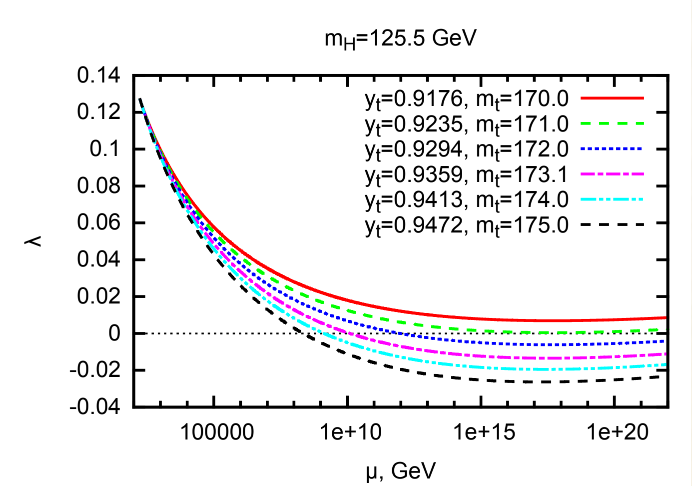
Standard Model Higgs in the inflationary Universe

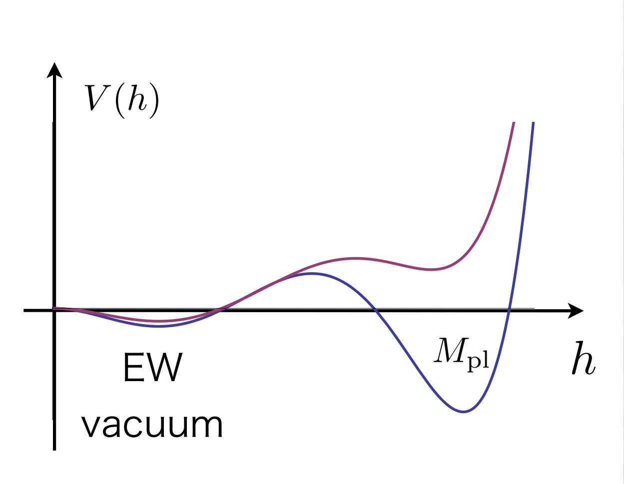
based on: KK PLB 742 (2015) 126, arXiv: 1409.5078 [hep-ph]

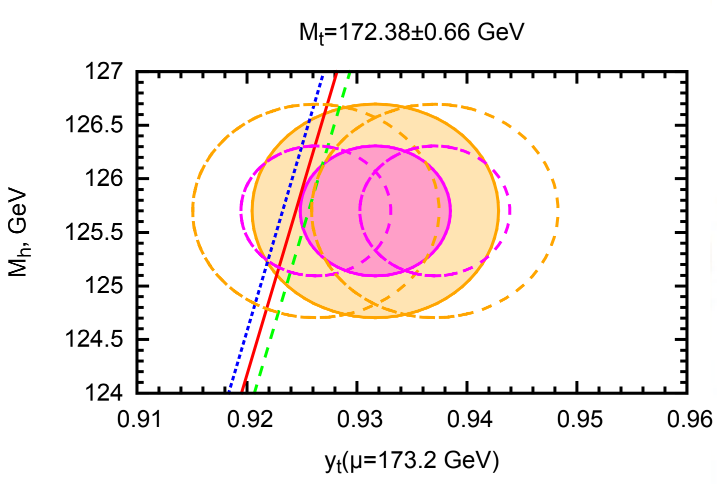
Kohei Kamada
(Arizona State University)

DSU 2015 @ Kyoto, 12/14/2015

LHC discovered a 125 GeV Higgs boson.
The important implication from 125 GeV Higgs
-> stability of Higgs potential







Bezrukov+ (14)

