Light Inflaton and Reheating

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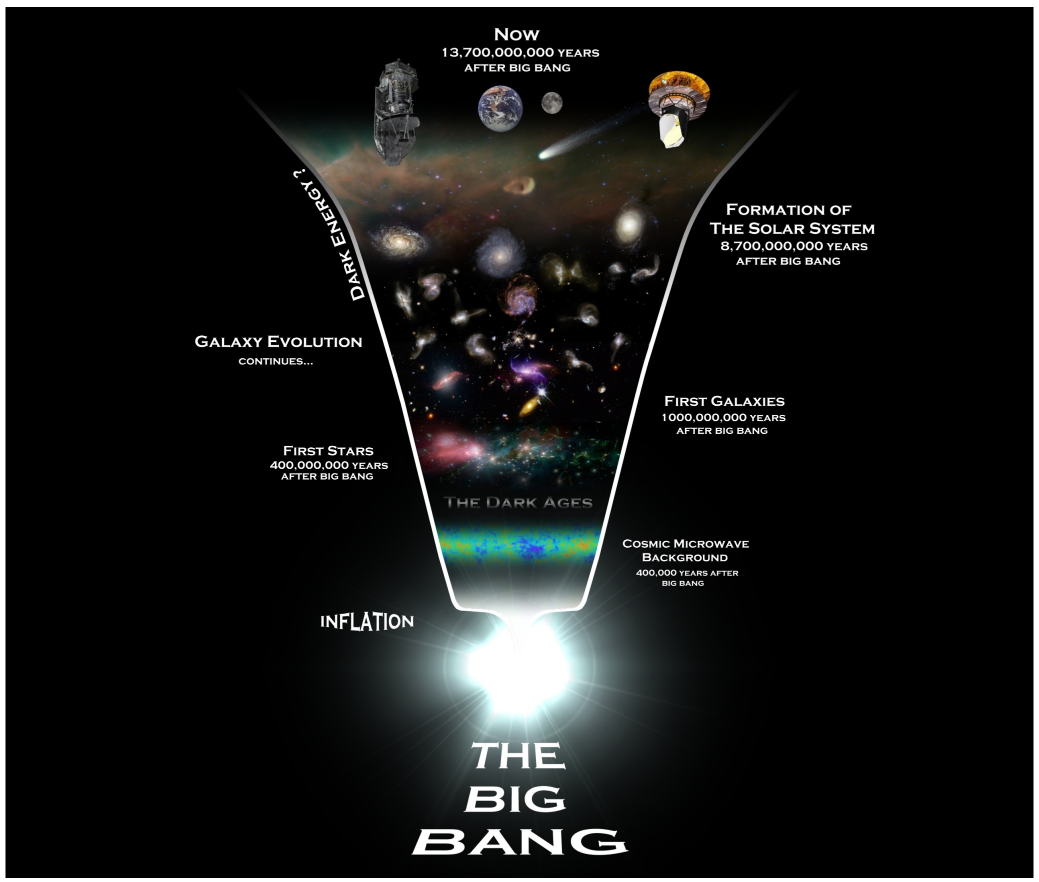
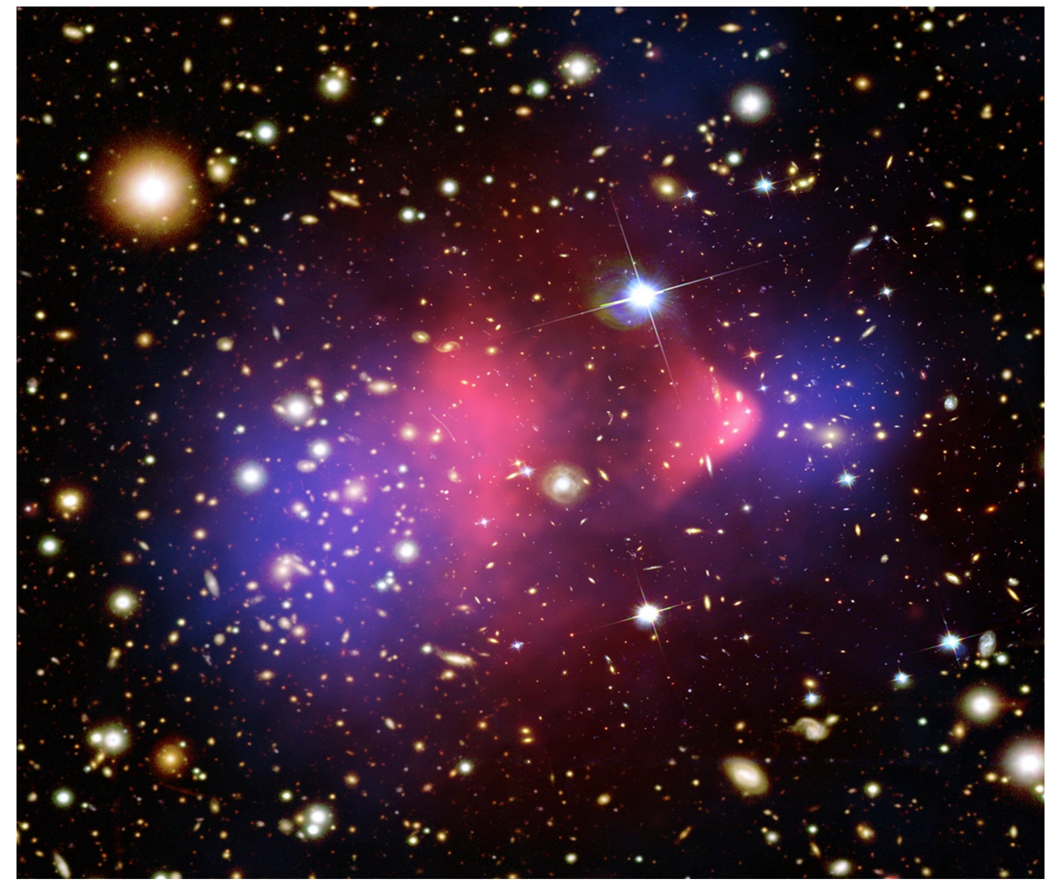
Questions

