Hilltop-shaped inflation potential with additional scalar field

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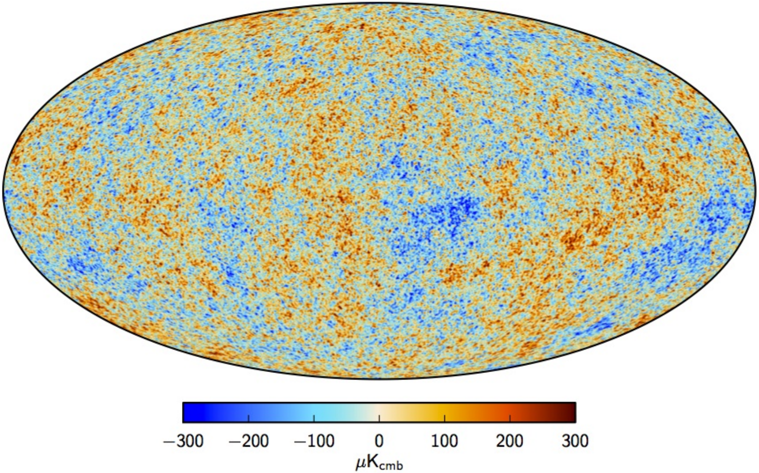
Outline

Inflationary Cosmology

- Current cosmological observations are well consistent with inflationary big bang.
- The mechanism of inflation is still a mystery.



Chaotic Inflation

- The popular chaotic inflation with ϕ^2 potential should satisfy Lyth bound, $\Delta\phi > 15 M_{\rm Pl}$.
- Above inflation potential needs the mass parameters at the level of 10^{-10} in units of the reduced Planck mass.
- Inflation field excursion larger than Planck mass implies serious fine-tuning.
- Many models other than chaotic inflation are proposed, for example, natural inflation, hilltop inflation, etc.

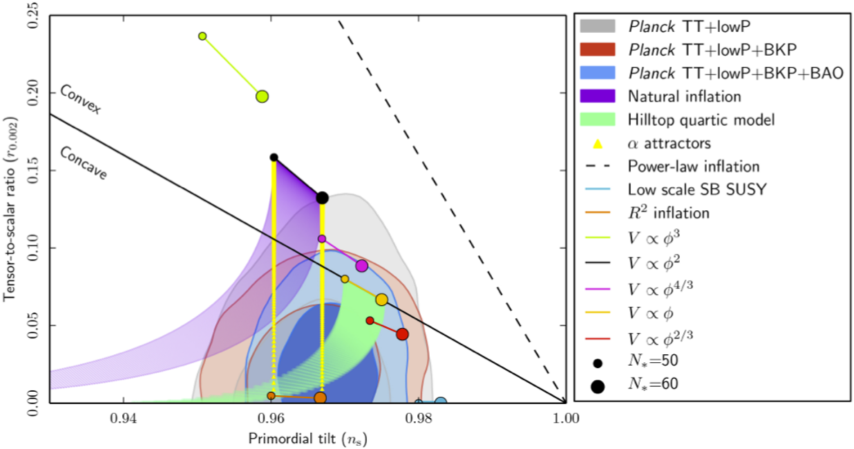
Planck/BICEP

- In 2014, BICEP2 collaboration claimed that they measured large r.
- Large r is the smoking gun evidence for the inflation.
- Large r indicates that there was the potential energy density of order around or larger than $M_{\rm GUT}$.

$$\frac{\Delta\phi}{M_{\rm Pl}} \sim \left(\frac{r}{0.01}\right)^{1/2} .$$

- After joint analysis by Planck/BICEP, we have only the bound for r, $r < 0.12$.

Planck/BICEP (2)



- Quadratic chaotic inflation and natural inflation are in danger.
- Hilltop potential is now favored.

One Inflaton Hilltop Potential

- The one inflaton hilltop potential with the symmetry $\phi \to -\phi$, satisfying three conditions $V'(0) = 0$, $V(f_{\rm DE}) = 0$, $V'(f_{\rm DE}) = 0$, can be parametrized as

$$V = \frac{\lambda M_{\rm P}^4}{4!}(\phi^2 - f_{\rm DE}^2)^2 \equiv \frac{\tilde{\lambda}}{4!}(\phi^2 - f_{\rm DE}^2)^2.$$

- One can calculate tensor-to-scalar ratio r and one of slow-roll parameters η,

$$r = \frac{128\phi^2}{(\phi^2 - f_{\rm DE}^2)^2},$$

$$\eta = \frac{12(\phi^2 - \frac{1}{3}f_{\rm DE}^2)}{(\phi^2 - f_{\rm DE}^2)^2}.$$

Difficulty of One Inflaton Potential

Spectral index n_s is given by

$$n_s = 1 - \frac{3}{8} r + 2\eta.$$

- The inflaton ϕ eventually converges to the ground value $f_{\rm DE}$.
- ϕ tends to be much smaller than $f_{\rm DE}$ to give the *e*-fold number 50-60 while η is usually negative.
- Even if $\phi_{\rm ground}$ is comparable to $f_{\rm DE}$ for positive η, then $f_{\rm DE} > 40$ in which η $\mathcal{O}(0.001)$.
- We need to introduce another inflation.

