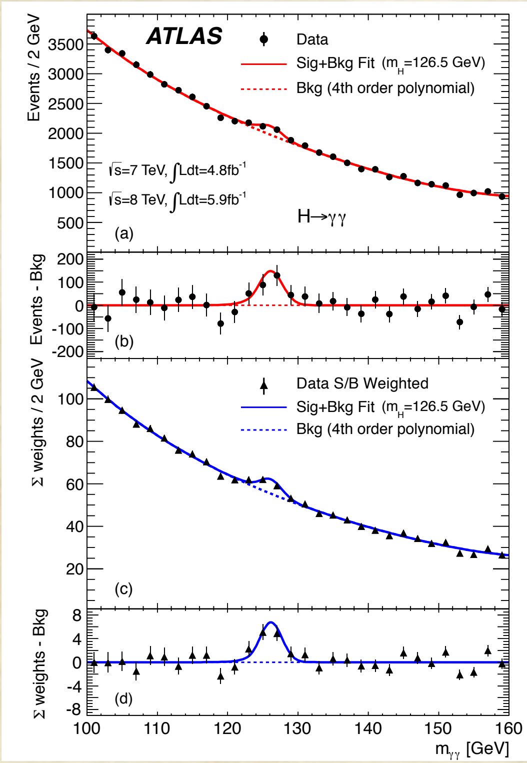
On the electroweak vacuum stability in the inflationary Universe

based on: M.Asano, KK, O.Lebedev, & A.Westphal, in preparation

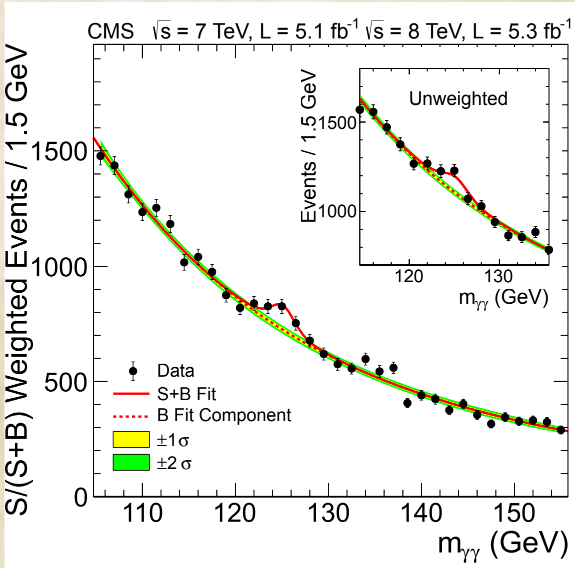
Kohei Kamada
(DESY theory group)

PLANCK2013 @ Bonn, 21/5/2013

July, 2012, a (SM) Higgs boson with mass around 125 GeV is found at LHC!



ATLAS, 1207.7214



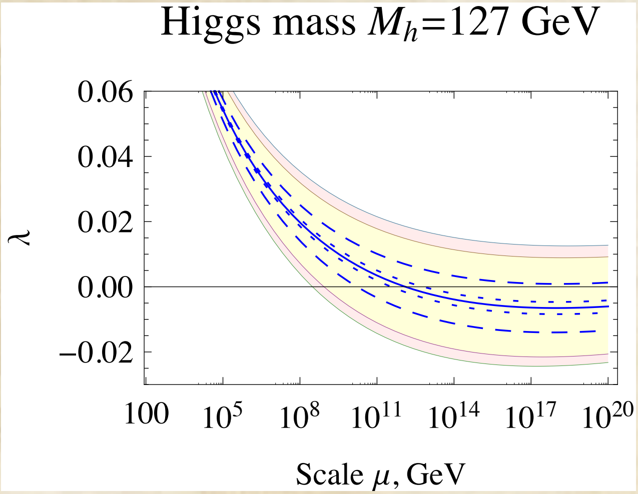
CMS, 1207.7235

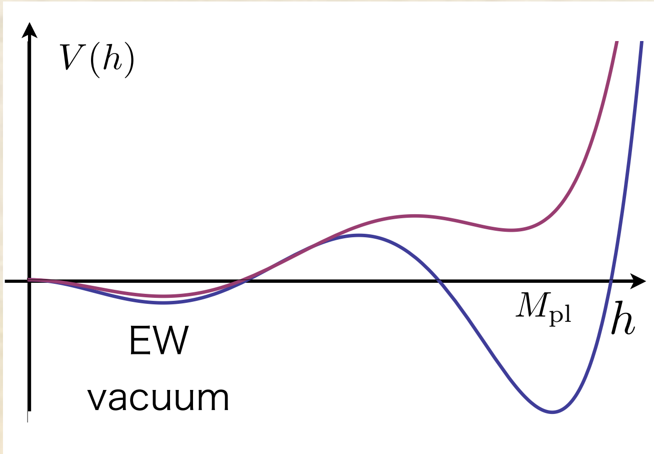
...and the data supports the SM more and more strongly.