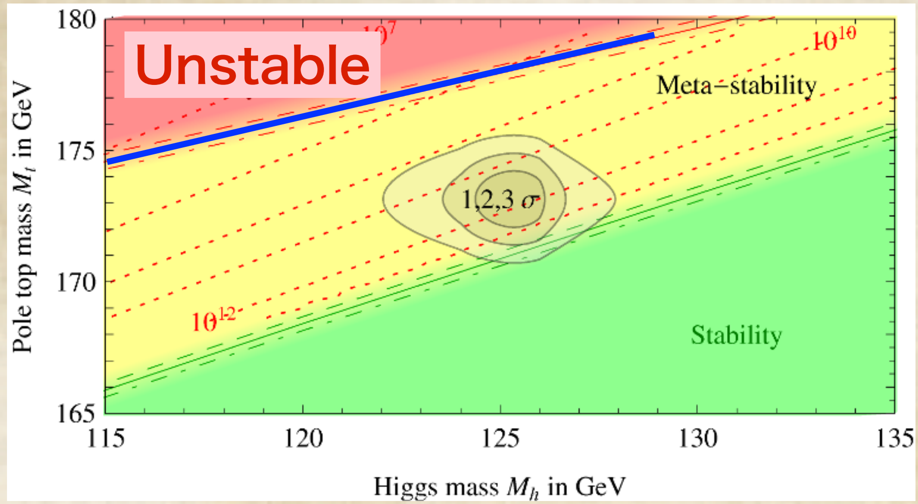
Many part of the allowed parameter space suggests that the electroweak vacuum is not stable if there are no new physics beyond the SM.

-> Do we need BSM?

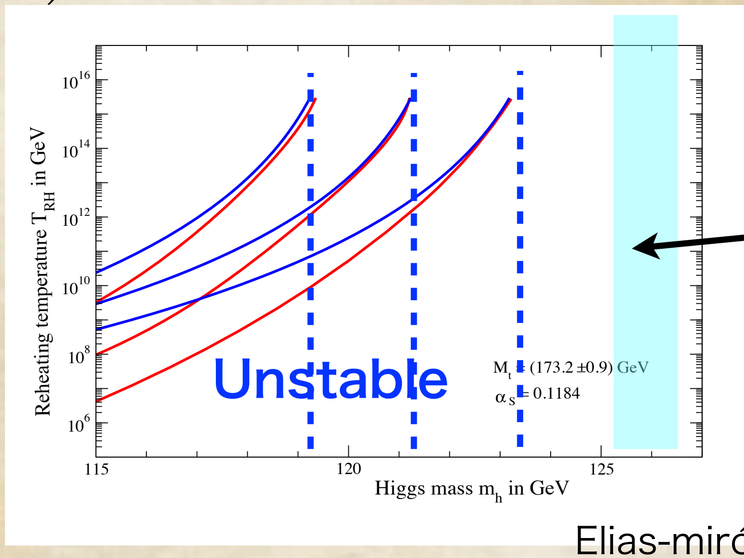
Can we live in a metastable electroweak vacuum?

-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)



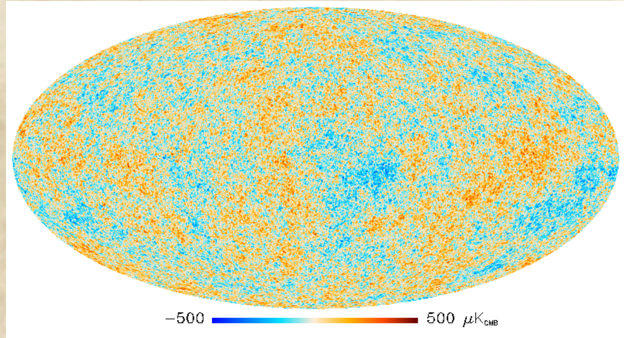
Elias-miró+ (12)

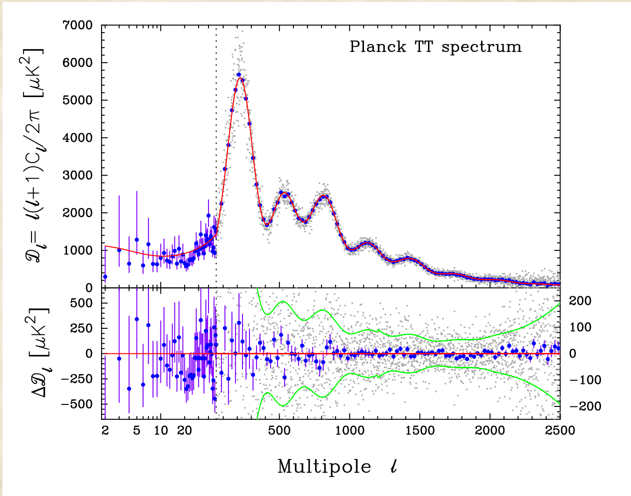
(See also ’15 Shkerin+.)