- Two popular topics in cosmology based on particle physics



Planck collaboration

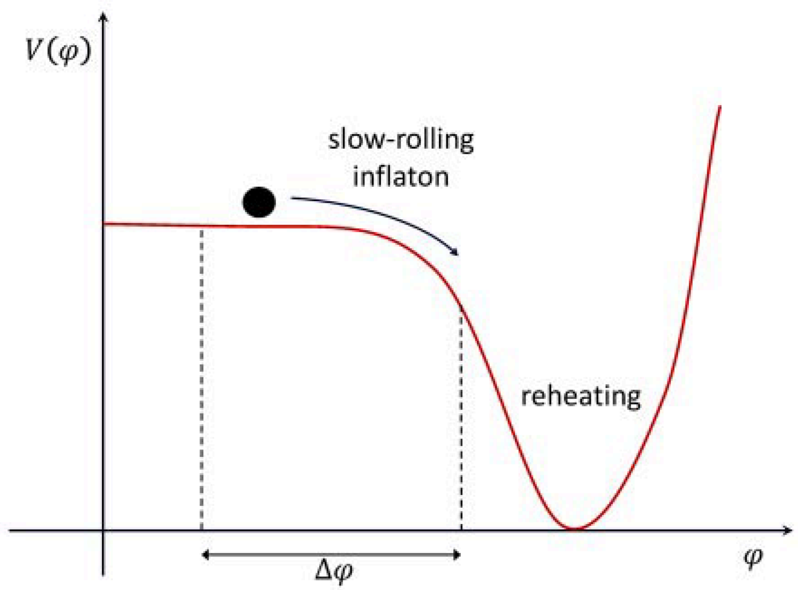


NASA/CXC/CfA

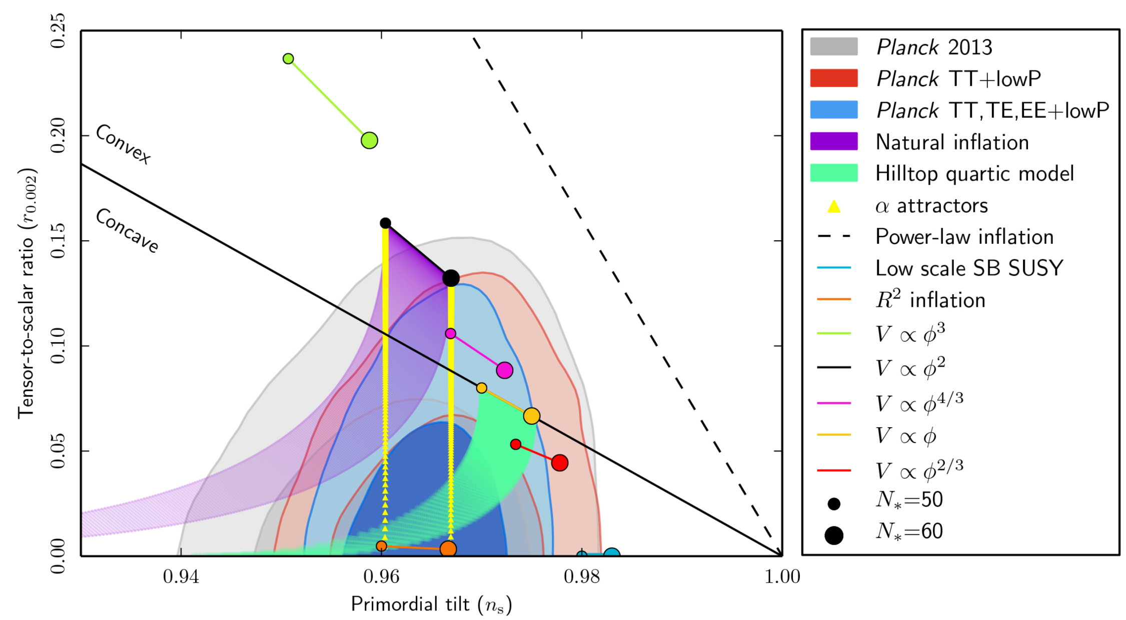
- Origins ? Models ?
- Can their origins be integrated ?

