

Filling the Gap : (Perturbative) Reheating in Higgs - R^2 Inflation

Dhong Yeon Cheong (Yonsei University)

2108.xxxxx

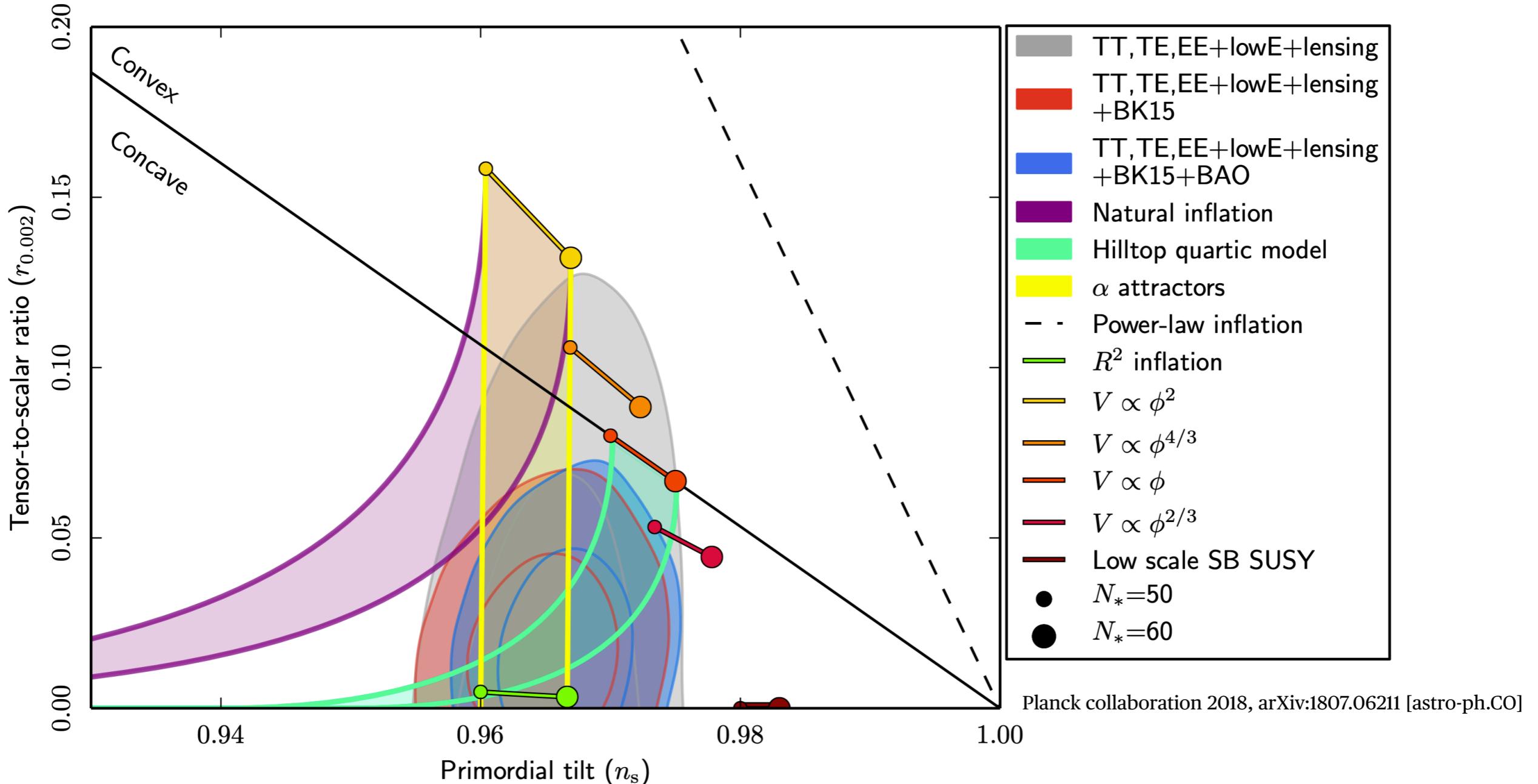
(in collab. with F. Bezrukov, S.M. Lee, S.C. Park, C. Shepherd)

*Asia-Pacific Workshop on Particle Physics and Cosmology 2021,
Aug. 3rd, 2021*



연세대학교
YONSEI UNIVERSITY

Introduction - Higgs Inflation



Observational constraints on inflation from CMB : Power law potentials seem unlikely..

Best-fit models : R^2 inflation & Higgs Inflation

Introduction - Higgs Inflation

F. Bezrukov and M. Shaposhnikov, Phys. Lett. B 659 (2008) 703-706

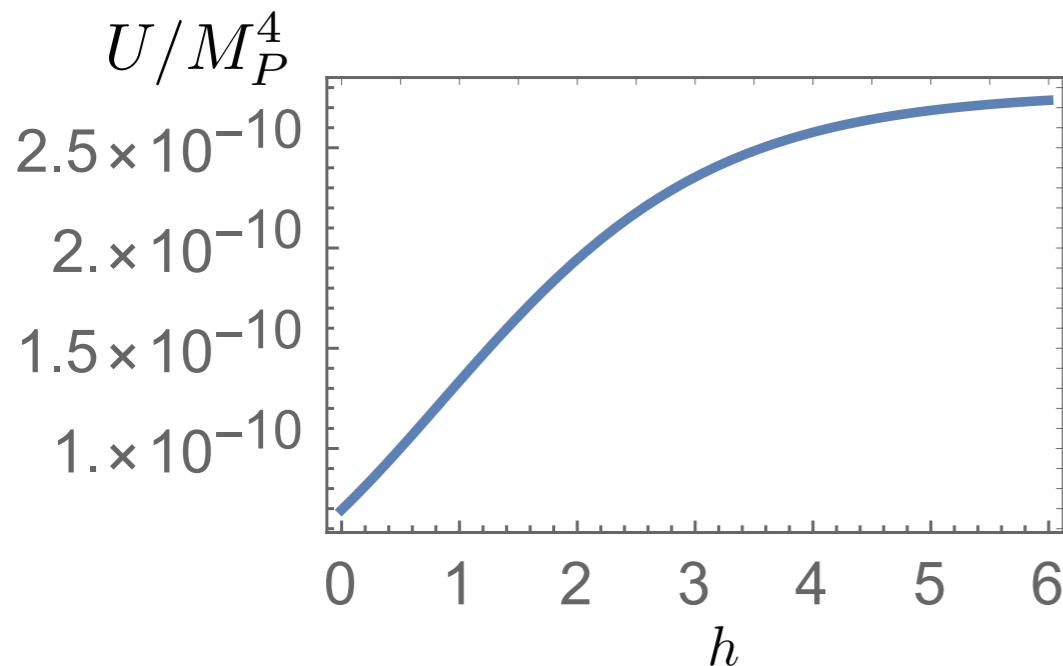
Higgs Inflation

$$S_J = \int d^4x \sqrt{-g_J} \left[\frac{1}{2} \left(M_P^2 + \xi h_J^\dagger h_J \right) R_J - \frac{1}{2} |\partial_\mu h_J|^2 - V(h_J) \right]$$

$$g_{\mu\nu} = \Omega(h_J)^2 g_{J\mu\nu} \quad \downarrow \quad \Omega(h_J)^2 = 1 + \frac{\xi h^2}{M_P^2}$$

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_P^2 R - \frac{1}{2} |\partial_\mu h|^2 - U(h) \right] \quad U(h) \simeq \frac{\lambda M_P^4}{4\xi^2} \left(1 + e^{-\sqrt{\frac{2}{3}} \frac{h}{M_P}} \right)^{-2}$$