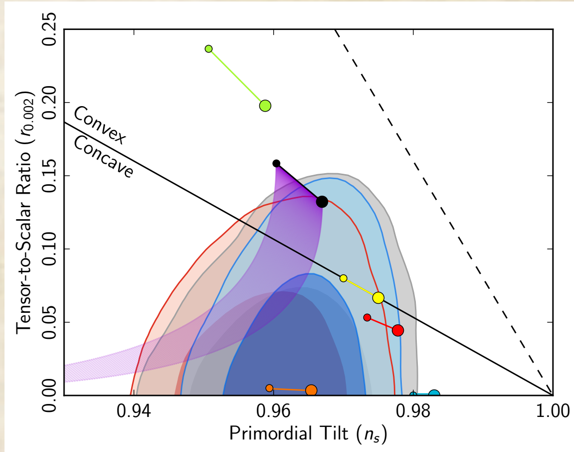
Current data suggests that
we live in a “safe” meta-stable vacuum.

=> We cannot say BSM is necessary in this aspect.

On the other hand, CMB observation such as Planck strongly suggests inflation.







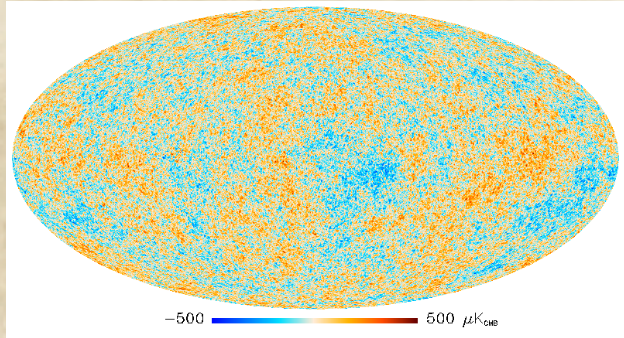
Planck collaboration (13)

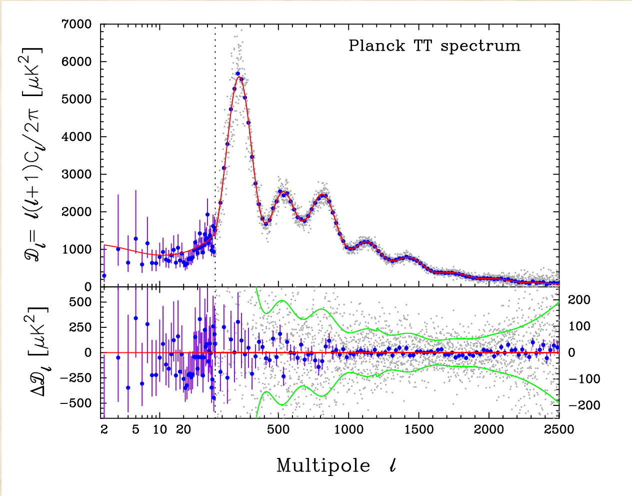
We need other scalar field to realize inflation since Higgs inflation is impossible if the Higgs potential is negative around the GUT scale. (See however, '15 Bezrukov+.)

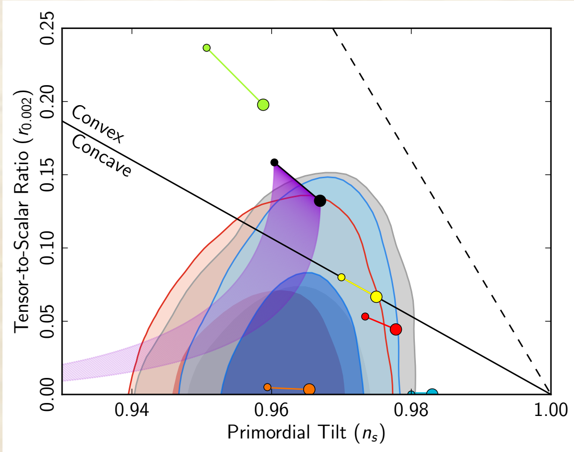
Furthermore, another problem arises,

"how to stabilize Higgs during inflation?".

On the other hand, CMB observation such as Planck strongly suggests inflation.







