim 0}$

$N \approx \frac{3}{2}\left(\frac{1}{|\eta|} - \frac{1}{|\eta_{end}|}\right)$ → $\eta \sim -0.025$ → $n_s = 0.95$

In order to be consistent with the amplitude of scalar perturbation

$$\Delta_R^2 \approx \frac{V_0^4}{24\pi^2 M_{\rm Pl}^4 \epsilon} = \frac{3\lambda_0 M^4}{24 \times 88\pi^2 M_{\rm Pl}^4 \epsilon} = 2.215 \times 10^{-9}$$

$\longrightarrow$ $\lambda_0 = 10^{-16}$ → $M_\phi \sim 10^{-8}\, M_{B-L}$

$T_{EW} < M_{N1} < T_{RH} < M_\phi \sim T_c \ll M_{Z'} \sim M_{N2} \sim M_{B-L}$

e.g. 500 GeV $5 * 10^7$ TeV

Conclusions

- LHC results tell us about the shape of the Higgs potential

  Constraint on susy → Naturalness problem → classical conformal

  126 GeV → flat Higgs potential at Planck scale

- Classically conformal models with flat potential at Planck

  Experimentally, SM is NOT sufficient.

  (neutrino mass, baryon number, DM etc.)

  Theoretically too. Radiative generation of EW scale needs BSM.

[Origin of Higgs potential (EWSB)]

→ classical conformal B-L model with flat boundary condition at M_{PL}

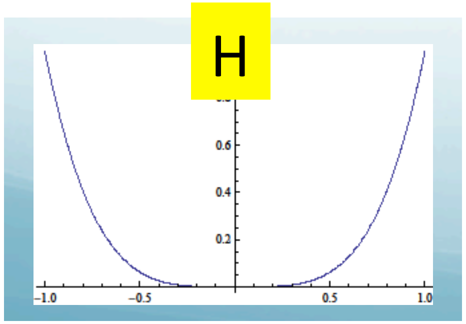
prediction : TeV scale B-L (or further extended) sector

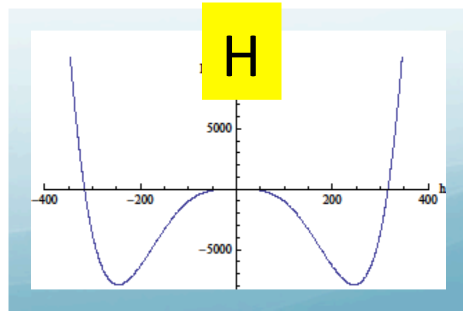
very light SM singlet scalar $M_{\Phi} < M_{Z'}$

also TeV scale seesaw $M\nu_R$

Various types of Coleman-Weinberg models

(1) original type

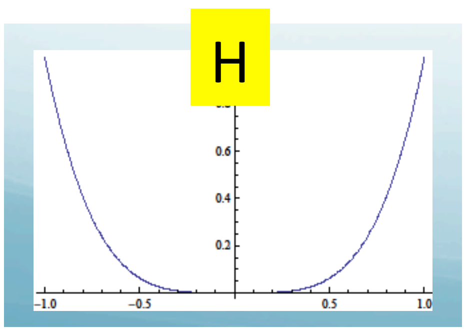




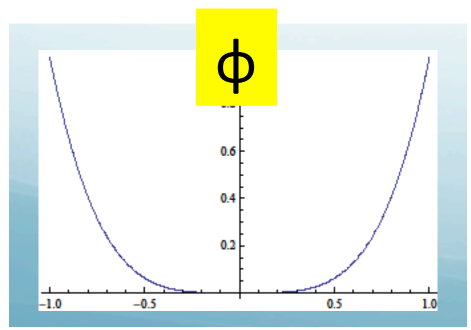
Coleman -
Weinberg (1973)

But CW does not work in SM. Introduce ϕ sector.

(2) SM + additional sector



+



$-\lambda_{mix} H^2 \Phi^2$ coupling assumed

Meissner Nicolai (2007)
Foot et.al (2007)

Iso Okada Orikasa (2009)
Holthausen Lindner Schmidt (2009)
Hill, Lykken
and many others after LHC

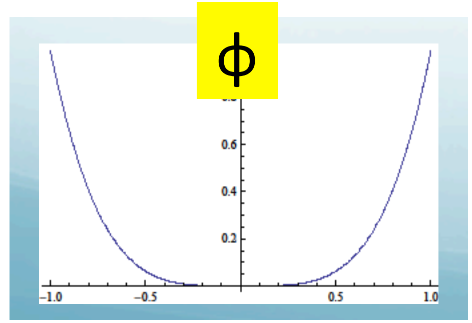
(3) Radiative generation of V(H) and scalar mixing

126 GeV (stability)

flat potential

H

+



Iso Orikasa (2012)

- $\lambda_{mix} H^2 \Phi^2$ coupling radiatively generated via U(1) mixing

(4) Flatland scenario

flat potential

H

+

flat potential

ϕ

Chung Jung Lee (2013)
Hashimoto Iso Orikasa (2013, 14)

Everything can be radiatively generated.

Important issues to be understood

(1) Supercooling problem

2 approaches : enhance tunneling rate

or combined with inflationary scenario

inflation → potential becomes extremely shallow

$M_\phi \ll M_{B\text{-}L}$

(2) Planck scale boundary condition

gauge-Higgs unification at Planck scale

or Nonsupersymmetric vacuum of superstring

with GUT broken at M_{string}

stable massless scalar with flat potential

Thank you for your attention.

You are welcome to visit KEK
based on MOU between us.