Inflation and Slow-Roll

- Cosmic inflation can solve the horizon, flatness problem and so on
- Inflation can be described by the slow-rolling inflaton



Matarrese et al (2016)



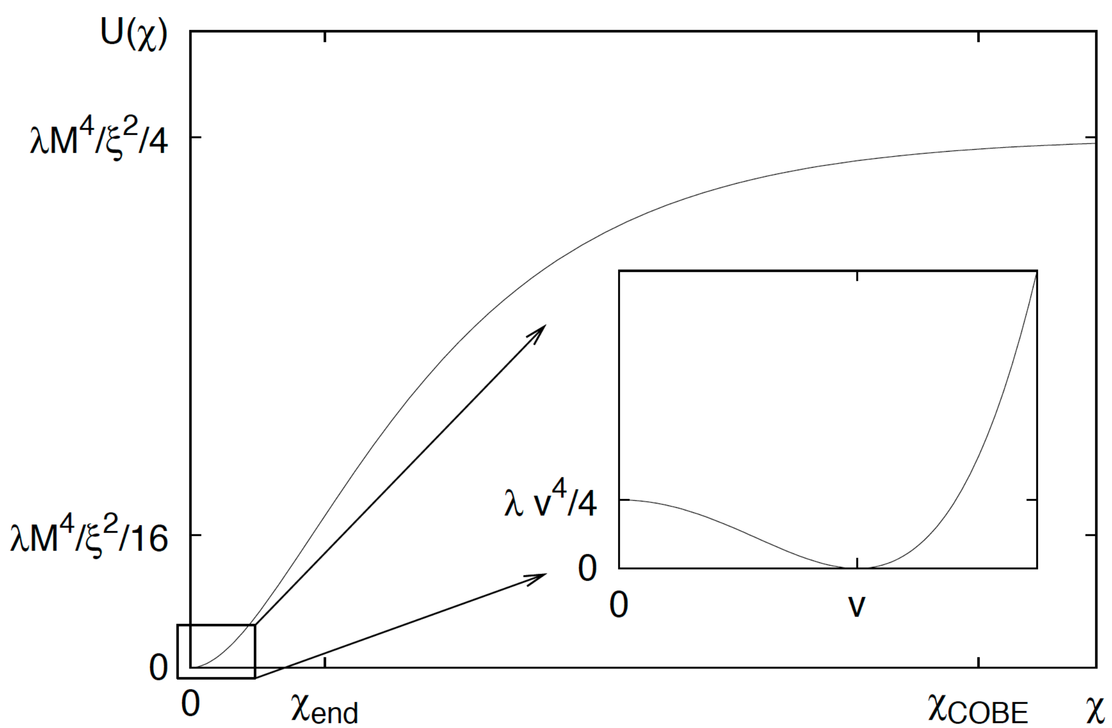
Planck 2015

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = M_p^2\frac{V''}{V}, \quad N = \int_{\chi_f}^{\chi_i} \frac{\text{sign}(V')}{\sqrt{2\epsilon}} d\chi, \quad n_s = 1 - 6\epsilon_* + 2\eta_*, \quad r = 16\epsilon_*$$

Higgs Inflation

- Higgs can be an inflaton as a key of the inflation origin
- Large non-minimal coupling is required for the CMB data

$$\frac{\mathscr{L}_J}{\sqrt{-g_J}} = \frac{1}{2}\left(M_P^2 + 2\xi H^\dagger H\right)R - |D_\mu H|^2 - \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$



- Consistent with CMB data

$$\Rightarrow \quad \xi \approx 5\times 10^4 \frac{m_H}{\sqrt{2}v}$$

$$n_s \approx 1 - \frac{2}{N} = 0.966$$

$$r \approx \frac{12}{N^2} = 0.0033$$

F. Bezrukov, M. Shaposhnikov (2007)

Unitarity Problem

- Due to the large non-minimal coupling, there is a unitary problem

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \frac{1}{2}\left(M_P^2 + 2\xi H^\dagger H\right)R - |D_\mu H|^2 - \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

$$\Rightarrow \frac{\mathcal{L}_E}{\sqrt{-g_E}} \supset -\frac{3\xi^2}{M_P^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) + \cdots \qquad \Lambda_{\text{cufoff}} \sim \frac{M_p}{\xi} \sim \frac{M_p}{10^4}$$