Exponentially flat potential at large fields, successful inflation



- Theoretical issues reside? : $\frac{\lambda}{\xi^2} \sim 10^{-10}$
- Naive cutoff scale appears at $\Lambda \sim \frac{M_P}{\xi}$ for $\xi \sim \mathcal{O}(10^3)$

Higgs- R^2 Inflation — Setup

- Add a dim-4, R^2 term to the action!

$$S_J = \int d^4x \sqrt{-g_J} \left[\frac{M_P^2}{2} \left(R_J + \frac{\xi h^2}{M_P^2} R_J + \frac{R_J^2}{6M^2} \right) - \frac{1}{2} g^{\mu\nu} \nabla_\mu h \nabla_\nu h - \frac{\lambda}{4} h^4 \right],$$

non minimal coupling R^2 term Higgs effective potential

- Lagrange multiplier
- Weyl transformation

Y. Ema, Phys. Lett. B770:403-411, 2017

Y-C. Wang, T. Wang, Phys. Rev. D96(12):123506, 2017

M.He, A. A. Starobinsky, J. Yokoyama, JCAP, 1805(05):064, 2018

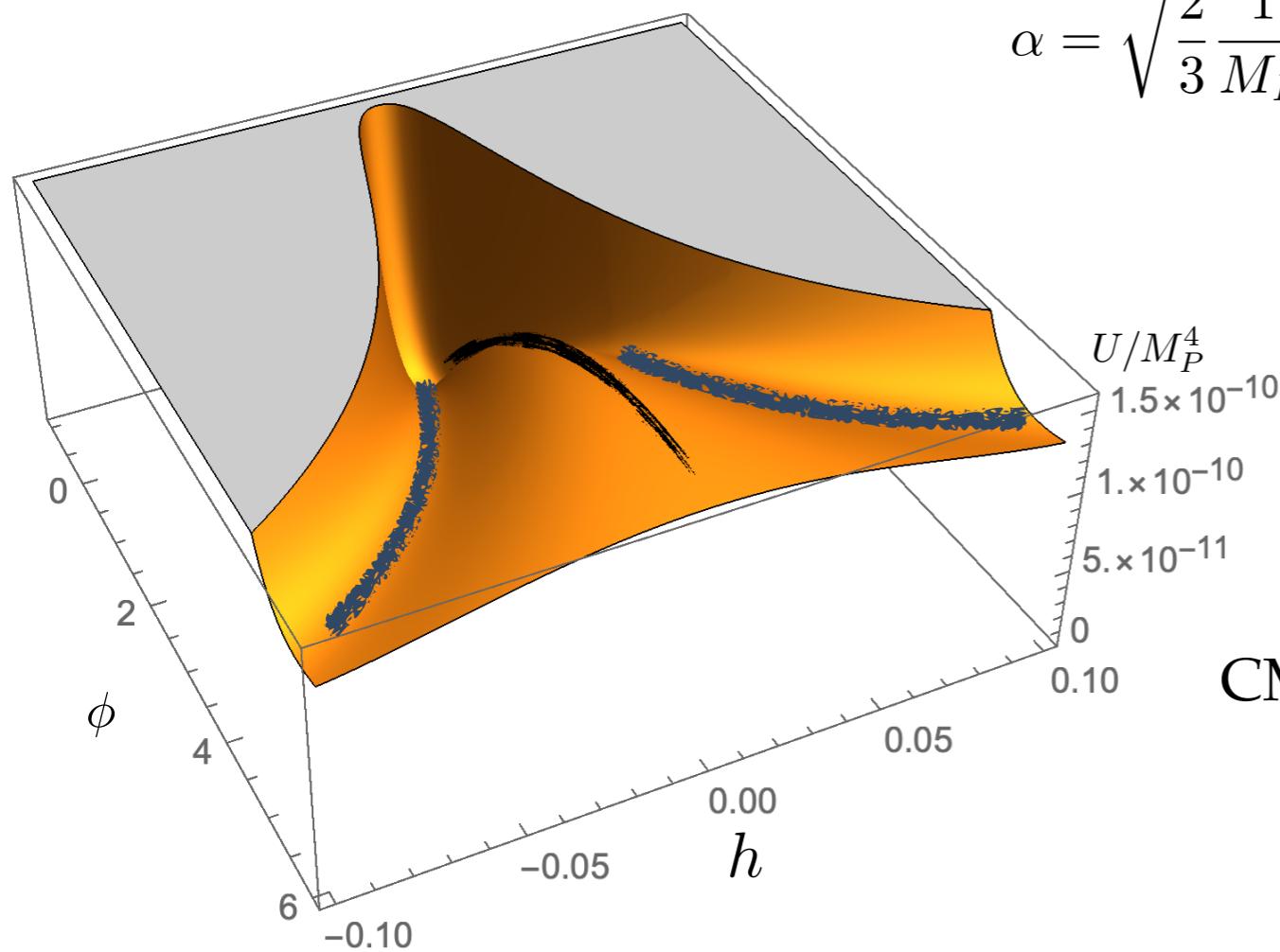
$$S_E = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - \frac{1}{2} e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} g^{\mu\nu} \nabla_\mu h \nabla_\nu h - U(\phi, h) \right]$$

- ϕ : additional scalar degree of freedom \rightarrow “scalarmon”
- Multi-field potential in nature, both ϕ, h being coherent background fields.
- Cutoff scale for Higgs R2 $\Lambda \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 M^2}\right) M_P > M_P$

Higgs- R^2 Inflation — Potential

- What about the shape of the potential?

$$U(\phi, h) = e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} \left[\frac{3}{4} M_P^2 M^2 \left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} - 1 - \frac{\xi h^2}{M_P^2} \right)^2 + \frac{\lambda}{4} h^4 \right]$$



$\alpha = \sqrt{\frac{2}{3}} \frac{1}{M_P}$ • “Valley” structure, trajectory follows,

$$h_v^2 = \frac{e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} - 1}{\frac{\xi}{M_P^2} + \frac{\lambda}{3\xi M^2}} \text{ for } \phi > 0$$