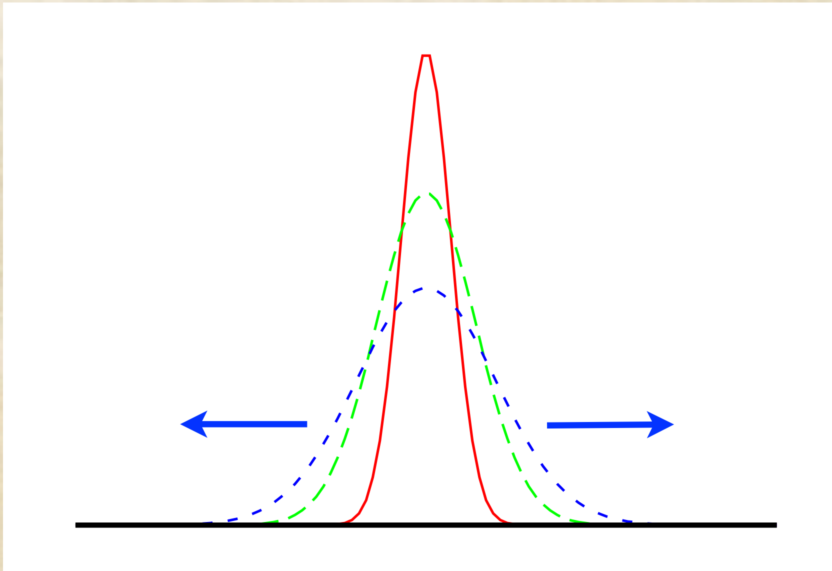
Planck collaboration (13)

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.

Quantum fluctuation during inflation can be harmful.

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

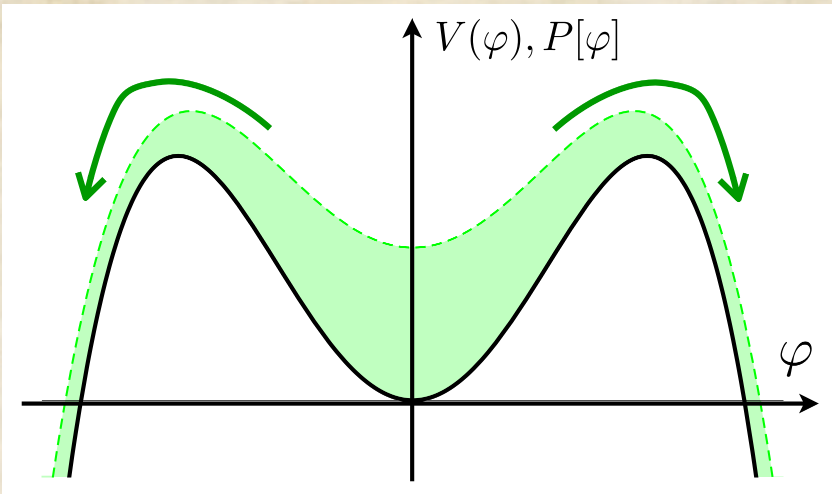
$$\langle \varphi^2 \rangle = \frac{H_{\rm inf}^2}{4\pi^2} \mathcal{N}_e$$



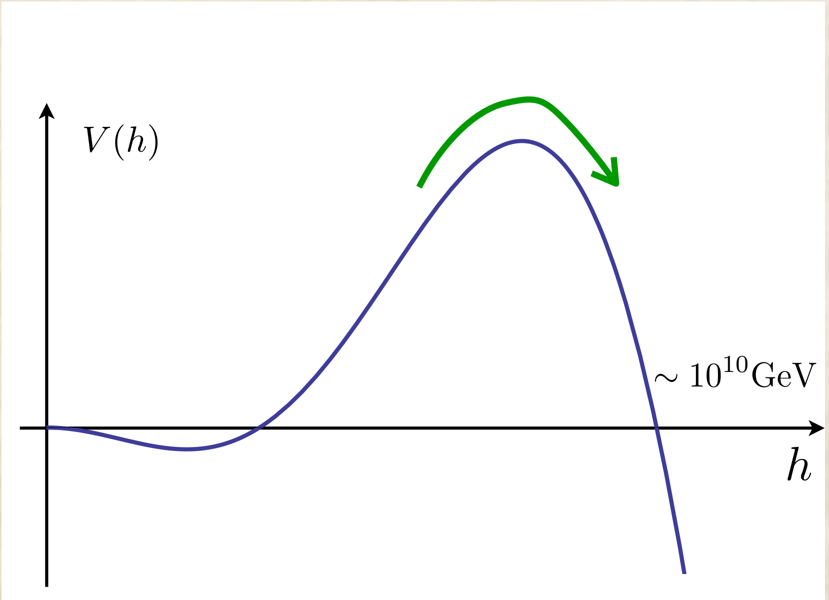
For more complicated potential, one can solve Fokker-Planck equations or Langevin equations.

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.