- Unitarity problem is solved by the simple extension σ

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \frac{1}{2}\left(M_P^2 + \xi\sigma^2 + 2\zeta H^\dagger H\right)R - \frac{1}{2}(\partial_\mu\sigma)^2 - |D_\mu H|^2 - V(\sigma, H)$$

- Higher dimensional terms are suppressed by $\Rightarrow \Lambda_{\text{cutoff}} \sim M_P$

C. P. Burgess, H. M. Lee, M. Trott (2009), G. F. Guidice, H. M. Lee (2010)

The Model of Light Inflaton

- Unitarized light inflaton with linear non-minimal coupling
- Approximate Z_2 symmetry, but broken by ξ_1

$$\frac{\mathscr{L}_J}{\sqrt{-g_J}} = -\frac{1}{2}\Omega(\sigma, H)R + \frac{1}{2}(\partial_\mu\sigma)^2 + |D_\mu H|^2 - V(\sigma, H)$$

$$\Omega(\sigma, H) \equiv 1+\xi_1\sigma + \xi_2\sigma^2 + 2\xi_H|H|^2, \quad M_p = 1$$

$$V(\sigma, H) \equiv \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{4}\lambda_\sigma\sigma^4 + \frac{1}{2}\lambda_{\sigma H}\sigma^2|H|^2 + m_H^2|H|^2 + \lambda_H|H|^4$$

$$g_{\mu\nu} = \frac{1}{\Omega}g^E_{\mu\nu} \quad \& \quad H^T = \frac{1}{\sqrt{2}}(0, \phi)$$

$$\frac{\mathscr{L}_E}{\sqrt{-g^E}} = -\frac{1}{2}R(g^E) + \frac{1}{2\Omega}(\partial_\mu\sigma)^2 + \frac{3}{4}(\partial_\mu \log\Omega)^2 + \frac{1}{2\Omega}(\partial_\mu\phi)^2 - \frac{1}{\Omega^2}V(\sigma, \phi)$$

H. M. Lee (2018), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Inflationary Dynamics

- Introduce a new set of fields during inflation

$$\frac{\mathscr{L}_E}{\sqrt{-g^E}} = -\frac{1}{2}R(g^E) + \frac{1}{2\Omega}(\partial_\mu\sigma)^2 + \frac{3}{4}(\partial_\mu \log\Omega)^2 + \frac{1}{2\Omega}(\partial_\mu\phi)^2 - \frac{1}{\Omega^2}V(\sigma,\phi)$$

$$\Omega(\sigma, H) \approx \xi_1\sigma + \xi_2\sigma^2 + \xi_H\phi^2 \gg 1$$

$$e^{\frac{2}{\sqrt{6}}\chi} \equiv \xi_1\sigma + \xi_2\sigma^2 + \xi_H\phi^2 \quad \& \quad \tau \equiv \frac{\phi}{\sigma}$$