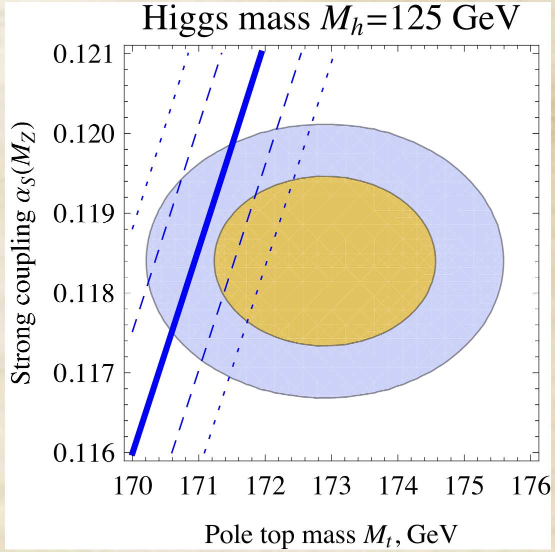
Any deviation from the SM has not been reported thus far.

The important implication from 125 GeV Higgs

-> stability of Higgs potential





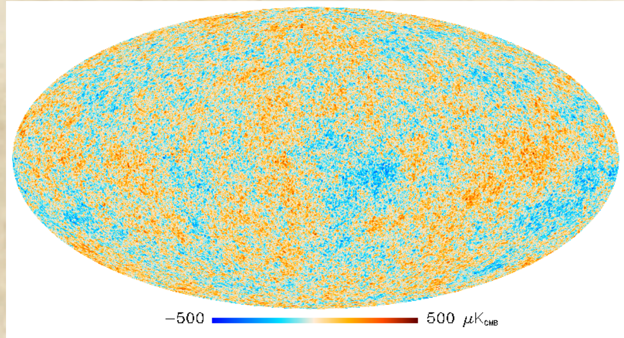


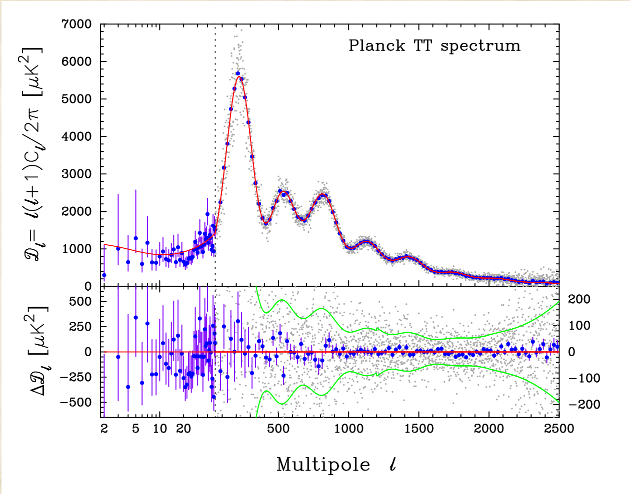
Bezrukov+ (12)

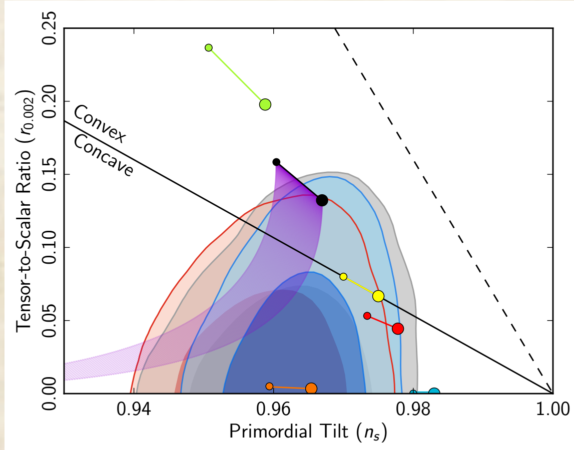
There remain possibilities of "Higgs inflations."

But, parameter space becomes very small. Bezrukov+ (08), KK+ (12)

CMB observation such as Planck strongly suggests inflation.