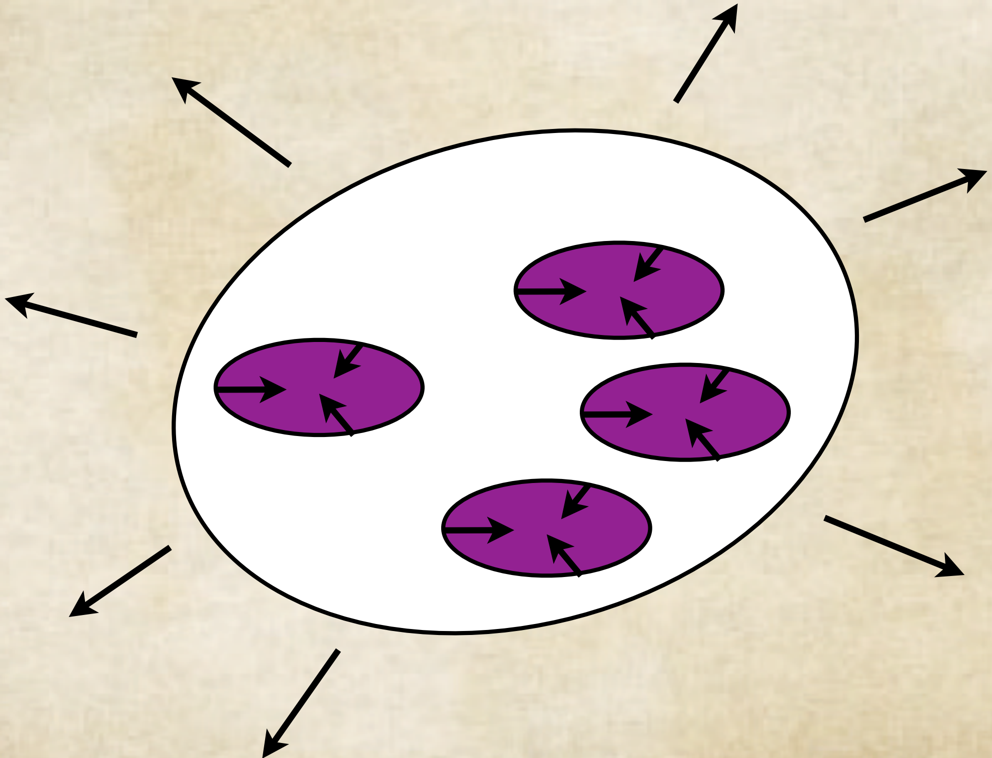


In the case of metastable SM electroweak vacuum,
if the Hubble parameter during inflation is larger than 10^{10} GeV,
the Higgs field easily climbs up the potential barrier.



Is this really harmful? There are two possibility,

- Harmful. the region that fell down to the AdS vacuum will “eat” other region and the Universe will be destroyed.
- Harmless. the region that fell down to the AdS vacuum collapses, form BHs, and evaporate quickly. They will not affect the evolution of other region.



There are still discussions.

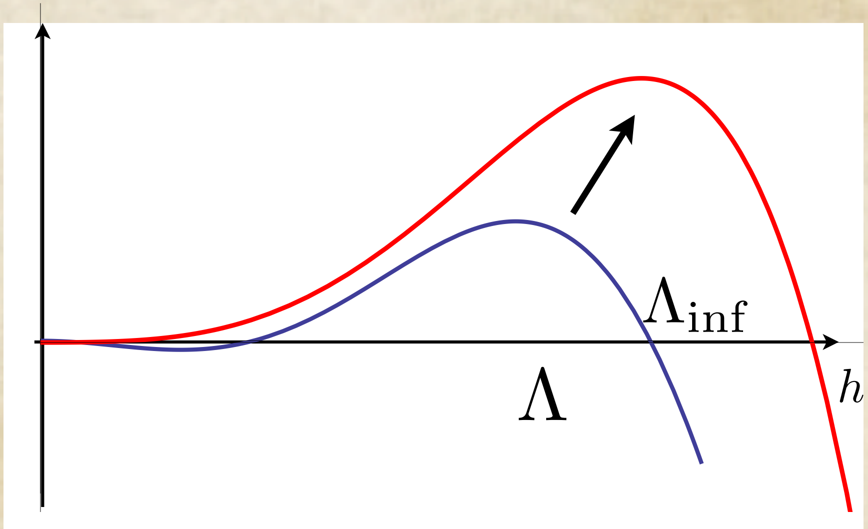
See e.g.

’08 Espinosa+, ’13 Kobakhidze+, ’14 Herranen+, ’15 Hook+, ’15 Espinosa+, ... and so on...

Here we require that the square root of the Higgs expectation value squared does not overwhelm the barrier of the potential.

This can be acomplished by introducing "Hubble-induced mass" during and after inflation to modify the Higgs potential.

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



The potential barrier becomes further and higher.

