Reheating the Universe at Criticality

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Ref. S.-M Choi, HML, K.-C. Kim, To appear.

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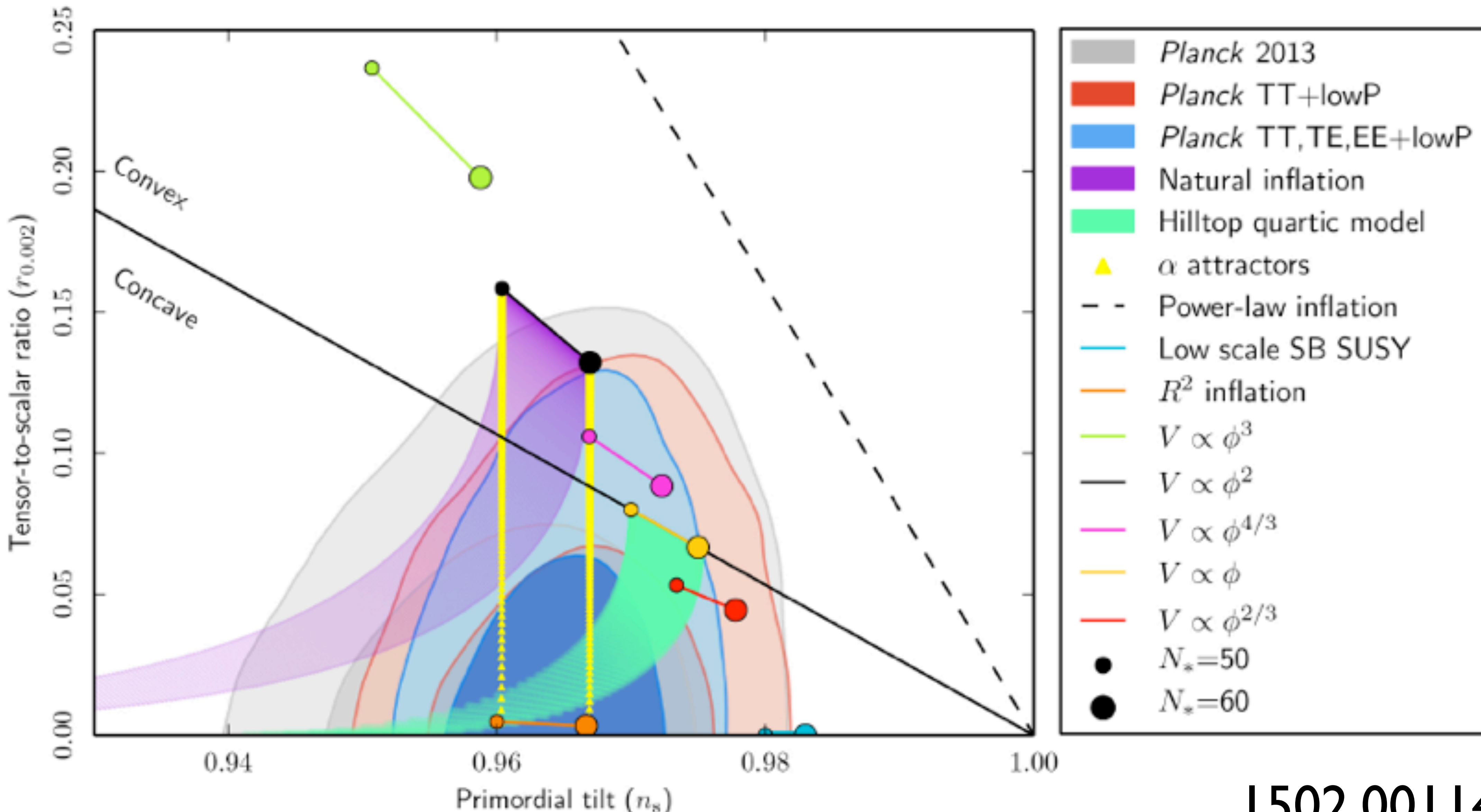
Outline

- Introduction
- Inflation and reheating at inflection point
- Higgs inflation at criticality
- Conclusions