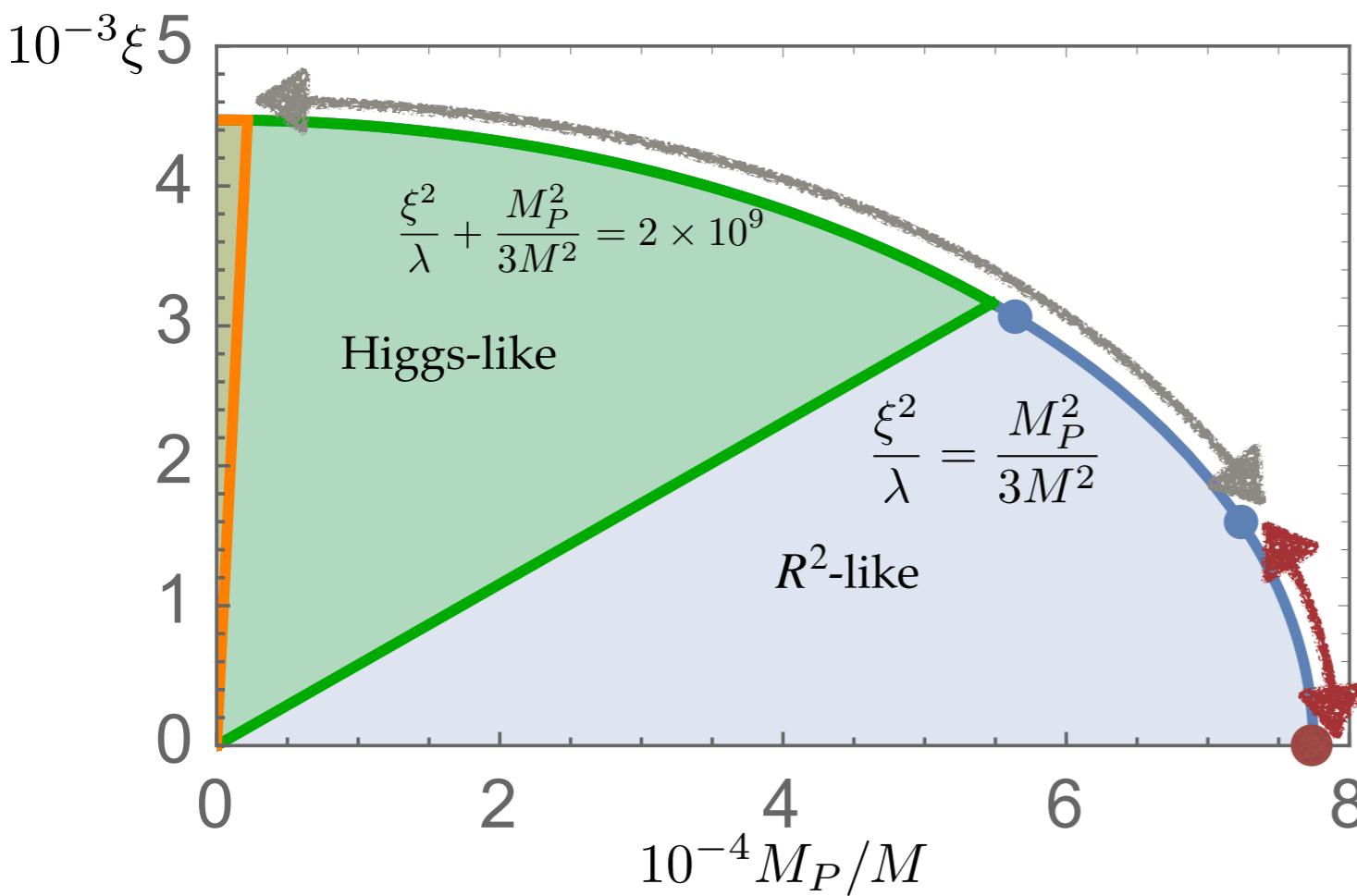
$$U(\phi \rightarrow \infty, h_v) \rightarrow \frac{\lambda M_P^4}{4\xi^2 \left(1 + \frac{\lambda M_P^2}{3\xi^2 M^2} \right)}$$

$$\text{CMB normalization : } \frac{\xi^2}{\lambda} + \frac{M_P^2}{3M^2} = 2 \times 10^9$$

- “Tachyonic Direction” at $h = 0$ for $\phi > 0$

$$m_h^2(\phi, 0) = -\sqrt{6}M^2\xi\phi \text{ near } \phi \ll 1$$

Higgs- R^2 Inflation — Parameters



Small ξ (Deep - R^2) Limit

$$\frac{\xi^2}{\lambda} + \frac{M_P^2}{3M^2} = 2 \times 10^9 \quad \text{RG running of the SM Higgs indicates } \lambda_{\text{inf}} < \lambda_{\text{EW}}$$

More realistic SM like parameters indicate a smaller ξ , closer to our known universe

How does the theory reheat in this limit? What are its predictions and connection to the R^2 inflation?

Preheating (Non-perturbative)

- He, M., Jinno, R., Kamada, K., Park, S. C., Starobinsky, A. A., & Yokoyama, J. I. (2019). *PLB*, 791, 36-42.
- Bezrukov, F., Gorbunov, D., Shepherd, C., & Tokareva, A. (2019). *PLB*, 795, 657-665.
- Bezrukov, F. & Shepherd, C. (2020) *JCAP* 2020.12: 028.

Reheating (Perturbative)

- He, Minxi. *JCAP* (2021), 2021.05 021..

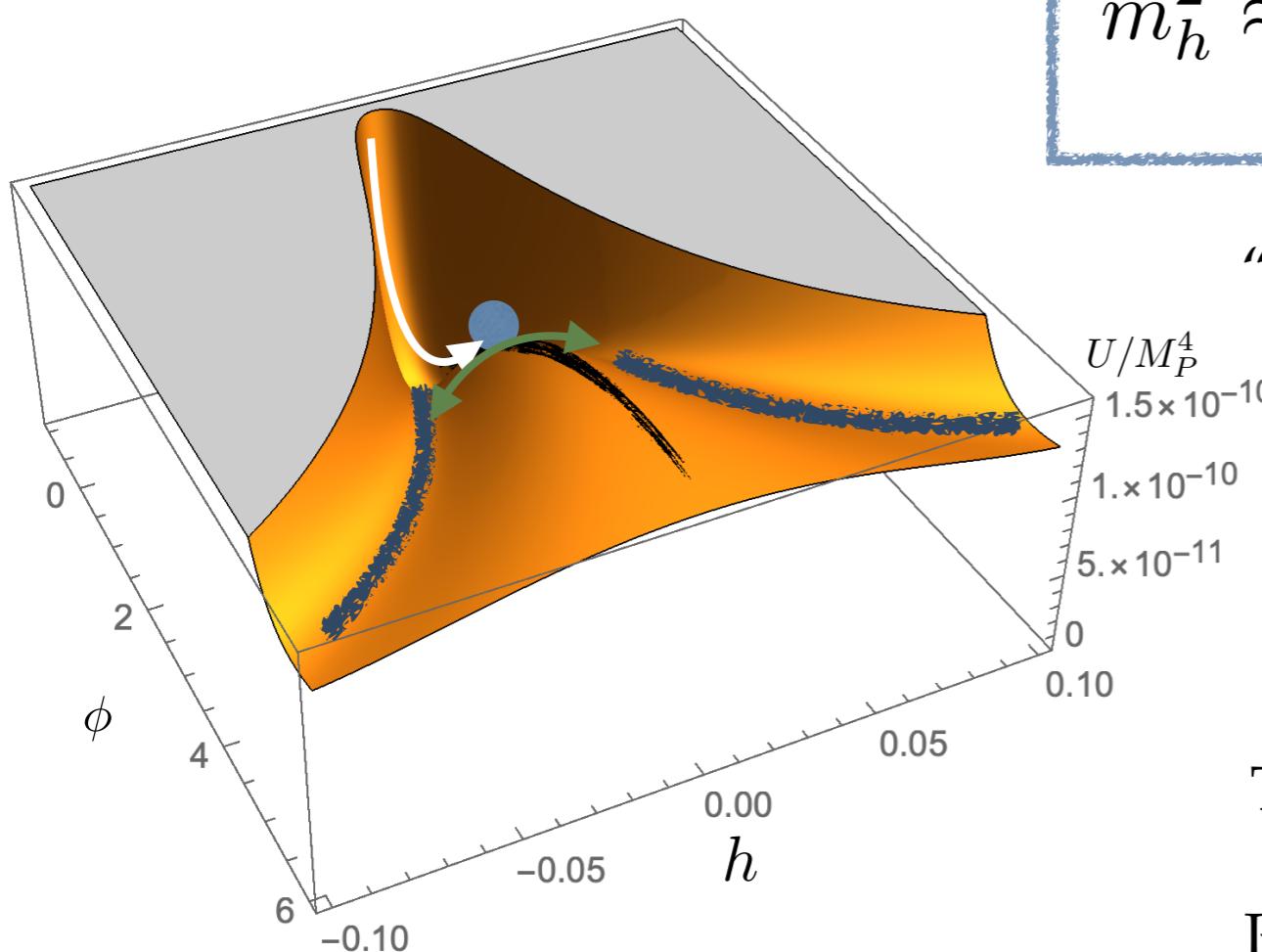
Extensive work on large ξ values

However, Higgs inflation and R^2 reheat differently

Higgs- R^2 Inflation — Reheating

TWO background fields : need to consider the depletion of both.