Two Inflaton Hilltop Potential

$$V = \frac{\lambda_\phi}{4!}(\phi^2 - f_{\rm DE}^2)^2 + \frac{\lambda_X}{4!}(X^2 - \gamma[\phi^2 - m^2])^2.$$

- The inflation path is set to choose $X = 0$ at $\phi = 0$ up to $\phi = \pm m$, X is the waterfall field.
- Since the large field value ψ (=inflaton path field) experiences the large Hubble friction, it prevents an effective ending of inflation.

$$\ddot{\psi} + 3H\dot{\psi} + V_{,\psi} = 0$$

- If the Hubble friction is large, the field velocity reaches its terminal velocity $\dot{\psi}_{\rm ter} = -V_{,\psi}/3H$.
- In this case, end point for the inflation is fixed.
- Another mechanism is needed to end the inflationary period.

Two Inflaton Hilltop Potential (2)

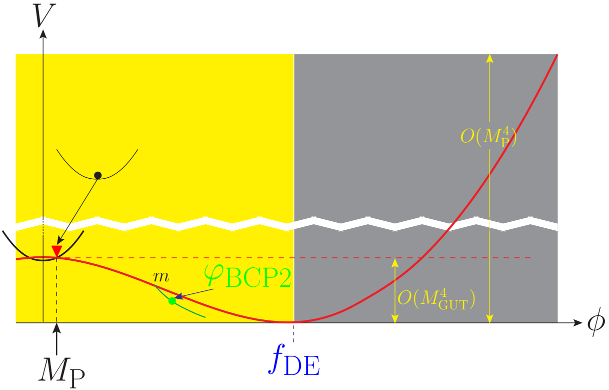
- To end inflation effectively when ψ passes $\psi_{\rm max}$, we introduce the following new field Y,

$$-\theta(\psi - \psi_{\rm max}) Y^2 m^2 \frac{\psi}{M_{\rm Pl}} \in \mathcal{L}_{\rm inflation\ end}$$

- Y decays to SM particles and reheats the Universe by

$$\frac{Y}{M_{\rm Pl}} \mathcal{L}_{SM} \in \mathcal{L}_{\rm Y\ decay} \tag{1}$$

Inflation Path



- The order of the inflation potential is roughly 10^{-8}. This determines the order of couplings λ_ϕ, λ_X in following way,

$$\lambda_\phi = \mathcal{O}(10^{-8})/f_{\rm DE}^4,$$

$$\lambda_X = \mathcal{O}(10^{-8})/f_{\rm DE}^4.$$

Inflation Path (2)

We introduce the boundary condition near the hilltop,

$$\text{BC0: } \phi(0) = \phi_i, \ \ \dot{\phi}(0) = 0.$$

At the point m, we choose the following for the numerical calculation,

$$\text{BCm: } \phi(t_m) = \phi_m = m, \ \ X(t_m) = 0, \ \ \dot{X}(t_m) > 0. \tag{2}$$

r and n_s are given by

$$r = 8\left(\frac{V'_{[\varphi-\mathrm{dir}]}}{V}\right)^2, \ \ n_s = 1 - \frac{3}{8}r + 2\eta,$$

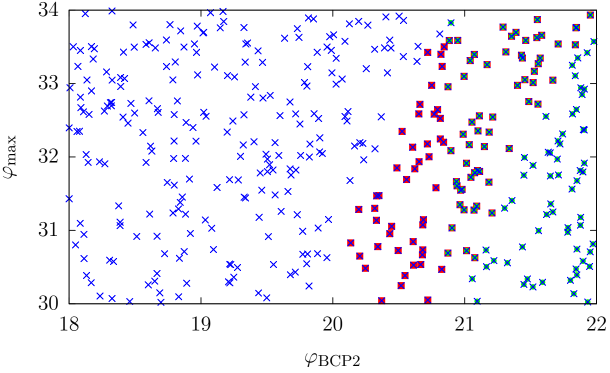
where

$$\eta = \left(\frac{V''_{[\psi-\mathrm{dir}]}}{V}\right).$$

Inflation Path (3)

$$V'_{[\psi-\mathrm{dir}]} = V_{,\phi}\Delta\widehat{\psi}_\phi + V_{,X}\Delta\widehat{\psi}_X.$$

$$V''_{[\psi-\mathrm{dir}]} = V_{,\phi\phi}\Delta\widehat{\psi}_\phi\Delta\widehat{\psi}_\phi + 2V_{,\phi X}\Delta\widehat{\psi}_X\Delta\widehat{\psi}_\phi + V_{,XX}\Delta\widehat{\varphi}_X\Delta\widehat{\psi}_X.$$



Conclusion

- We have considered hilltop-shaped inflation potential with two scalar field, ϕ and X.
- By varying model parameters and initial conditions, the inflaton-path field ψ is moved toward the Planck/BICEP point.
- With additional scalar field X, fine-tuning of the original hilltop potential can be reduced and more parameter space is allowed.
- We will re-examine the parameter space that satisfies the new Planck/BICEP observations.