$$\xi_2 \gg \xi_H \sim \mathcal{O}(1) \quad \text{(assumption)}$$

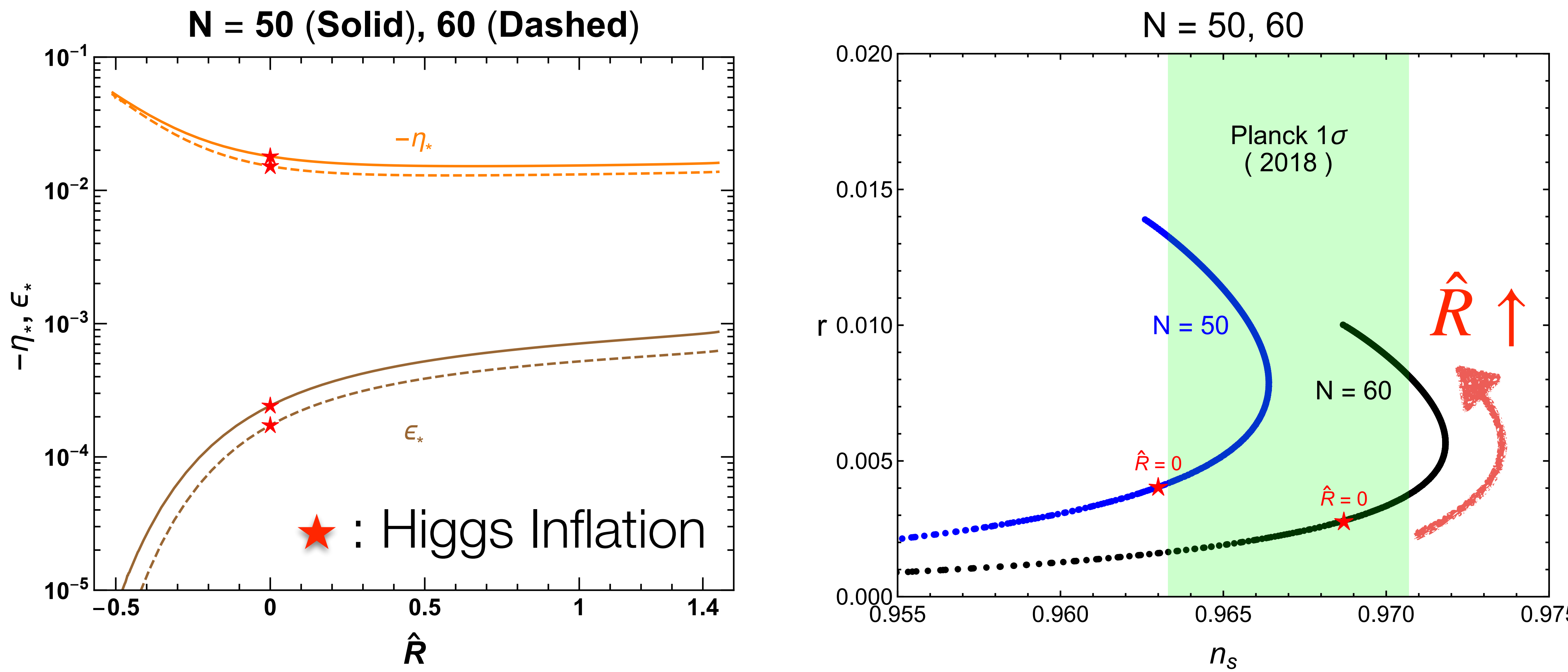
$$\frac{\mathscr{L}_E}{\sqrt{-g^E}} = -\frac{1}{2}R(g^E) + \frac{1}{2}(\partial_\mu\chi)^2 + \frac{1}{2\xi_2}(\partial_\mu\tau)^2 - V_E(\chi,\tau)$$

$$V_E(\chi,\tau) \approx V_I(\tau)\left(1 - 2\hat{R}e^{-\frac{1}{\sqrt{6}}\chi} - 2(1-\hat{R}^2)e^{-\frac{2}{\sqrt{6}}\chi}\right), \quad V_I(\tau) \equiv \frac{\lambda_H\tau^4 + \lambda_{\sigma H}\tau^2 + \lambda_\sigma}{4(\xi_2+\xi_H\tau^2)^2}, \quad \hat{R} \equiv \frac{\xi_1}{(\xi_2+\xi_H\tau^2)^2}$$

H. M. Lee (2018), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Slow-roll Parameter Space

- For the large $\hat{R}$, tensor-to-scalar-ratio is also increased
- This model is testable at future CMB experiments



$$\hat{R} \equiv \frac{\xi_1}{(\xi_2 + \xi_H \tau^2)^{1/2}}, \quad \epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = M_p^2 \frac{V''}{V}, \quad N = \int_{\chi_f}^{\chi_i} \frac{\text{sign}(V')}{\sqrt{2\epsilon}} d\chi, \quad n_s = 1 - 6\epsilon_* + 2\eta_*, \quad r = 16\epsilon_*$$

H. M. Lee (2018), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Stabilization from the Potential

- The minimazation of the potential for the tau field

$$V_E(\chi,\tau) \approx V_I(\tau)\left(1-2\hat{R}e^{-\frac{1}{\sqrt{6}}\chi}-2(1-\hat{R}^2)e^{-\frac{2}{\sqrt{6}}\chi}\right), \quad V_I(\tau) \equiv \frac{\lambda_H\tau^4+\lambda_{\sigma H}\tau^2+\lambda_\sigma}{4(\xi_2+\xi_H\tau^2)^2}$$

for $\xi_2 \gg \xi_H = \mathcal{O}(1) \quad (\tau = \phi/\sigma)$

$$(1)\ \tau = \sqrt{-\frac{\lambda_{\sigma H}}{2\lambda_H}}, \quad V_I = \frac{1}{4\xi_2^2}\left(\lambda_\sigma - \frac{\lambda_{\sigma H}^2}{4\lambda_H}\right) \quad : \quad \lambda_H > 0,\ \lambda_{\sigma H} < 0$$

$$(2)\ \tau = 0, \quad V_I = \frac{\lambda_\sigma}{4\xi_2^2} \quad : \quad \lambda_H > 0,\ \lambda_{\sigma H} > 0$$

$$(3)\ \tau = \infty, \quad V_I = \frac{\lambda_H}{4\xi_H^2} \quad : \quad \lambda_H < 0,\ \lambda_{\sigma H} < 0$$