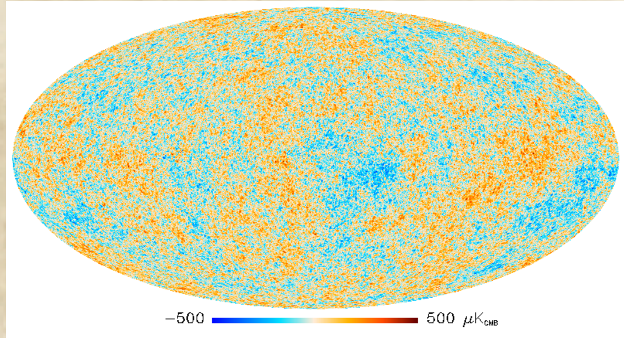


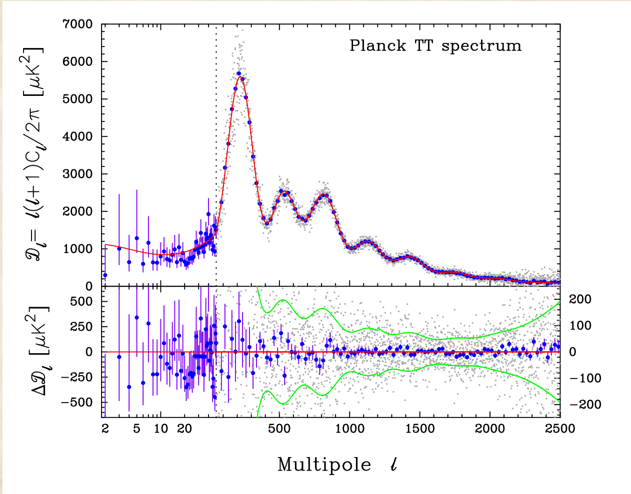
Planck collaboration (13)

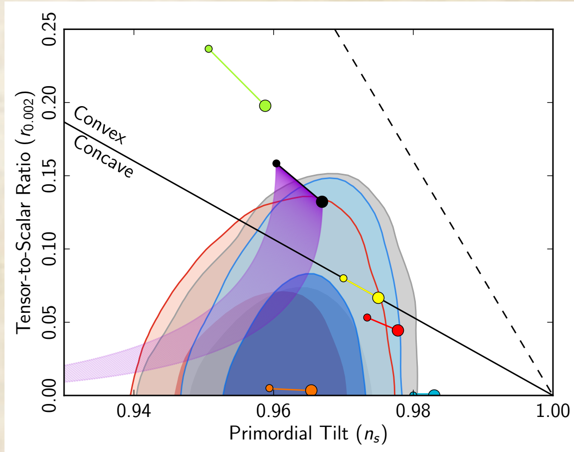
If the Electroweak vacuum is metastable, Higgs inflation is almost impossible, and hence we need other scalar field to realize inflation. Furthermore, another problem arises,

"how to stabilize Higgs during inflation?".

CMB observation such as Planck strongly suggests inflation.







Planck collaboration (13)

If the Electroweak vacuum is metastable, Higgs inflation is almost impossible, and hence we need other scalar field to realize inflation. Furthermore, another problem arises,

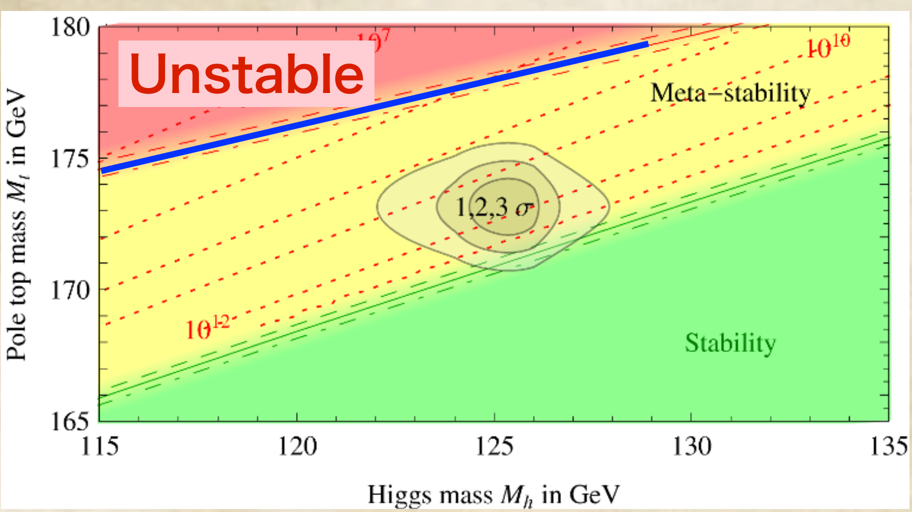
"how to stabilize Higgs during inflation?".

Here we assume that inflation is driven in the other sector than the SM, characterizing by $H_{\rm inf}$ and T_R , and focus on the electroweak vacuum stability.