Concerns on “tachyonic preheating”? May it be efficient?



$$m_h^2 \approx -\sqrt{6} \frac{M^2}{M_P} \xi \phi + 3 \left(\lambda + 3 \frac{M^2}{M_P^2} \xi^2 \right) h^2$$

“Tachyonic” preheating depends strongly on ξ

Small ξ region : less tachyonic Higgs direction

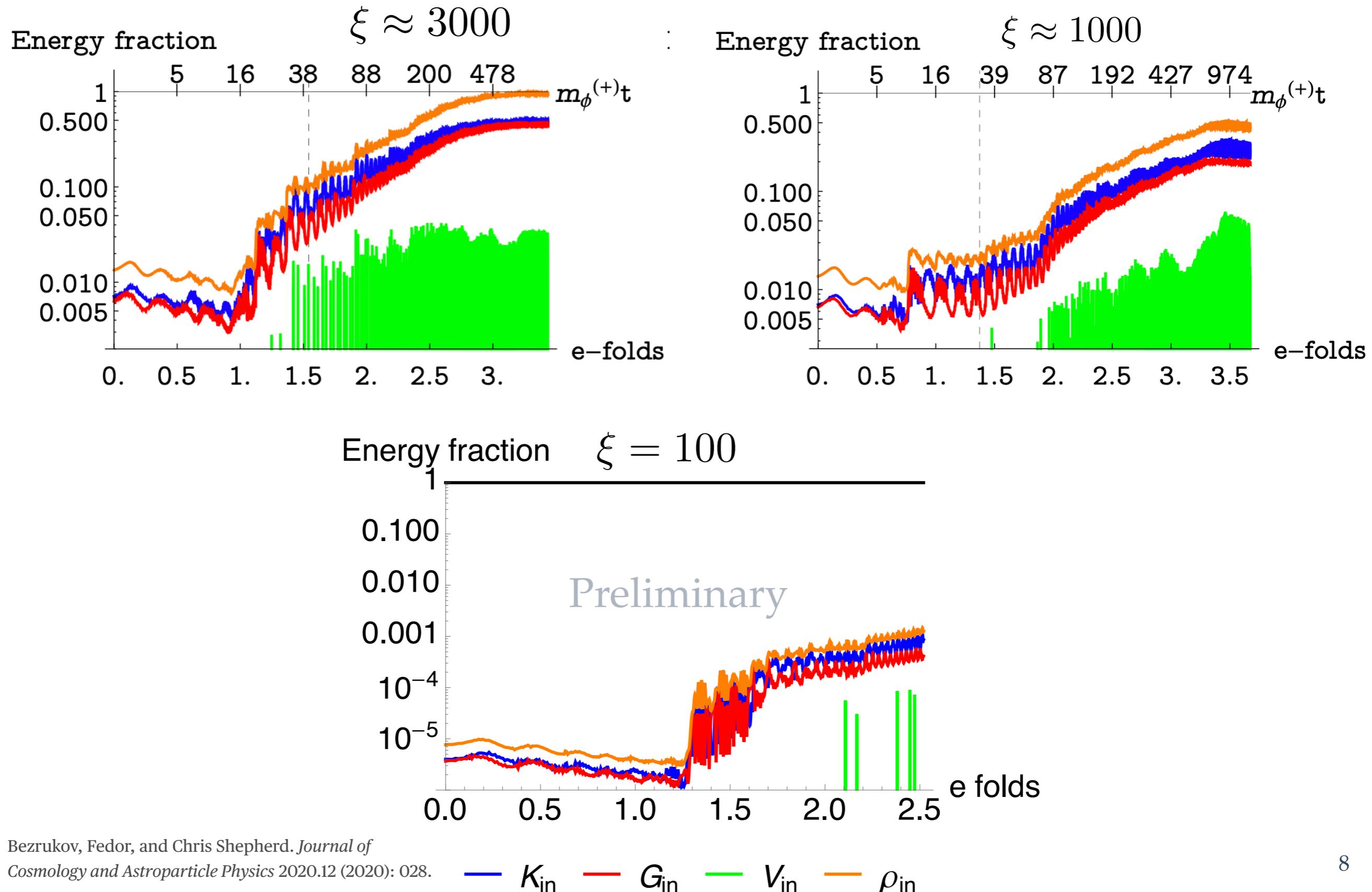
Preheating process inefficient.

The inflaton energy density remains dominant

Perturbative decay will dominate in this space.

- Bezrukov, Fedor, and Chris Shepherd. *Journal of Cosmology and Astroparticle Physics* 2020.12 (2020): 028.

Higgs- R^2 Inflation — Reheating



Higgs- R^2 Inflation – Reheating

Relevant interaction terms :

Scalor dof ϕ : couples with T_μ^μ

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2} e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} T_\mu^\mu \supset -\frac{1}{\sqrt{6} M_P} \phi (\partial h)^2 + \frac{\sqrt{6} M^2 \xi}{M_P} \phi h^2$$

$$\Gamma_{\phi \rightarrow hh} = 4 \frac{(6\xi + 1)^2}{192\pi} \frac{M^3}{M_P^2} \sqrt{1 - \frac{4m_h^2}{M^2}}$$

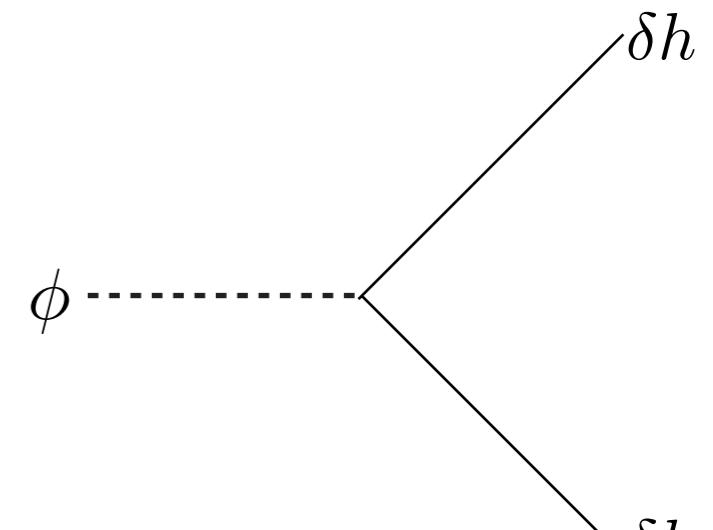
Other terms are Planck suppressed, hence subdominant.

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset \frac{y_f}{\sqrt{6} M_P} h \bar{f} f \phi$$

Higgs dof. h : dominant channel being $h \rightarrow \bar{t}t$ in the SM

$$\Gamma_{h \rightarrow tt} = \frac{3y_t^2}{16\pi} m_h \left(1 - \frac{4m_t^2}{m_h^2}\right)^{3/2}$$

Other terms have subdominant contributions.