Possible origin of the Hubble-induced mass

- Direct coupling to inflaton

(Lebedev&Westphal (13))

$$\lambda_i h^2 \phi_{\rm inf}^2 \to \frac{m_{h,\rm eff}^2}{2} h^2$$

(for massive chaotic inflation)

works in the case of large field inflation

- Non-minimal coupling to gravity

$$\xi R h^2 \to 12\xi H^2 h^2$$

works in any inflation models.

They may be the “minimal extension of the SM” at present.

How can we constrain these parameters?

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 !!

(See also '15 Gong+)

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 !!

(See also '15 Gong+)

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 !!

(See also '15 Gong+)

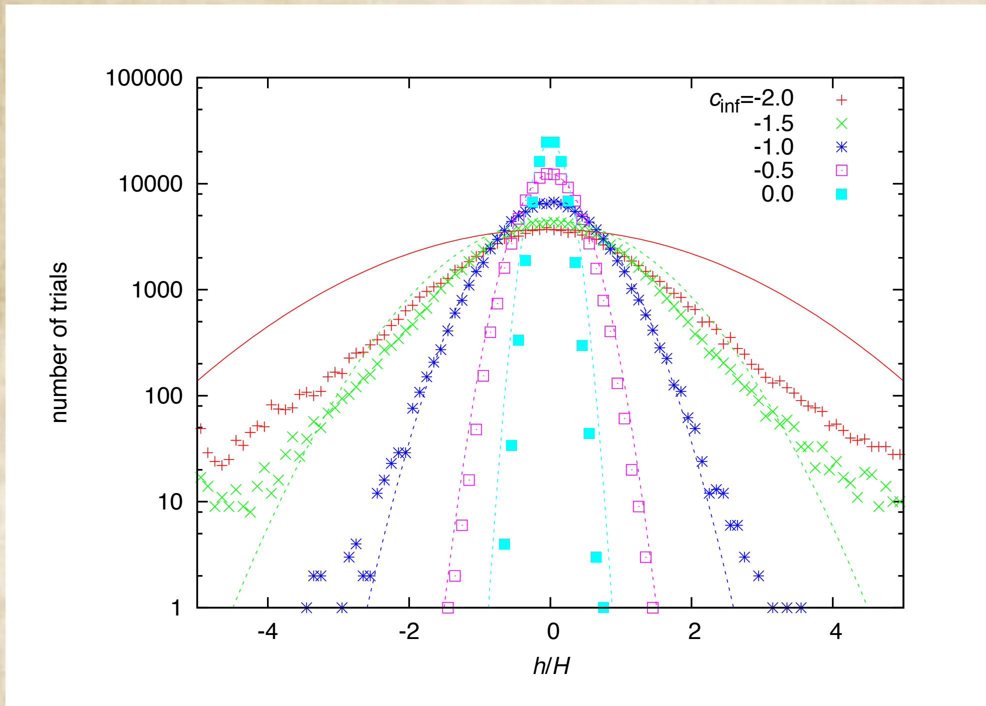
How small can the coefficient be?

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 !!

=> Open the possibility for the Higgs to leave some traces in the cosmological observables.

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

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

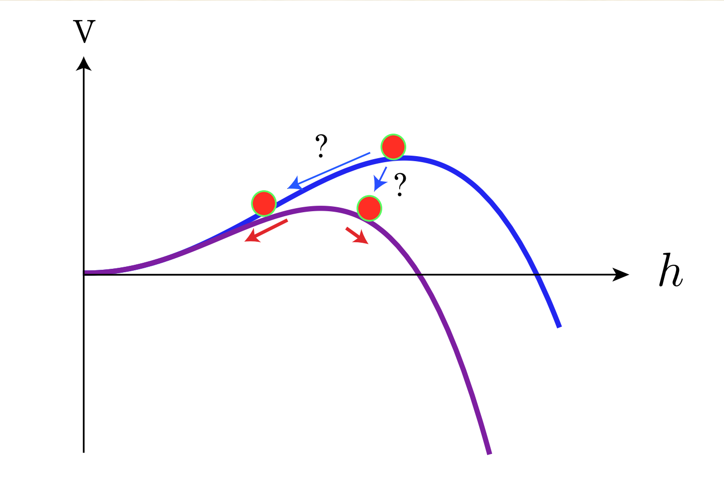
with an initial condition, typically, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \dfrac{\sqrt{3} H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

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, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \dfrac{\sqrt{3} H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

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.