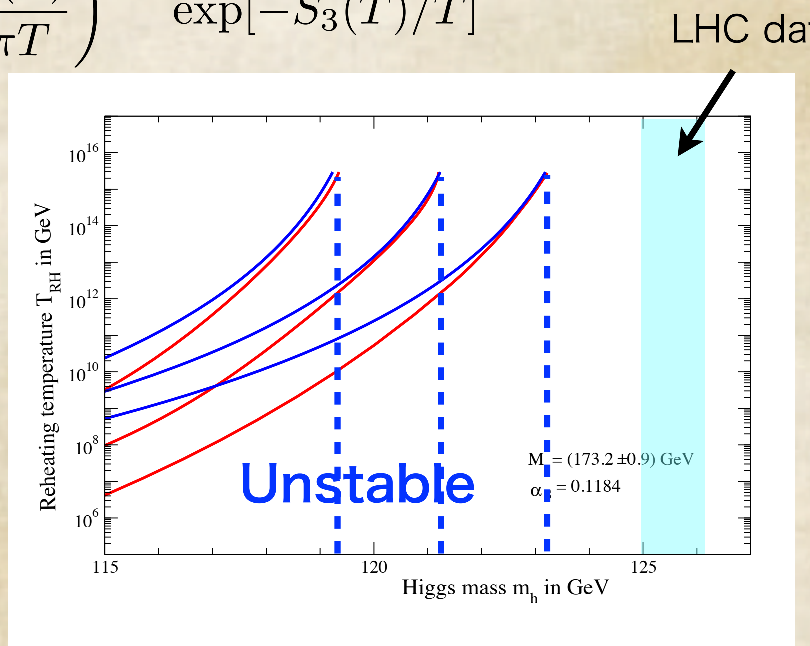
Can we live in a metastable electroweak vacuum?

-zero temperature decay : $p \sim \max \ \{\tau^4 h^4 \exp[-8/3|\lambda(h)|]\}$

-thermal decay : $\Gamma(T) \sim T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp[-S_3(T)/T]$



Degrassi+ (12)



Elias-miró+ (12)

Current data suggests that
we live in a “safe” meta-stable vacuum.

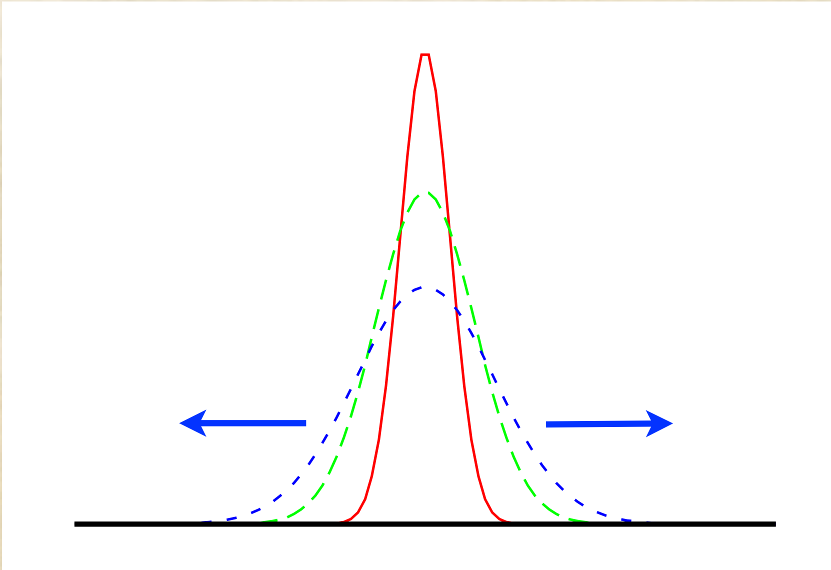
Are we all right?

No, quantum fluctuation during inflation is different and we need another consideration.

Are we all right?
No, quantum fluctuation during inflation is different and we need another consideration.

During inflation, or quasi-de Sitter BG, the expectation value of the light (massless) scalar field evolves as