Higgs- R^2 Inflation — Reheating

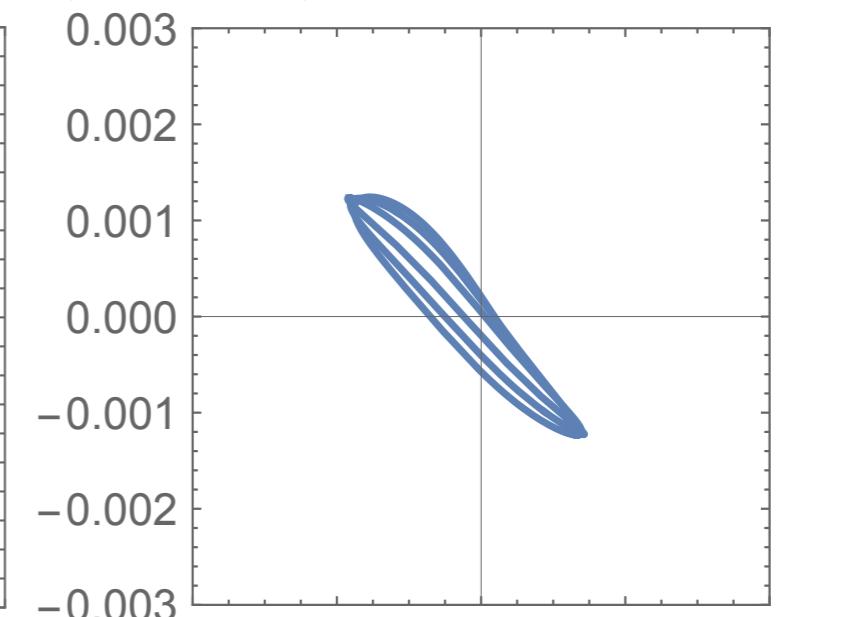
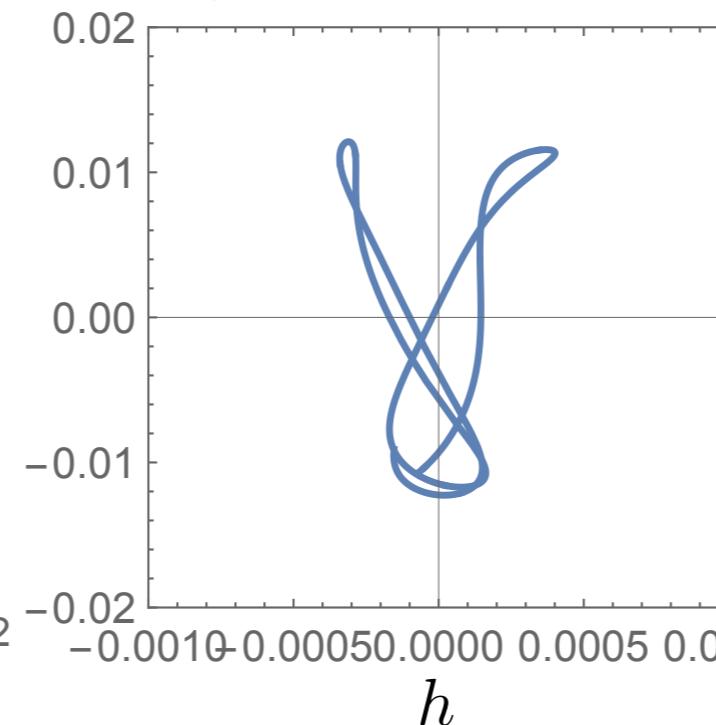
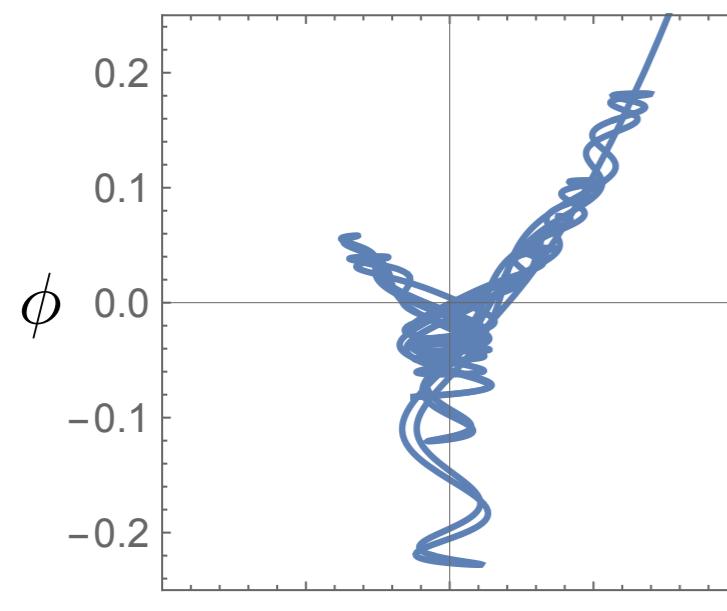
Relevant equation of motions for the homogeneous (coherent) background fields

$$\ddot{\phi} + (3H + \Gamma_{\phi \rightarrow hh})\dot{\phi} + \frac{\alpha}{2}e^{-\alpha\phi}\dot{h}^2 + \frac{\partial U}{\partial \phi} = 0$$

$$\ddot{h} + (3H + \Gamma_h)\dot{h} - \alpha\dot{\phi}\dot{h} + e^{\alpha\phi}\frac{\partial U}{\partial h} = 0$$

$$\dot{\rho}_{\text{rad}} + 4H\rho_{\text{rad}} = \Gamma_{\phi \rightarrow hh}\dot{\phi}^2 + \Gamma_{h \rightarrow tt}\dot{h}^2$$

$$3M_P^2 H^2 = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}e^{-\alpha\phi}\dot{h}^2 + U(\phi, h) + \rho_{\text{rad}}$$



Higgs- R^2 Inflation — Reheating

$$\Gamma_{h \rightarrow tt} = \frac{3y_t^2}{16\pi} m_h \left(1 - \frac{4m_t^2}{m_h^2}\right)^{3/2}$$

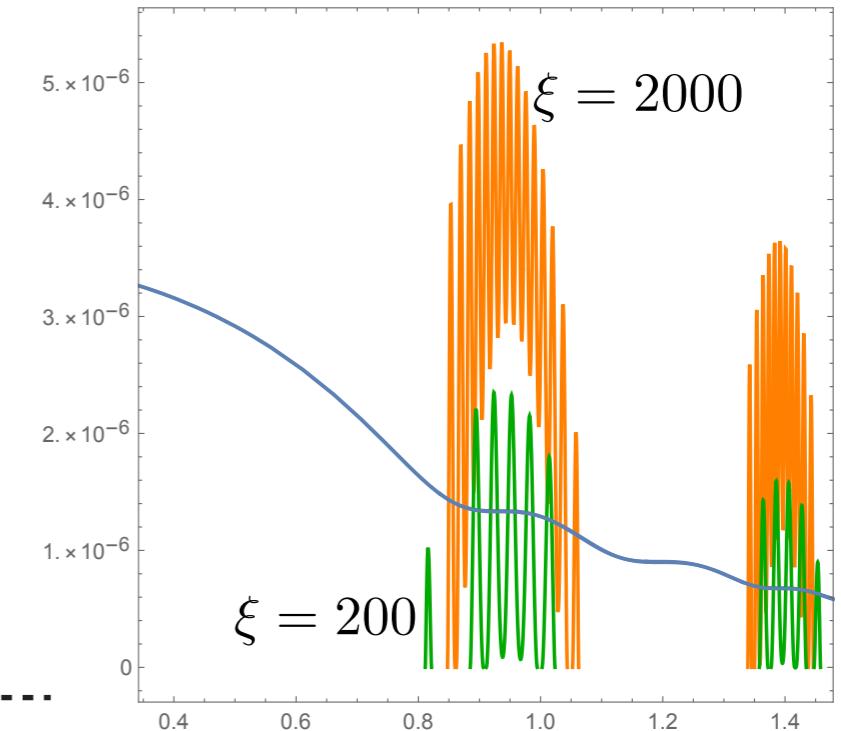
Decay opens when $m_h > 2m_t$, approximately

$$-\sqrt{6} \frac{M^2}{M_P} \xi \phi + 3 \left(\lambda + \frac{3M^2 \xi^2}{M_P^2} \right) h^2 \gtrsim 2y_t^2 h^2$$