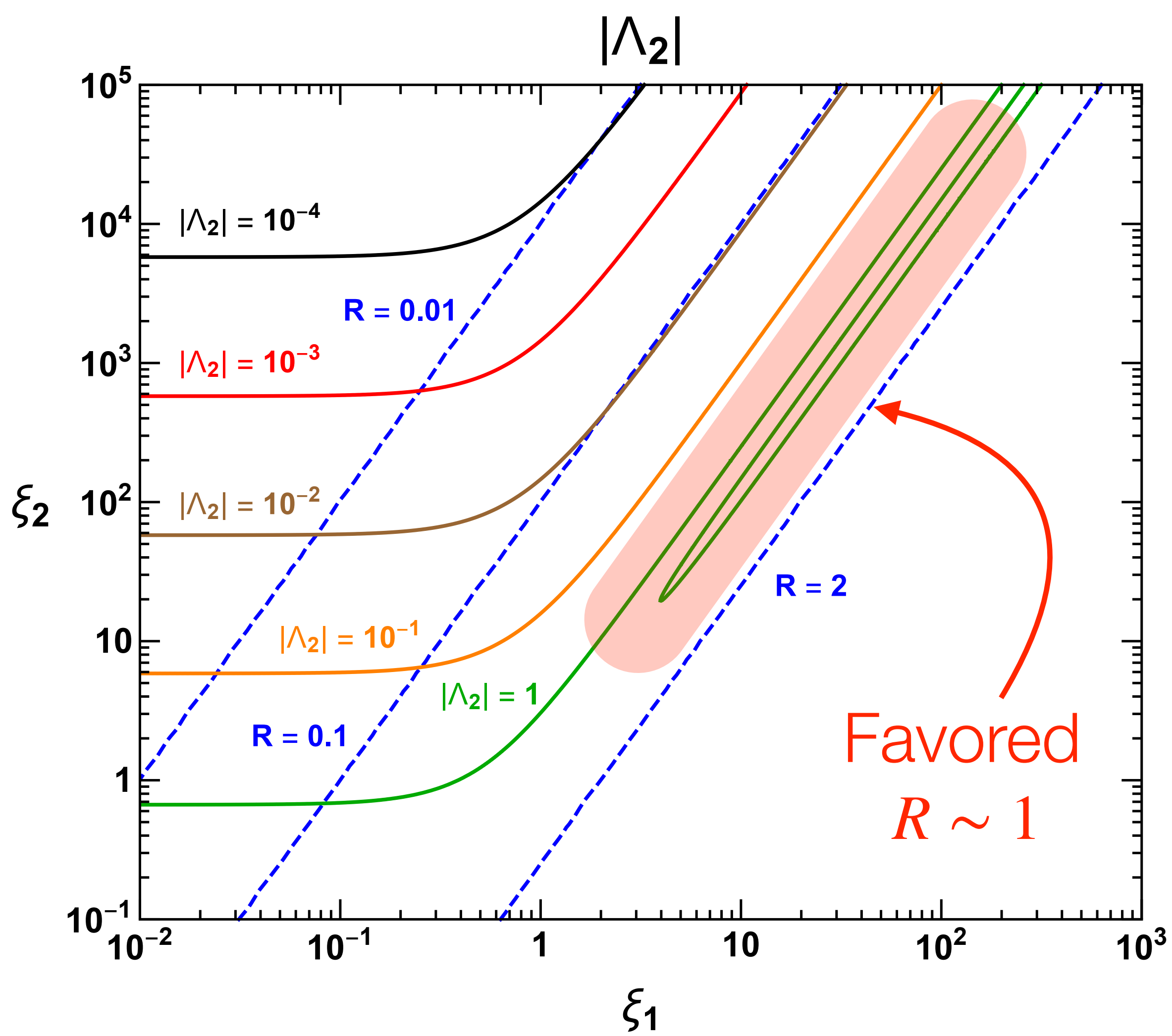
$$(4)\ \tau = 0 \text{ or } \infty, \quad V_I = \frac{\lambda_\sigma}{4\xi_2^2} \text{ or } \frac{\lambda_H}{4\xi_H^2} \quad : \quad \lambda_H < 0,\ \lambda_{\sigma H} > 0$$