Planck 2015



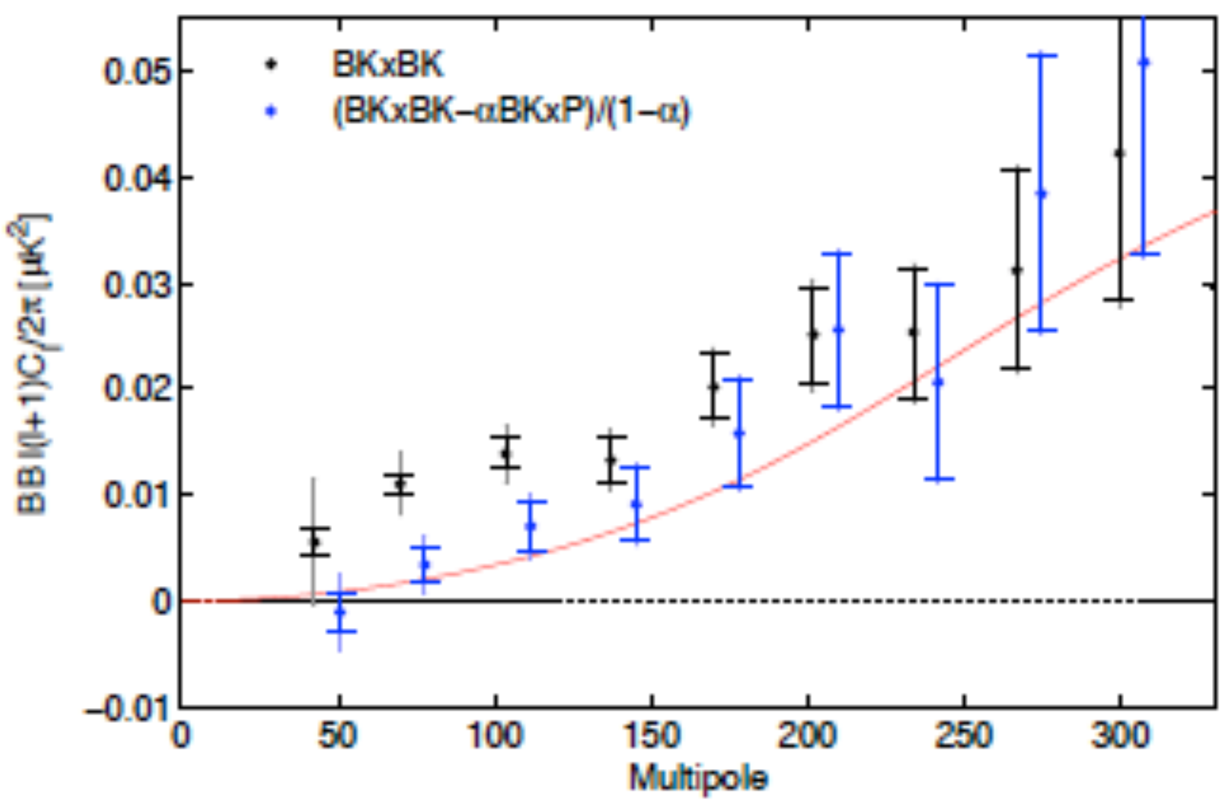
1502.00114

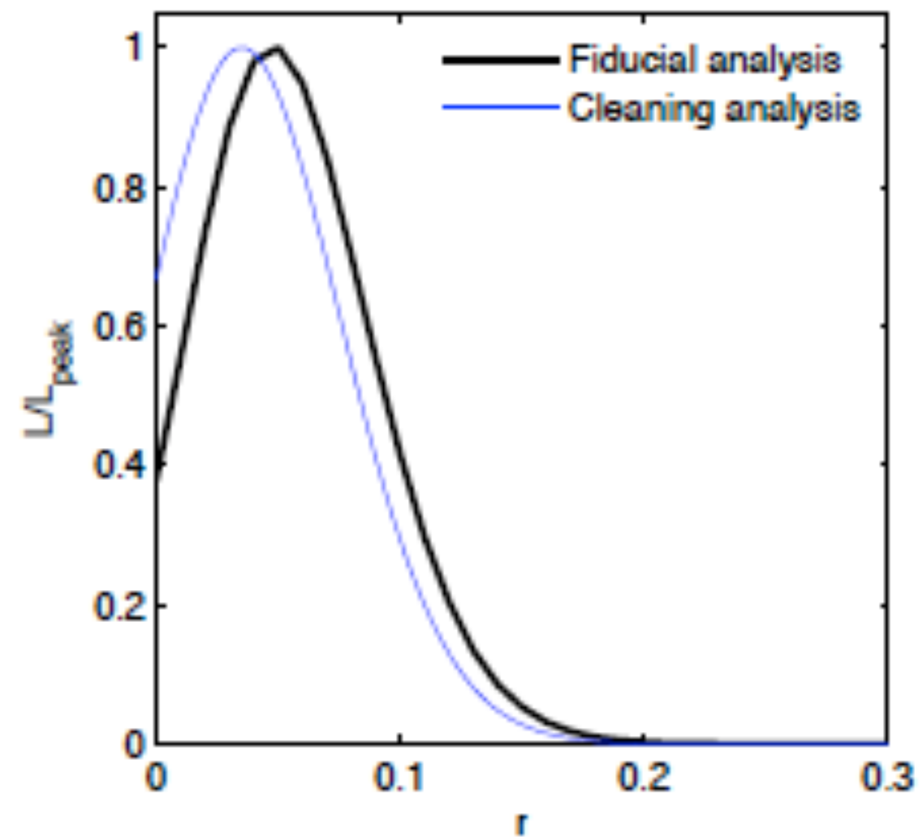
- Bound on tensor mode: Planck TT+lowP: $r_{0.002}$<0.10 (95% CL)

  ➡ + running: $r_{0.002}$<0.18 (95% CL)

- No non-Gaussianity observed: canonical single field inflation favored. e.g. $f_{NL}^{\rm local} = 0.8 \pm 5.0$ (T & E 68% CL)