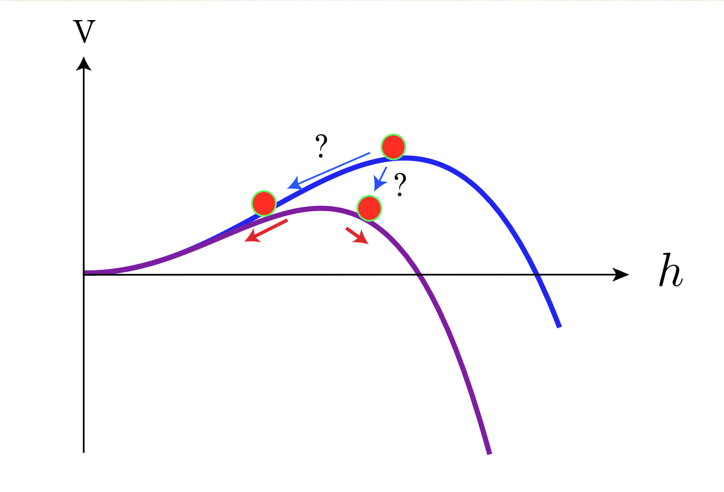


After inflation, the Higgs field evolves as

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

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

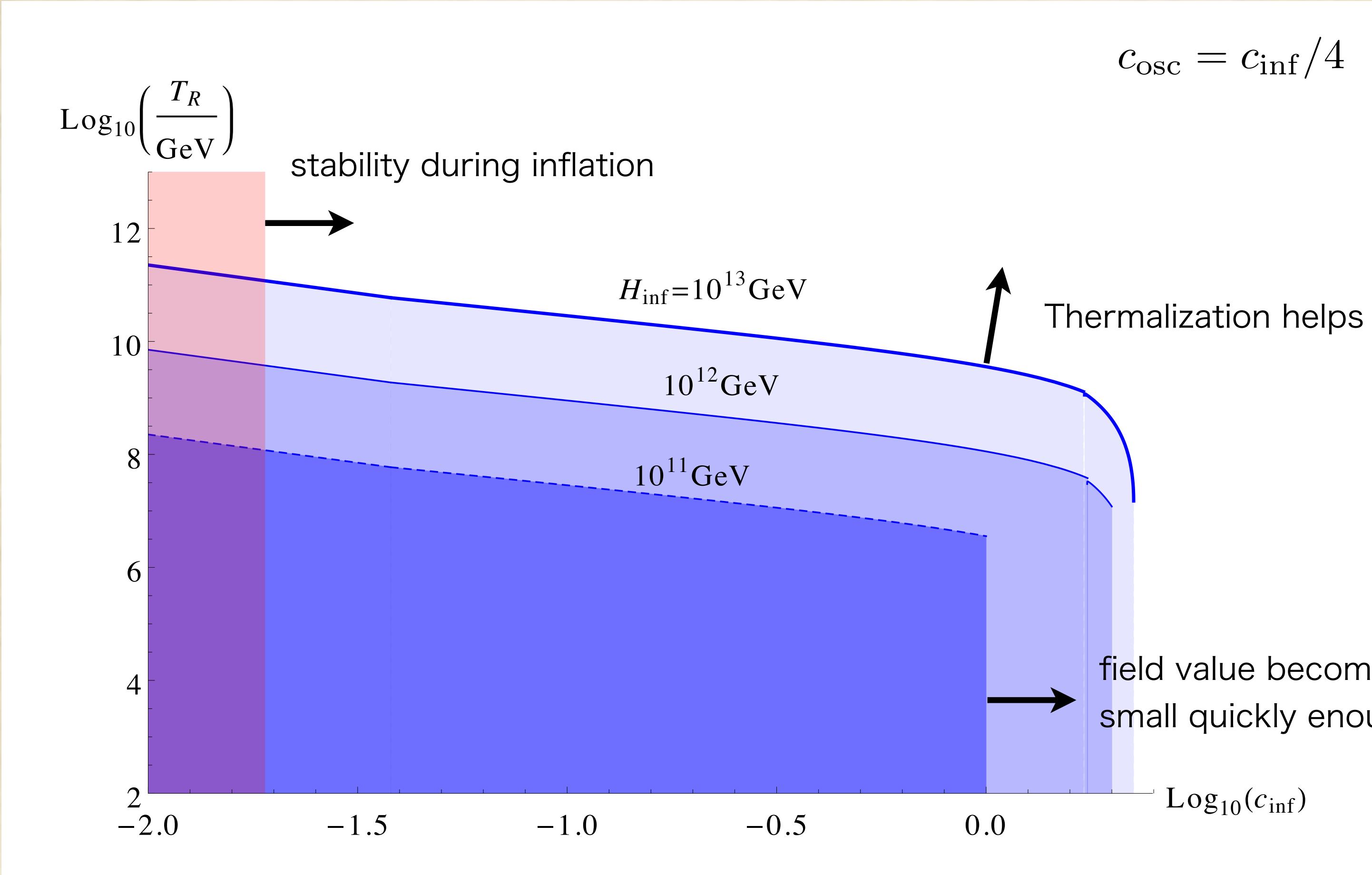
For small coefficient, $c_{\rm osc} < 9/16$, the Higgs field decreases much slower than the potential barrier and may be taken over by it.