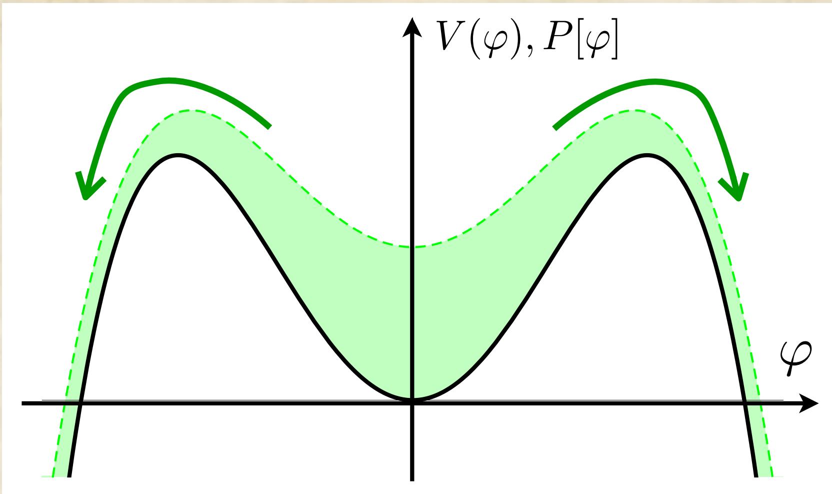
$$\langle \varphi^2 \rangle = \frac{H_{\rm inf}^2}{4\pi^2} \mathcal{N}_e$$



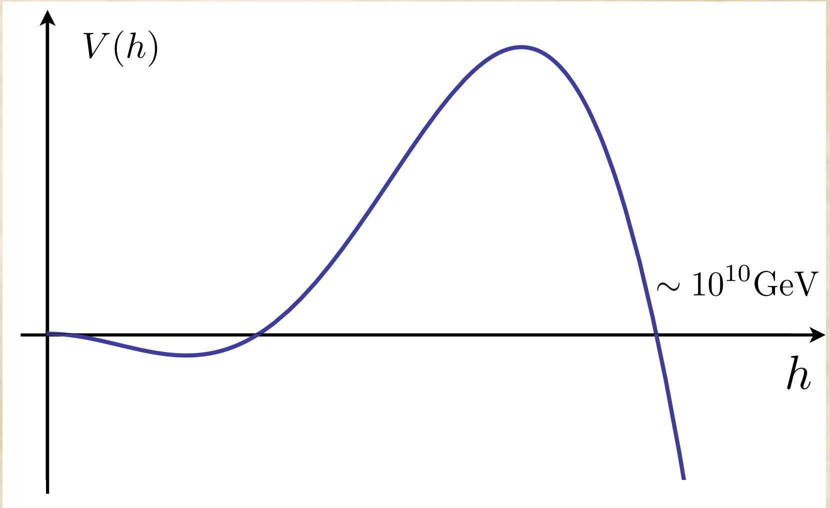
For more complicated potential, one can solve Fokker-Planck equations or Langevin equations.

Starobinsky & Yokoyama (93)

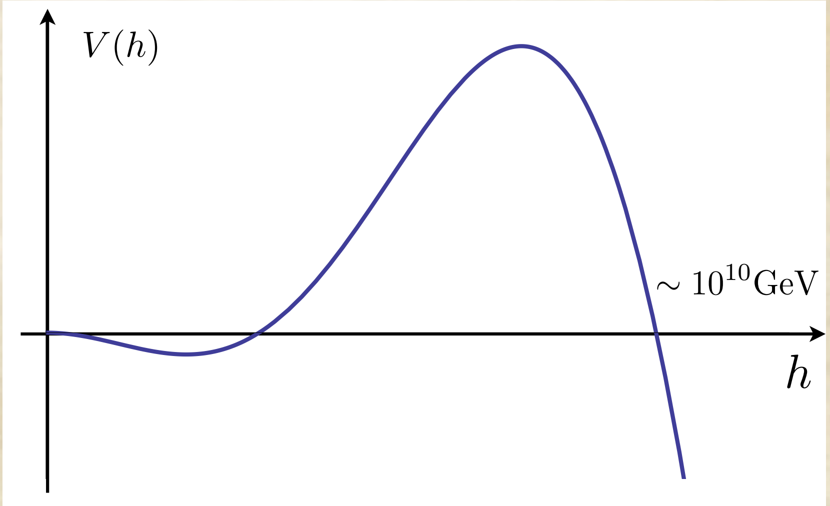
As a result, even if the field starts from the metastable vacuum, it easily takes over the potential barrier and falls down to the unwanted vacuum if the potential barrier is low enough compared to the Hubble parameter during inflation.



In the case of metastable SM electroweak vacuum, if the Hubble parameter during inflation is larger than 10^{10} GeV, the Higgs field easily climbs up the potential barrier and makes our Universe very unlikely, which can be determined by the observation of the tensor perturbation in CMB.



In the case of metastable SM electroweak vacuum,
if the Hubble parameter during inflation is larger than 10^{10} GeV,
the Higgs field easily climbs up the potential barrier and
makes our Universe very unlikely,
which can be determined by the
observation of the tensor
perturbation in CMB.