For late times (ϕ decay), small ξ , condition invalidated

Except for $h = 0$ (zero crossing), $m_t = 0$,

Bursts of radiation from the Higgs decay

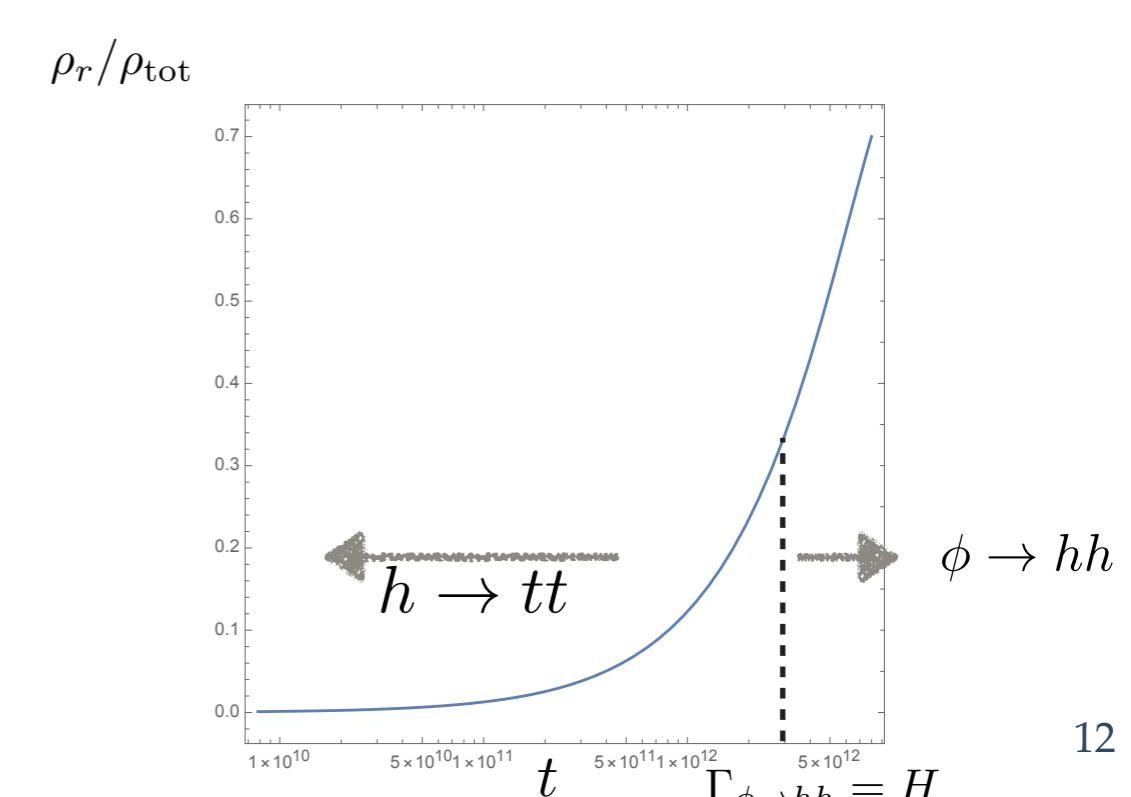
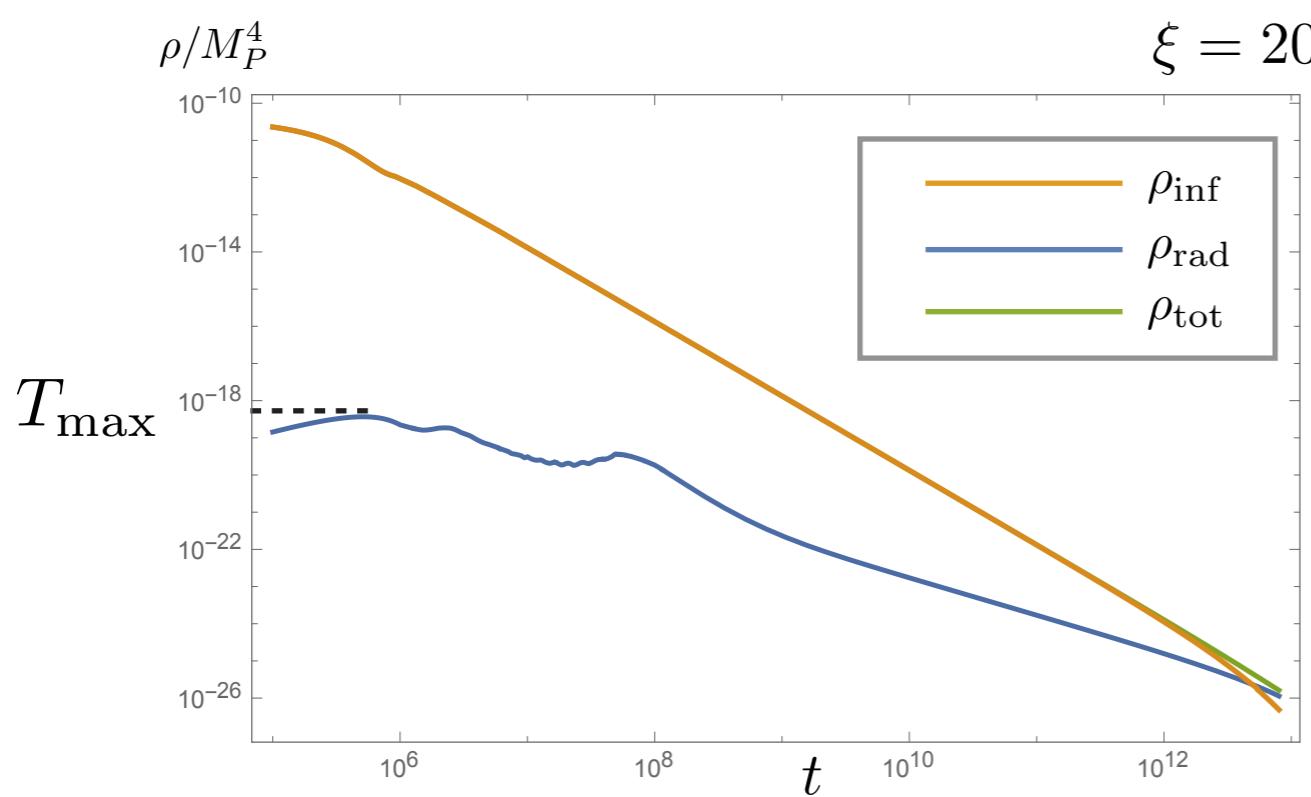
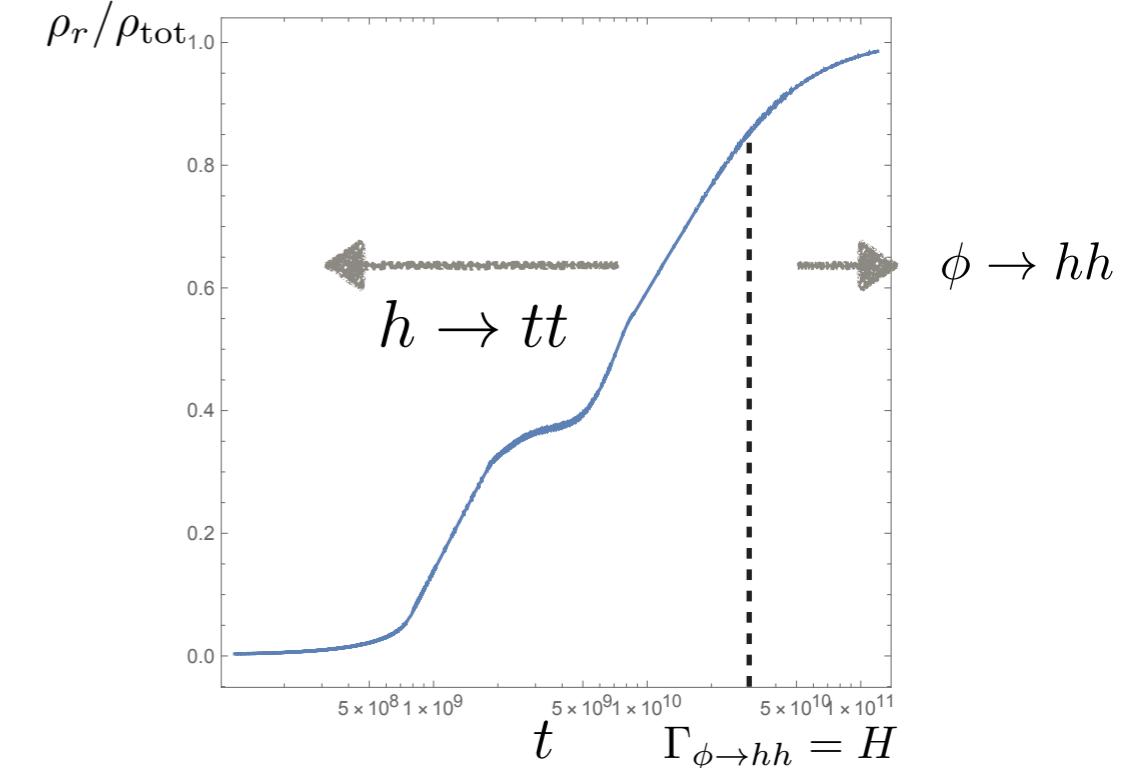
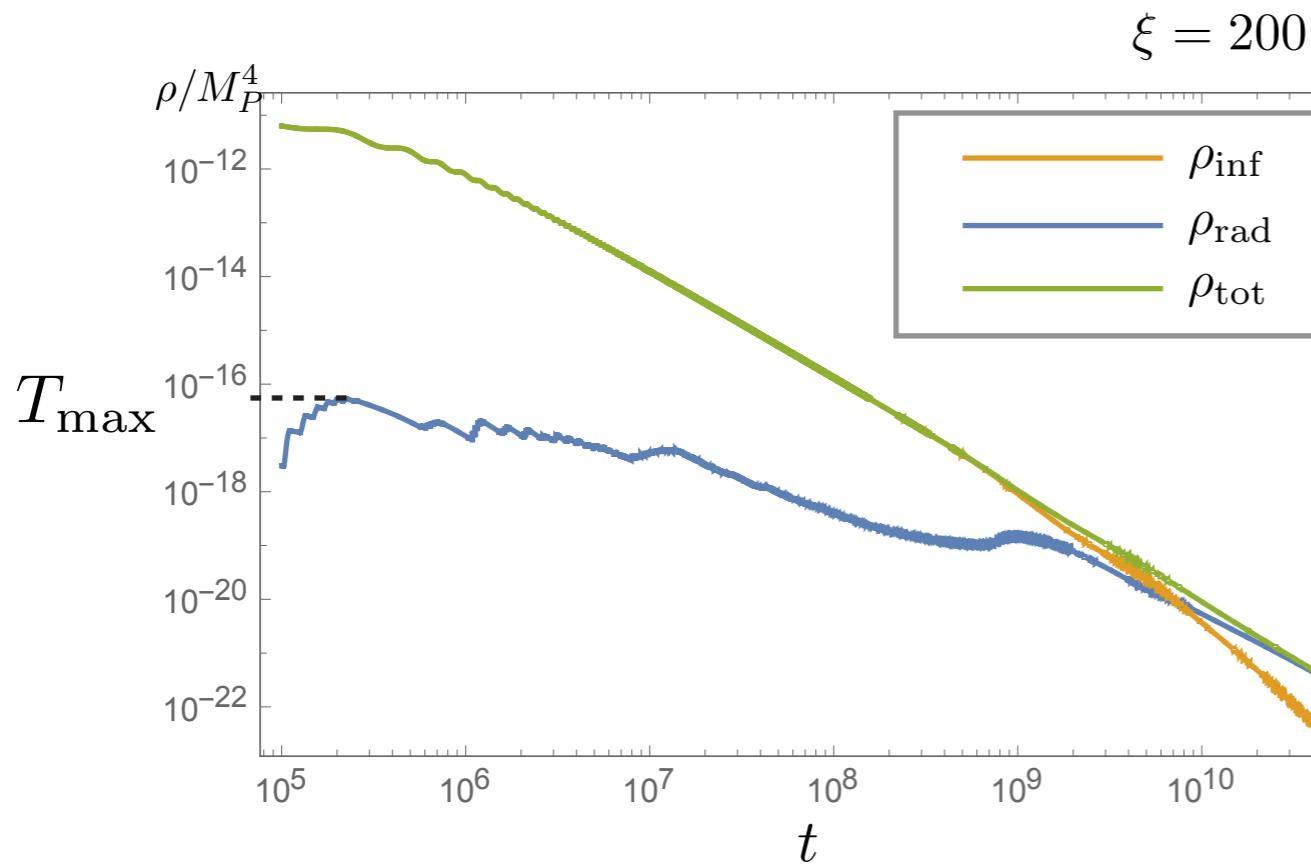