Dust and tensor mode



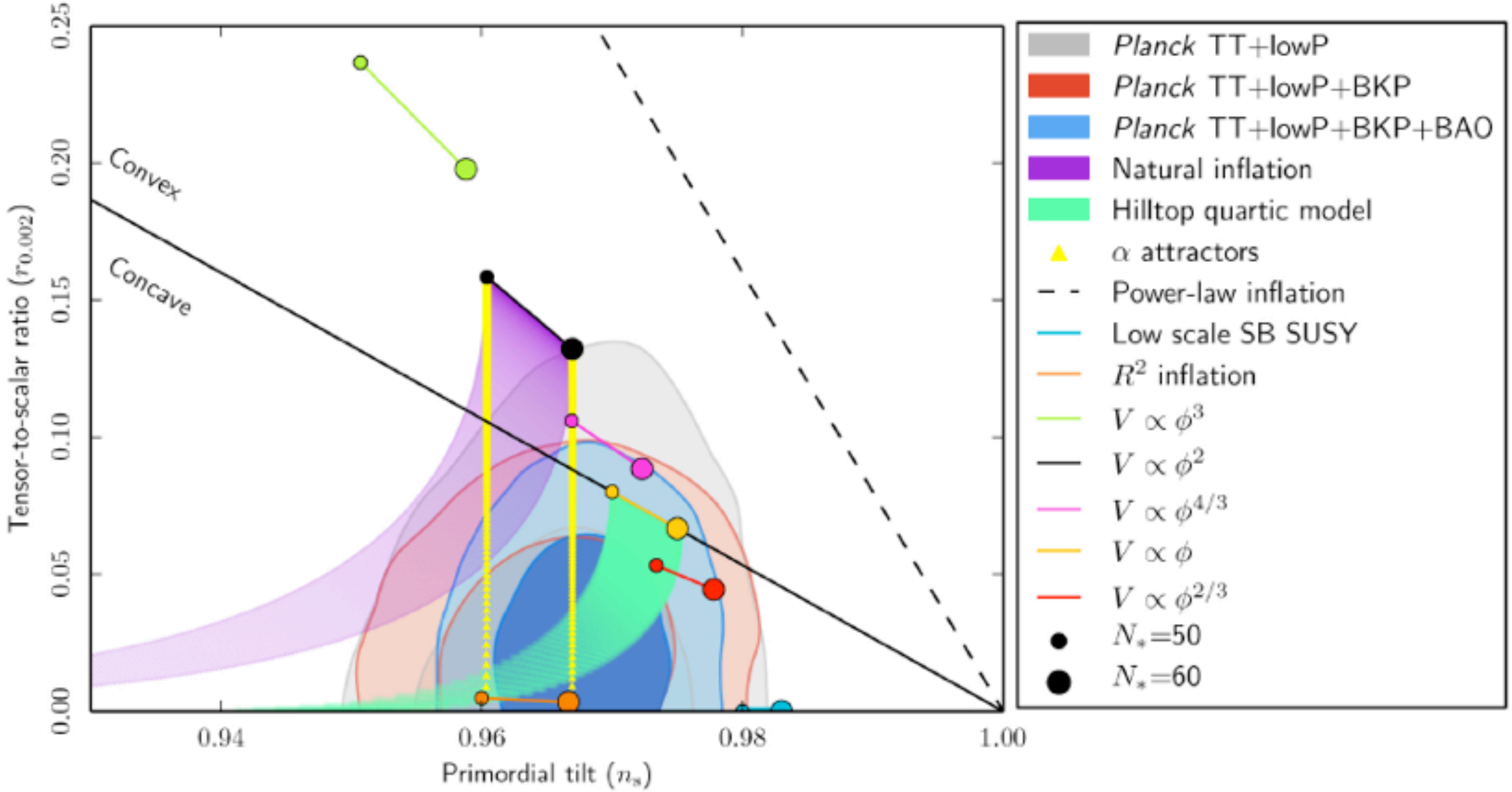


Blue: after subtraction of dust, estimated from Planck 353GHz.

1502.00612

- Posterior probability peaks at r=0.05, but r=0 is allowed with large probability.