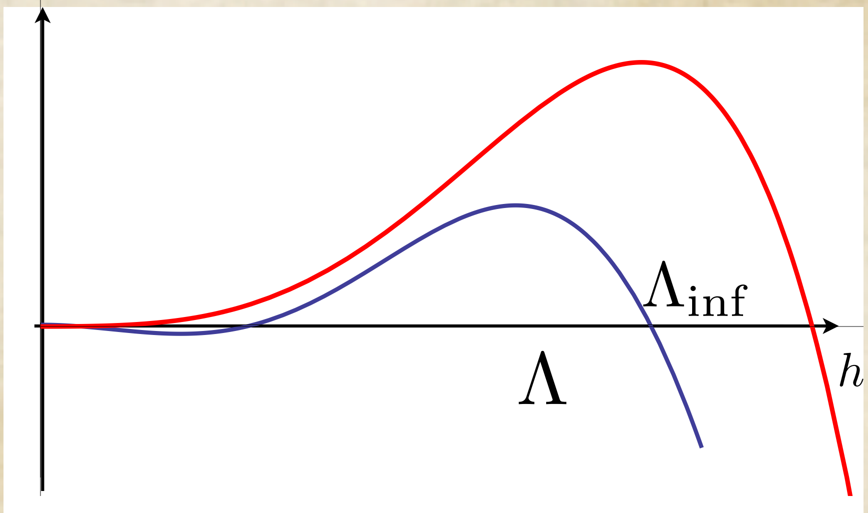
One solution may be to say
our Universe is selected anthropically,
but is there any way to relax the situation
without introducing another physical degree of freedom?

Here we propose another solution, which does not need any anthropic discussion.

Here we propose another solution, which does not need any anthropic discussion.

Introduce "Hubble-induced mass" during and after inflation to modify the Higgs potential.

$$\Delta V(h) = \frac{1}{2} c_{\mathrm{inf/osc}} H^2 h^2$$



The potential barrier becomes further and higher.

We comment on the origin of the Hubble induced mass later.

If the coefficient $c_{\rm inf}$ is much larger than one, the Higgs field is fixed at the origin with very small quantum fluctuation ⇒ sufficiently safe. cf. Lebedev&Westphal (13)

Initial value problem of the Higgs field is also solved !!

If the coefficient $c_{\rm inf}$ is much larger than one, the Higgs field is fixed at the origin with very small quantum fluctuation ⇒ sufficiently safe. cf. Lebedev&Westphal (13)

Initial value problem of the Higgs field is also solved !!

How small can the coefficient be?

Can not the case with $c_{\rm inf} < 1$ relax the situation?

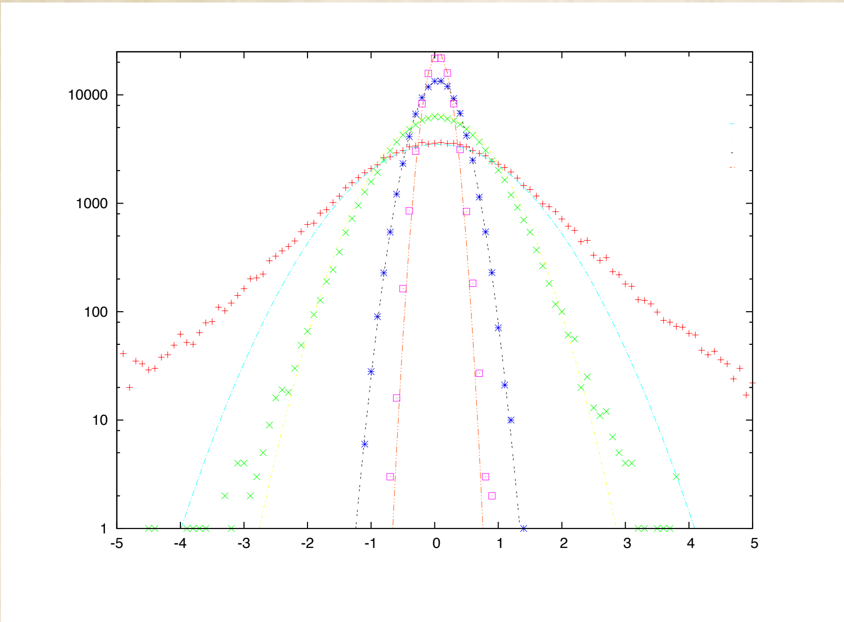
If the coefficient $c_{\rm inf}$ is much larger than one, the Higgs field is fixed at the origin with very small quantum fluctuation ⇒ sufficiently safe. cf. Lebedev&Westphal (13)

Initial value problem of the Higgs field is also solved !!