O. Lebedev, H. M. Lee (2011), H. M. Lee (2018), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Unitarity Scale

- For $\sigma, \phi \ll 1$, the kinetic term is field-independent
- Recovering the unitarity up to the Planck scale

$$\mathscr{L}_{\rm kin} \approx \frac{1}{2}\left(1+\frac{3}{2}\xi_1^2\right)(\partial_\mu\sigma)^2 \Rightarrow \chi \approx \left(1+\frac{3}{2}\xi_1^2\right)^{1/2}\sigma \Rightarrow \mathscr{L}_{\rm kin} \approx \frac{1}{\Lambda_2^2}\chi^2(\partial_\mu\chi)^2 + \cdots$$



$$|\Lambda_2| = \frac{\sqrt{2}(1+\frac{3}{2}\xi_1^2)}{|\xi_1^2(1+\frac{9}{2}\xi_1^2) - \xi_2(1+15\xi_1^2 - 6\xi_2)|^{1/2}}$$

$$\approx \frac{R^2}{|R^4 - \frac{2}{3}(5R^2-2)|^{1/2}}$$

$$R \equiv \frac{\xi_1}{\sqrt{\xi_2}}$$

H. M. Lee (2018), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

During Reheating

- In the presence of the quartic inflaton potential

$$V_E \approx \frac{\lambda_\sigma}{9\xi_1^4}\chi^4, \quad \chi_c(t) = \chi_0(t)\ \mathrm{cn}\left(\omega(t)t, \frac{1}{\sqrt{2}}\right)$$

$$\mathscr{L} = -\frac{1}{4}\lambda_\chi\chi^4 - \frac{1}{4}\lambda_{\chi H}\chi^2 h^2, \quad \lambda_\chi \equiv \frac{4\lambda_\sigma}{9\xi_1^4}, \quad \lambda_{\chi H} \equiv \frac{2\lambda_{\sigma H}}{3\xi_1^2}$$

$$m_\chi^2(t) = 3\lambda_\chi\chi_c^2(t), \quad m_h^2(t) = \frac{1}{2}\lambda_{\chi H}\chi_c^2(t)$$

T. Tenkanen et al (2016), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Decays of Inflaton Condensate

- Inflaton condensate can decay to the perturbation and Higgs

$$\begin{aligned}\Gamma_{\chi_c} &= \Gamma_{\chi_c\to\chi\chi} + \Gamma_{\chi_c\to hh} \\ \Gamma_{\chi_c\to\chi\chi} &= 0.023\lambda_\chi^{3/2}\chi_0 \\ \Gamma_{\chi_c\to hh} &= 0.002\lambda_{\chi H}^2\lambda_\chi^{-1/2}\chi_0\end{aligned}$$

- Reheating temperature is determined by the decay process

$$\frac{\pi^2 g_*(T_{\rm RH})}{30}T_{\rm RH}^4 = \frac{\Gamma_{\chi_c\to hh}}{\Gamma_{\chi_c}} \times \frac{\lambda_\chi}{4}\chi_0^4(t_{\rm dec})$$

$$T_{\rm RH} = (4.4\times 10^6\ {\rm GeV})\left(\frac{100}{g_*(T_{\rm RH})}\right)^{1/4}\left(\frac{\lambda_{\chi H}}{10^{-8}}\right)^2\left(\frac{\xi_1}{\sqrt{\xi_2}}\right)^3\left(\frac{\Gamma_{\chi_c\to hh}}{\Gamma_{\chi_c}}\right)^{-3/4}\left(\frac{r}{0.01}\right)^{-3/4}$$

T. Tenkanen et al (2016), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Preheating from Higgs coupling

- Klein-Gordon equation of the Higgs Fourier mode

$$\ddot{h}_k + 3H\dot{h}_k + \left(\frac{k}{a^2} + m_h^2(t)\right)h_k \;=\; 0$$

$$\rightarrow H_k'' + \left(\kappa^2 + \frac{\lambda_{\chi H}}{2\lambda_\chi}\mathrm{cn}^2\left(x, \frac{1}{\sqrt{2}}\right)\right)H_k \;=\; 0$$

where $H_k(t) \equiv a(t)h_k(t),\ x \equiv \omega(t)t,\ \kappa^2 \equiv k^2/(\lambda_\chi \chi_0^2 a^2)$