Planck+BICEP2+Keck



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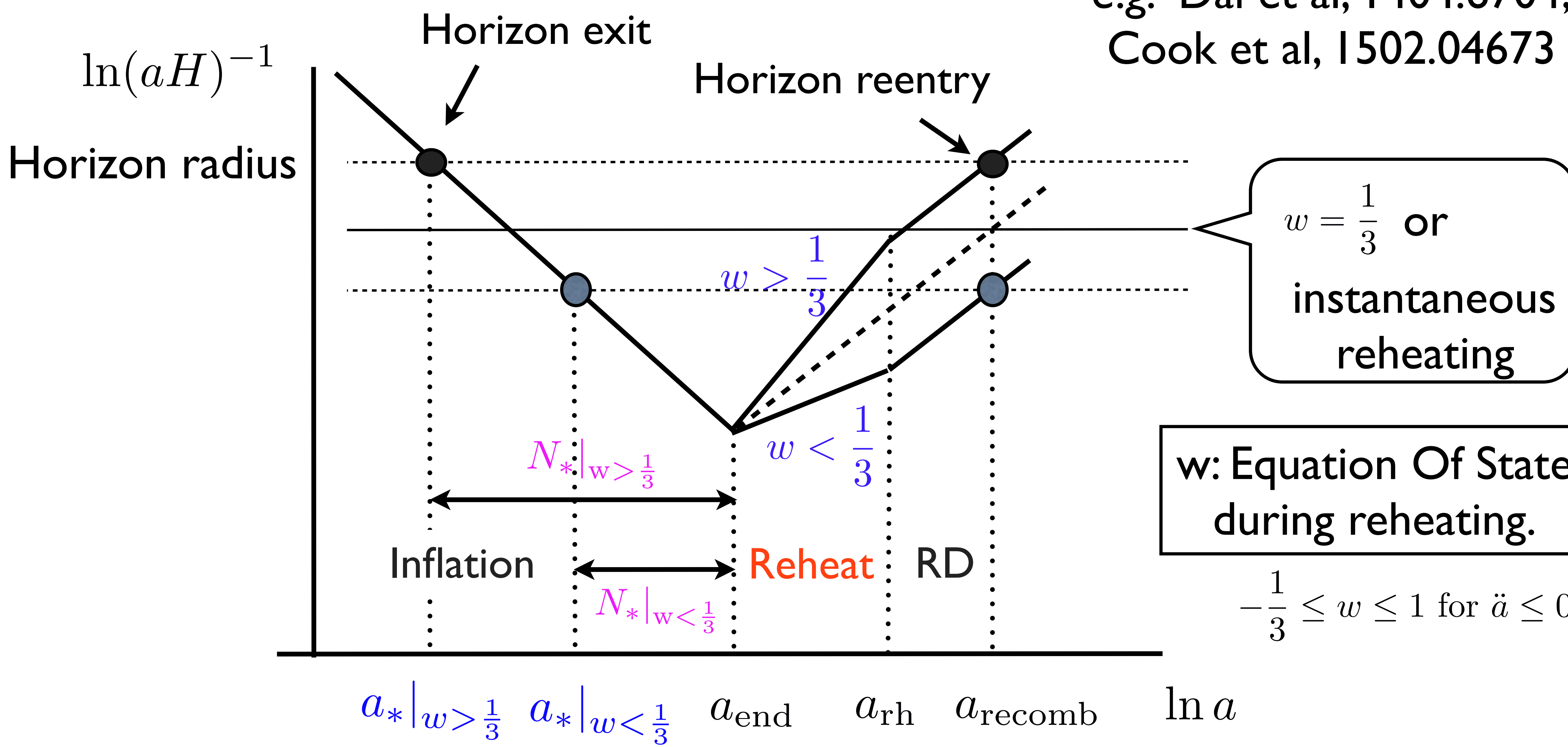
- BICEP2+Keck array data at 150GHz are consistent with Planck maps at higher frequencies.