How small can the coefficient be?
Can not the case with $c_{\rm inf} < 1$ relax the situation?

We find that even in the case $c_{\rm inf} < 1$
we can have a scenario that leads to the present Universe !!

We solved the Langevin equation numerically and found that the distribution of the Higgs field is well described by Gaussian if $\langle h^2 \rangle < \Lambda_{\rm inf}^2$



In this case, in many spatial part of the Universe the Higgs field remain inside the potential barrier and can be said “safe”.

$$c_{\rm inf} > \sqrt{\frac{-3\tilde{\lambda}}{8\pi^2}} \simeq 1.9 \times 10^{-2} \left(\frac{\tilde{\lambda}}{-0.01} \right)^{1/2}$$

After inflation, the Higgs field evolves as

$$\ddot{h} + 3H(t)\dot{h} + \frac{\partial V(H(t), h)}{\partial h} = 0$$

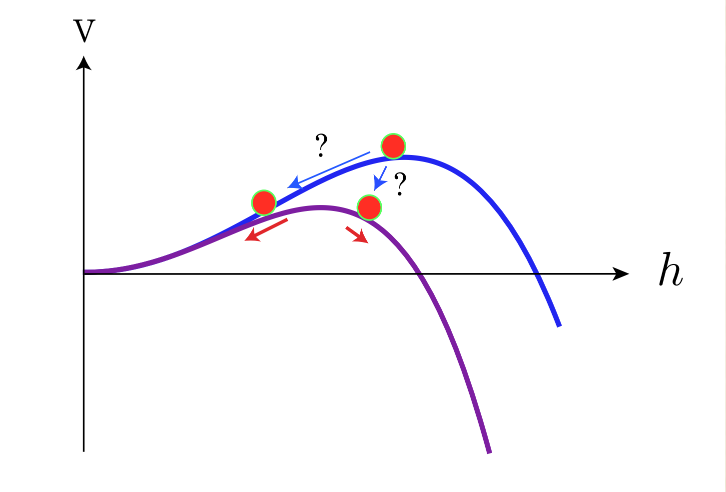
with an initial condition, typically, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \frac{\sqrt{3} H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

After inflation, the Higgs field evolves as

$$\ddot{h} + 3H(t)\dot{h} + \frac{\partial V(H(t), h)}{\partial h} = 0$$

with an initial condition, typically, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \frac{\sqrt{3} H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

For small coefficient, $c_{\rm osc} < 9/16$, the Higgs field decreases much slower than the potential barrier and may be taken over by it.

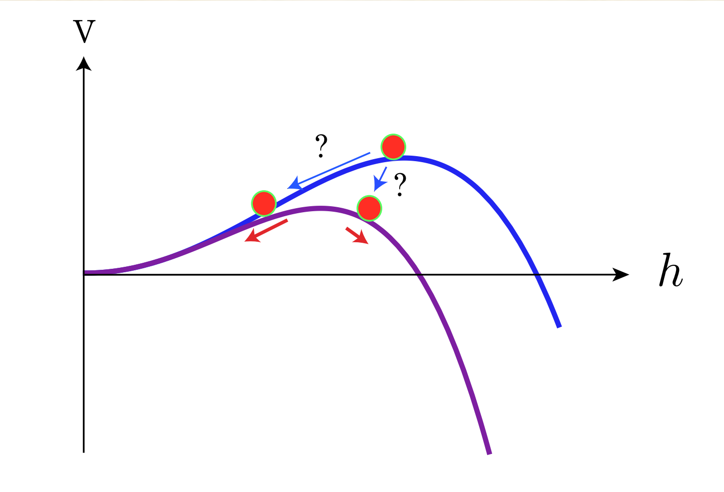


After inflation, the Higgs field evolves as

$$\ddot{h} + 3H(t)\dot{h} + \frac{\partial V(H(t), h)}{\partial h} = 0$$

with an initial condition, typically, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \frac{\sqrt{3}H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