$$\Gamma_{\phi \rightarrow hh} = 4 \frac{(6\xi + 1)^2}{192\pi} \frac{M^3}{M_P^2} \sqrt{1 - \frac{4m_h^2}{M^2}}$$

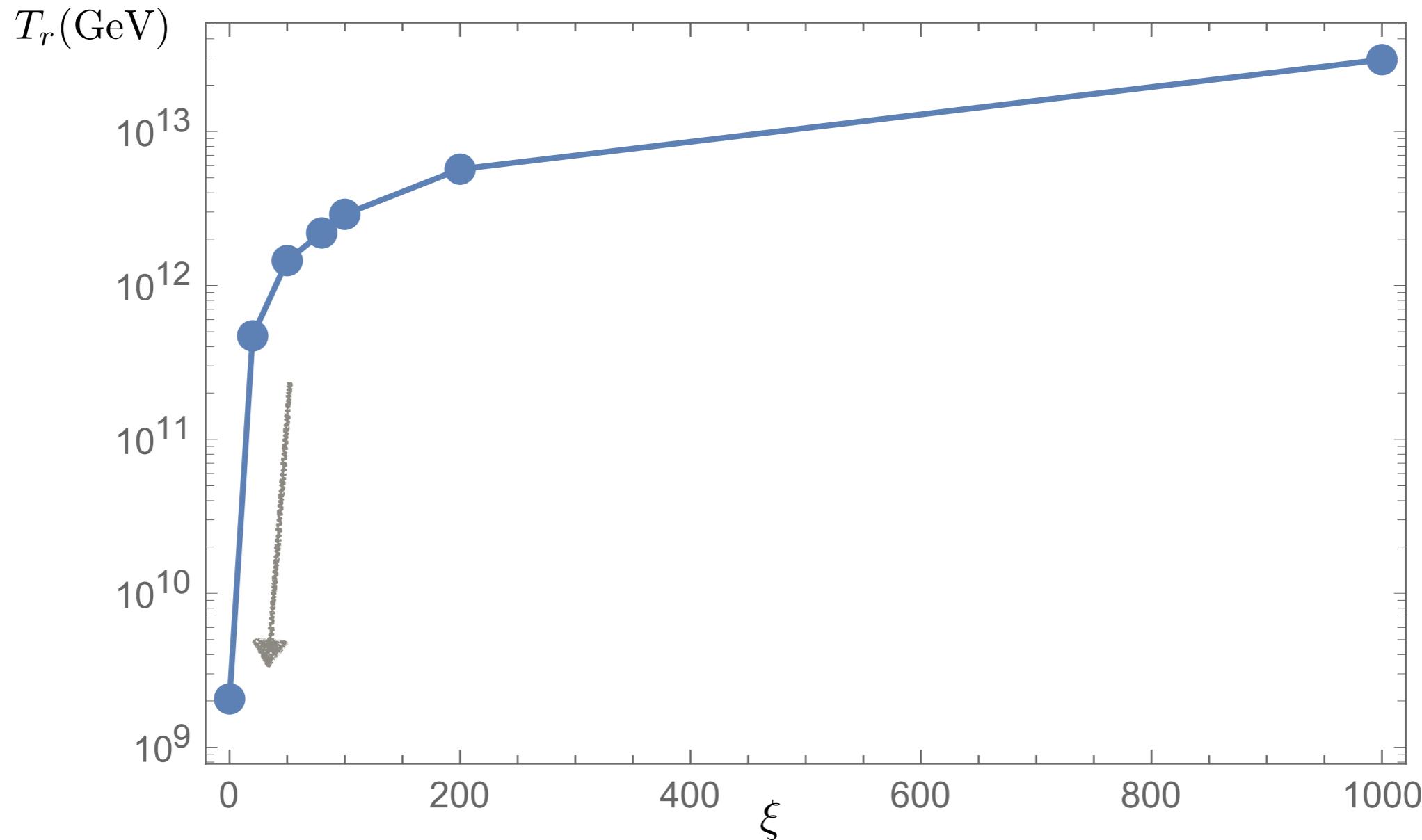
Typically, $\Gamma_{h \rightarrow tt} \gg \Gamma_{\phi \rightarrow hh}$ For $\xi \sim \mathcal{O}(10 - 100)$, $M \sim 10^{-5} M_P$, $y_t \sim 0.5$, $\lambda \sim 0.01$

However, $\Gamma_{\phi \rightarrow hh}$ being the dominant channel that depletes ϕ , will govern late time behavior and T_r .

Higgs- R^2 Inflation — Reheating



Higgs- R^2 Inflation – Reheating

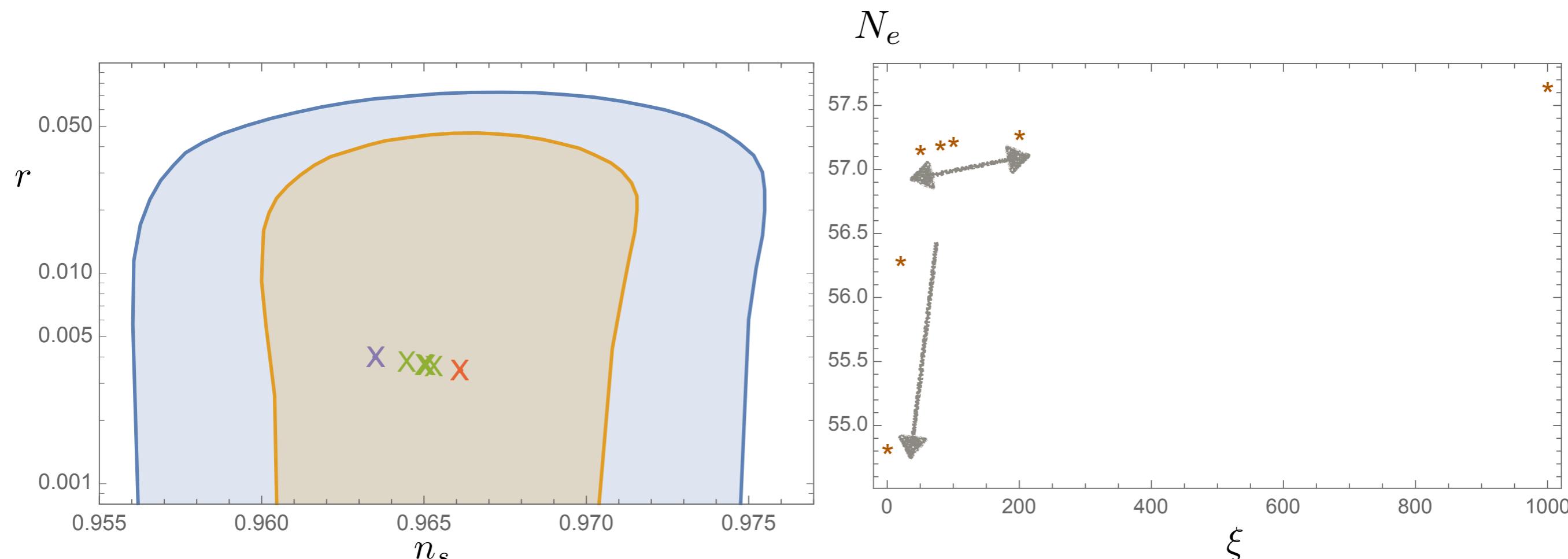


$$\rho_r = \frac{\pi^2}{30} g_* T_r^4 \text{ when } \Gamma_{\phi \rightarrow hh} = H(t_r)$$

$$T_{\max} \sim 10^{14} GeV$$

Higgs- R^2 Reheating — Observables?

$$N_e \approx 59.015 - \frac{1}{4} \ln \frac{\rho_r}{\rho_e} - \ln \frac{a_r}{a_e} \quad n_s \simeq 1 - \frac{2}{N_e} \quad r \simeq \frac{12}{N_e^2}$$



Predictions rapidly approach R^2 for $\xi \lesssim 50$.

Predictions indistinguishable today, but future experiments may be able to distinguish parameters

Conclusions & Outlooks

- The Higgs- R^2 model, being an extension to Higgs inflation, successfully realizes current Planck CMB constraints
- The small ξ regime (which incorporates realistic SM like parameters), less studied among the parameter region, is less tachyonic, with perturbative decays being the dominant channel .
- Having two coherent fields (ϕ, h) in the model, each field has to deplete in order to successfully end perturbative reheating
- Bursts of radiation , early stage behavior determined from $\Gamma_{h \rightarrow tt}(T_{\max})$, overall stage terminated by $\Gamma_{\phi \rightarrow hh'}(T_r)$.
- Critical λ RG running effects? Compatibility with matter antimatter asymmetry associated processes?

“Thank you!”