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.

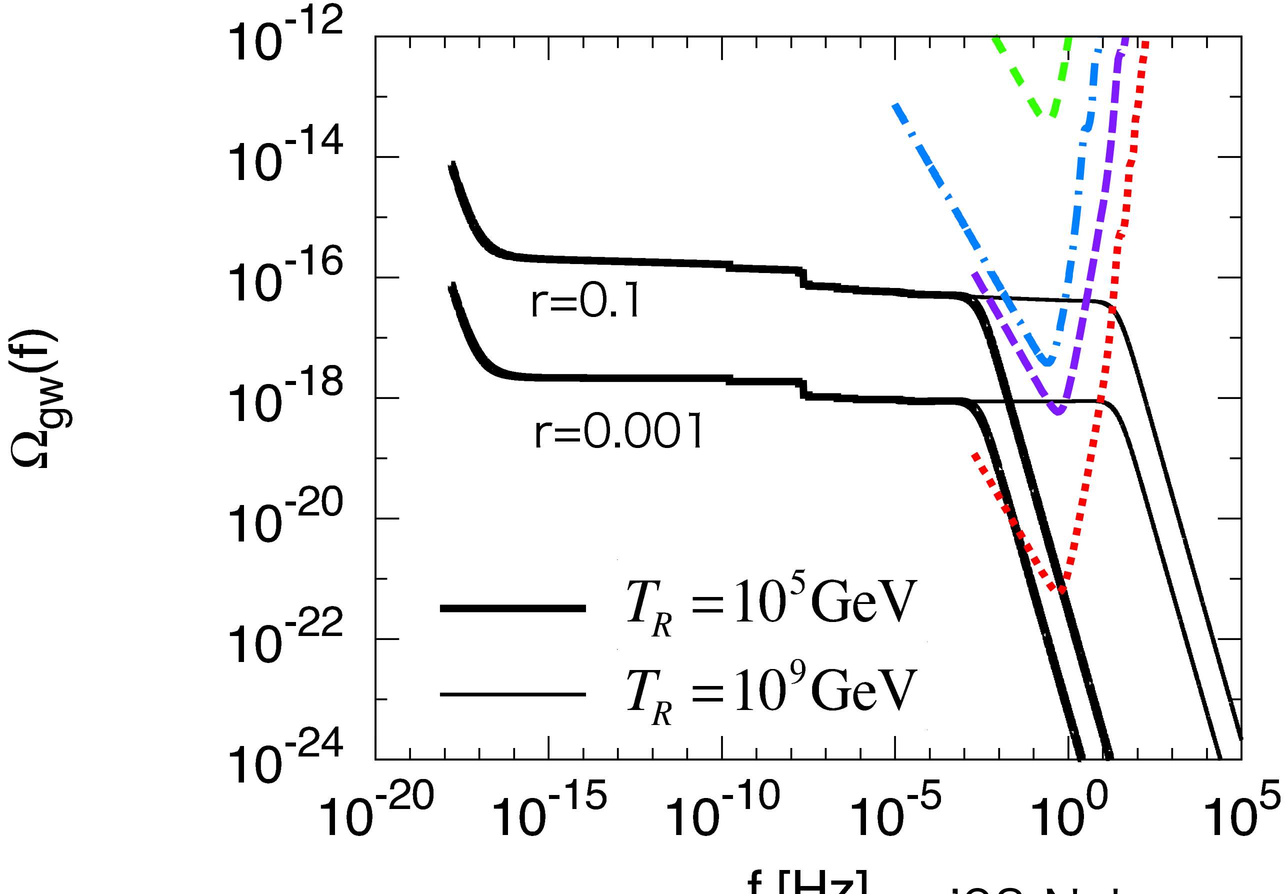
(cf. '08 Nakayama+)

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 can be 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.

Appendix

Determination of reheating temperature by GWB



'08 Nakayama+