Tensor-to-scalar ratio: $r_{0.05}$<0.12 (95% CL)

Reheating & EOS

e.g. Dai et al, 1404.6704; Cook et al, 1502.04673



w: Equation Of State during reheating.

$$-\frac{1}{3} \le w \le 1 \text{ for } \ddot{a} \le 0.$$

$$\ln(aH)_I^{-1} \sim -\ln a, \qquad \ln(aH)_{\rm rh}^{-1} \sim \frac{1}{2}(1+3w)\ln a, \qquad \ln(aH)_{\rm RD}^{-1} \sim \ln a,$$

$$\Rightarrow \quad N_*|_{w>\frac{1}{3}} > N_*|_{w=\frac{1}{3}} > N_*|_{w<\frac{1}{3}}$$

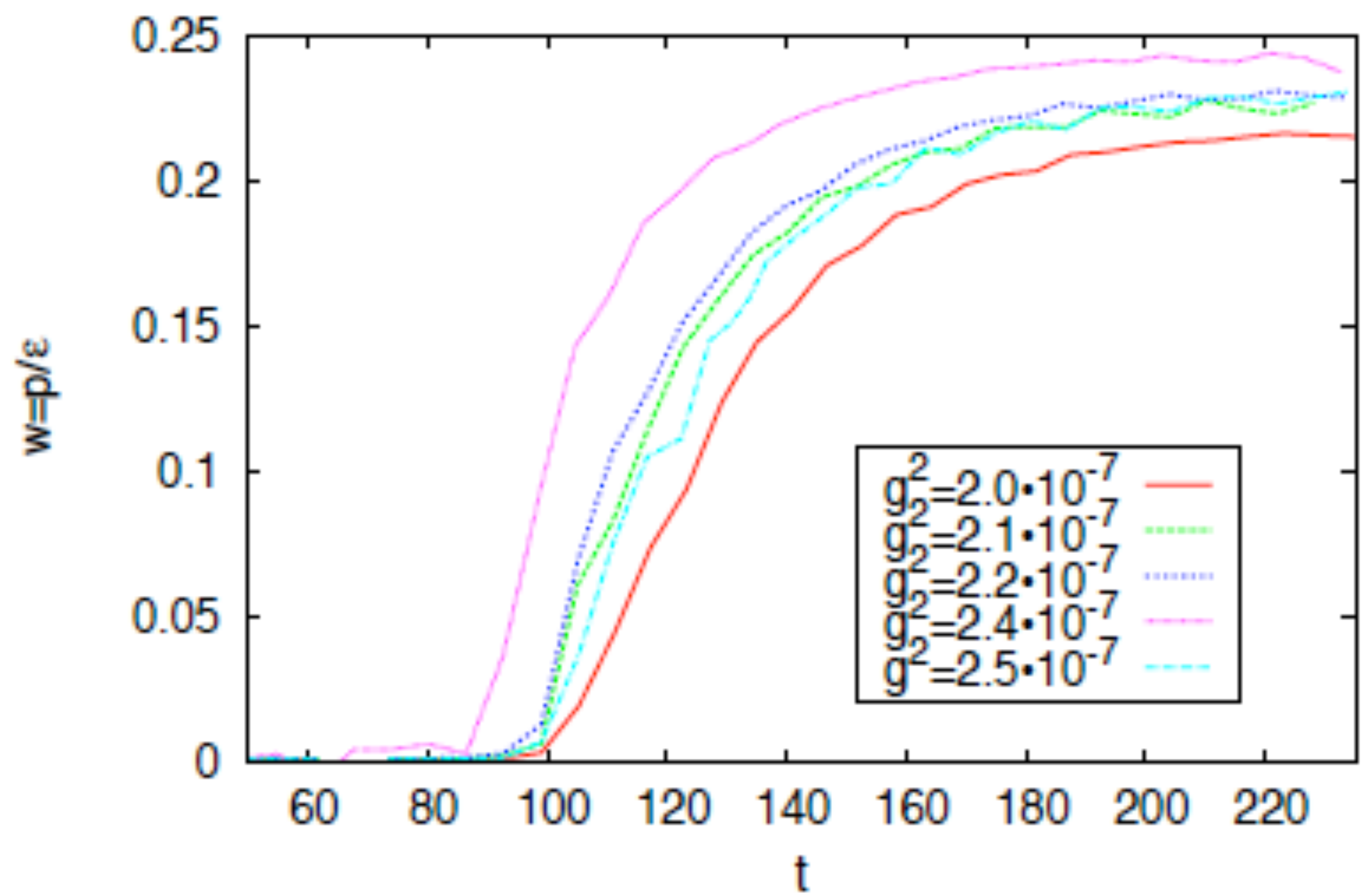
w from preheating

- A small coupling to another scalar can change the equation of state w during preheating.

e.g. quadratic inflation

Immediately after inflation, <w>=0

$$\mathcal{L}_{int} = -\frac{g^2}{2}\phi^2\chi^2$$



$\Rightarrow$

w changes sharply from w=0 at the end of preheating.