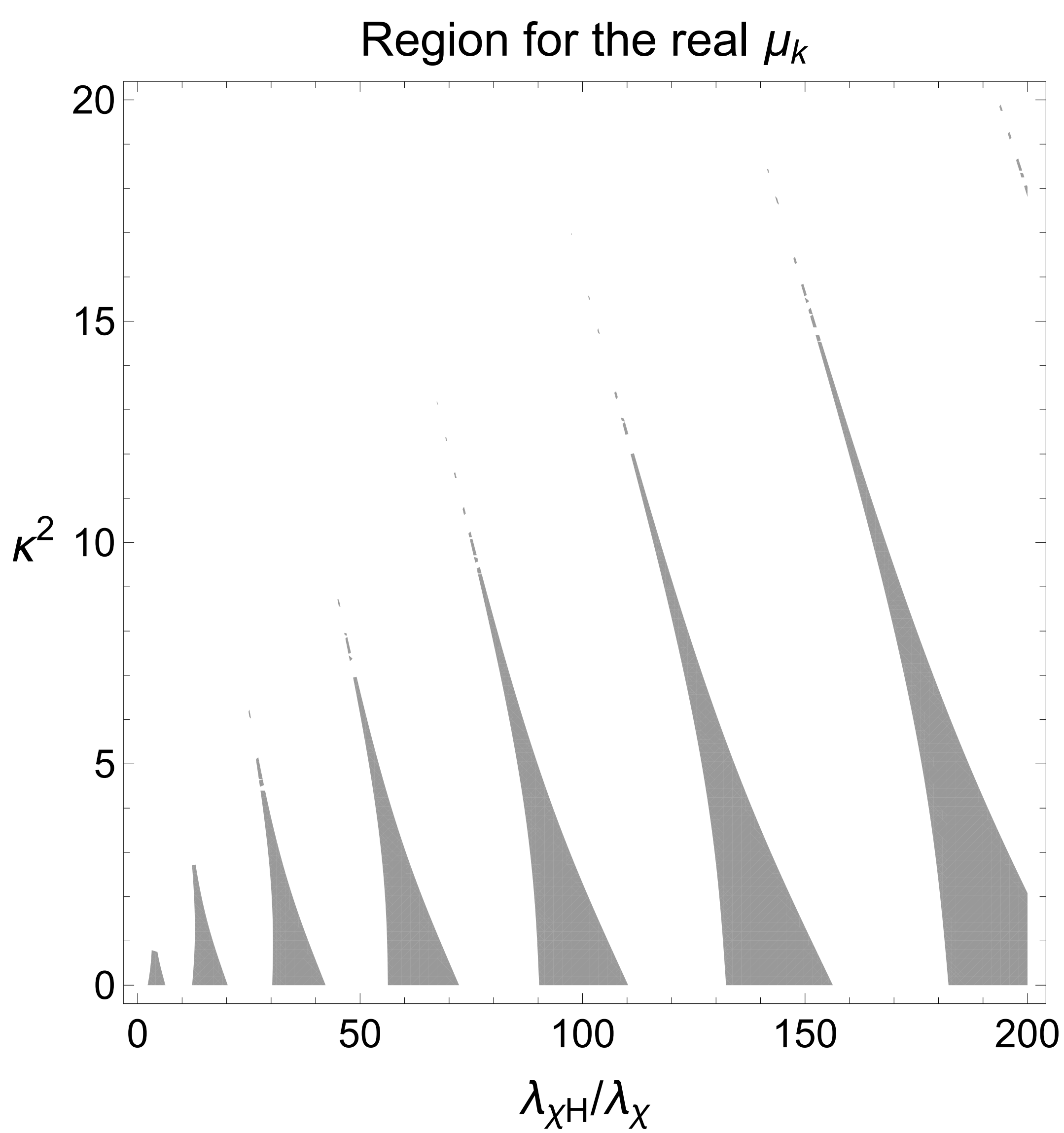
- The solution of the KG equation
and the number of Higgs created during preheating

$$n_k \sim |H_k|^2 \sim e^{2\mu_k x} \qquad \mu_k : \text{Floquet index}$$

A. D. Linde et al (1997), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Dominance of the Preheating

- Instability can be caused by the preheating process
- Preheating process can be dominant



- $\dfrac{\dot{n}_k}{n_k} \sim 2\mu_k \dot{x} \gtrsim \Gamma_h$ (Higgs decay rate)

$$\Rightarrow \mu_k \gtrsim 8.3 \times 10^{-5} \left(\frac{\lambda_{\chi H}}{10^{-7}}\right)^{1/2} \left(\frac{10^{-10}}{\lambda_\chi}\right)^{1/2}$$

- $\dfrac{\dot{n}_k}{n_k} \sim 2\mu_k \dot{x} \gtrsim \Gamma_{\chi_c \to hh}$

$$\Rightarrow \mu_k \gtrsim 2 \times 10^{-7} \left(\frac{\lambda_{\chi H}}{10^{-7}}\right)^{2} \left(\frac{10^{-10}}{\lambda_\chi}\right)$$

A. D. Linde et al (1997), S. M. Choi, Y. J. Kang, H. M. Lee, K. Yamashita (2019)

Conclusion

- We have studied the dynamics of inflation models of a singlet scalar field with both quadratic and linear non-minimal couplings.
- We have discussed the impacts of the linear non-minimal coupling on various dynamics from inflation to reheating process.
- In this model, unitarity is ensured up to the Planck scale by the sizable linear non-minimal coupling.
- The inflaton field (σ) can be a decaying dark matter by considering the non-thermal production mechanism. (→ Yoo-Jin's talk today)

S. M. Choi, Y. J. Kang H. M. Lee, K. Yamashita (2019)