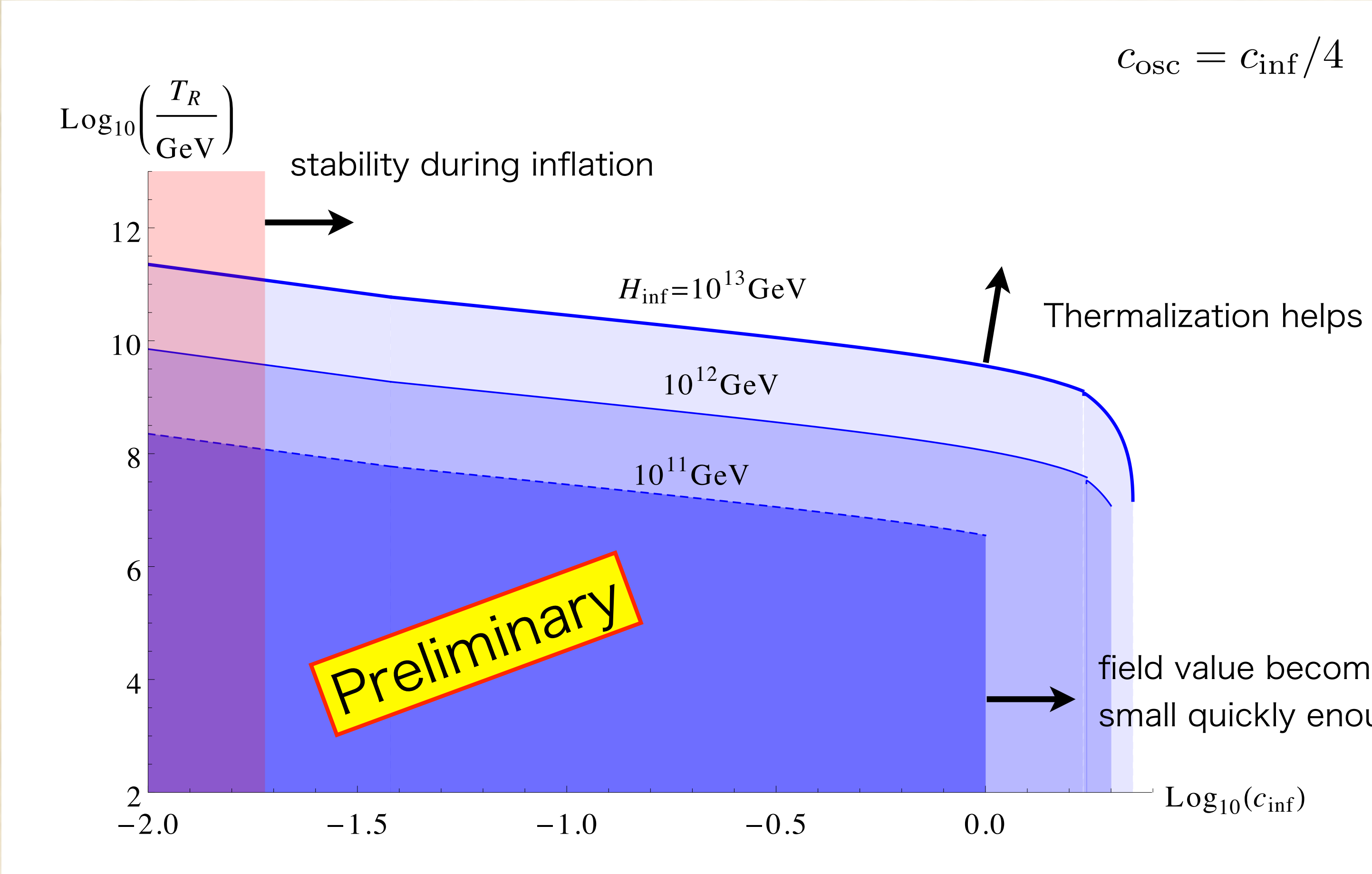
For small coefficient, $c_{\rm osc} < 9/16$, the Higgs field decreases much slower than the potential barrier and may be taken over by it.



We are safe if…

- Thermalization takes place earlier.
- The Higgs field value becomes small enough, $h(t) < \Lambda_0$ sufficiently quickly.

Then we get the constraint on the model parameters.



Relatively large reheating temperature is required, which can be tested by future gravitational wave experiments.

Possible origin of the Hubble-induced mass

- Direct coupling to inflaton

(Lebedev&Westphal (13))

$$\lambda_i h^2 \phi_{\rm inf}^2 \to \frac{m_{h,\rm eff}^2}{2} h^2 \quad \Rightarrow \quad \lambda_i \sim 10^{-12\sim 13}$$

(for massive chaotic inflation)

works in the case of large field inflation

- Non-minimal coupling to gravity

$$\xi R h^2 \to 12 \xi H^2 h^2 \quad \Rightarrow \quad \xi \sim 10^{-1\sim 2}$$

works in any inflation models.

Summary

- The present data of LHC suggests the metastability of the electroweak vacuum.
- Though it is safe against the zero-temperature and thermal decay, it is problematic for high-scale inflation.
- By considering non-minimal coupling of the Higgs field, the situation can be relaxed dramatically.
- If the reheating temperature high enough, the non-minimal coupling does not have to be large, which can be tested in the future gravitational wave experiments.
- In this case, we do not need any anthropic arguments.