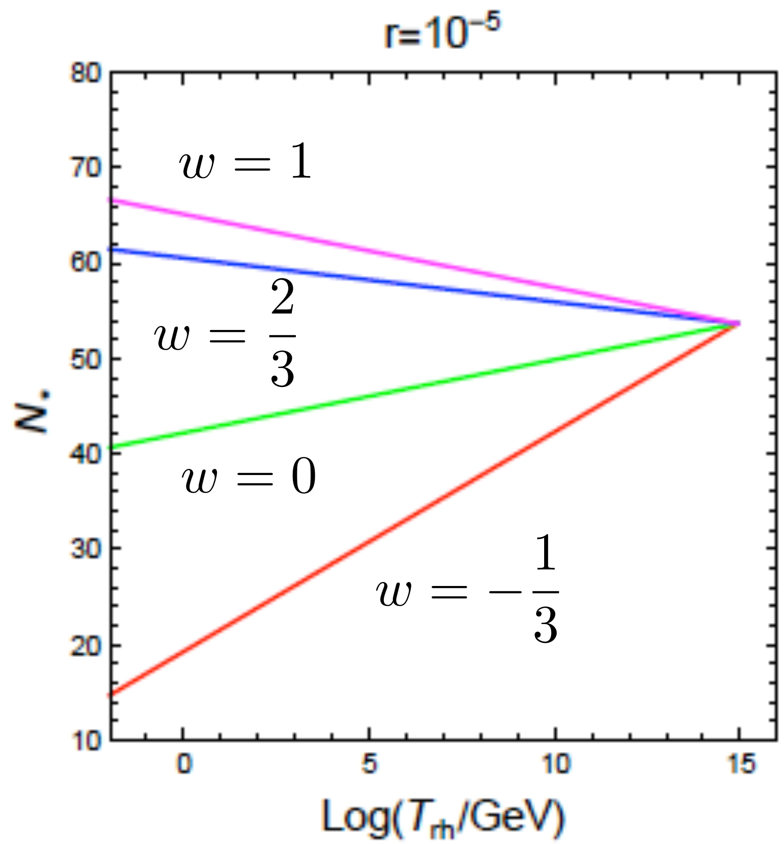
Podolsky et al, hep-ph/0507096

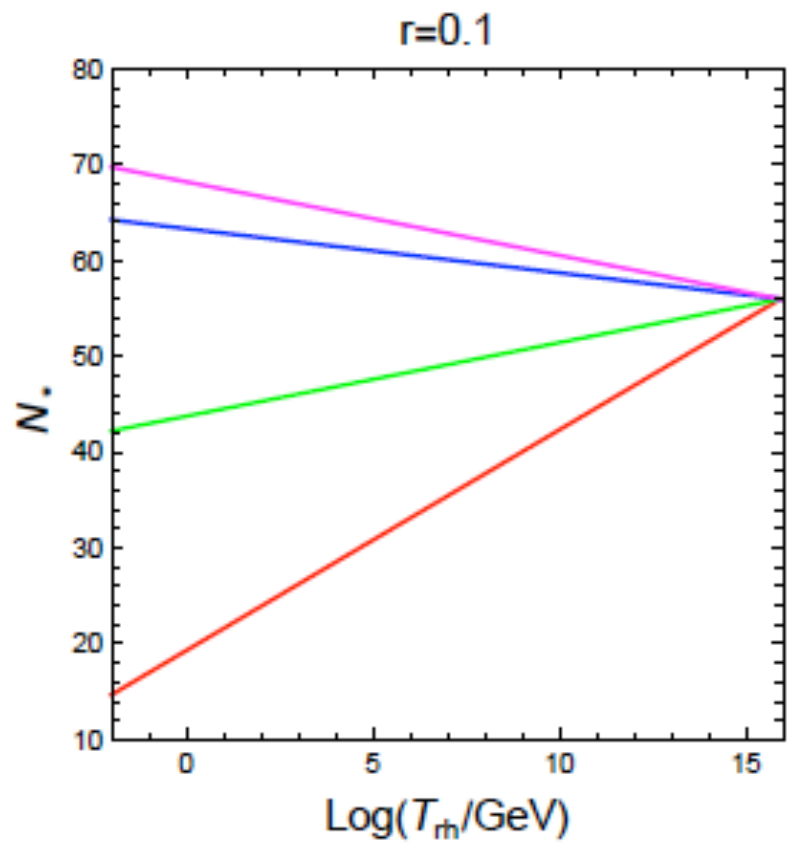
Number of efoldings

$$N_* = 67.2 + \frac{1}{4}(3w-1)N_{\rm rh} - \ln\left(\frac{k}{a_0 H_0}\right) - \ln\left(\frac{V_{\rm end}^{1/4}}{H_*}\right) - \frac{1}{12}\ln(g_*(T_{\rm rh}))$$

$$\Rightarrow \quad N_* = 61.4 + \frac{3w-1}{12(1+w)}\ln\left(\frac{45}{\pi^2}\frac{V_*}{g_*(T_{\rm rh})T_{\rm rh}^4}\right) - \ln\left(\frac{V_*^{1/4}}{H_*}\right).$$

Planck, 1303.5082; Cook et al, 1502.04673





cf. $\Delta N_* = 0$:

$$N_* = 53.7 + \tfrac{1}{4}\ln(r/10^{-5}).$$

- Reheating temperature and equation of state w could change N* and the inflation predictions.

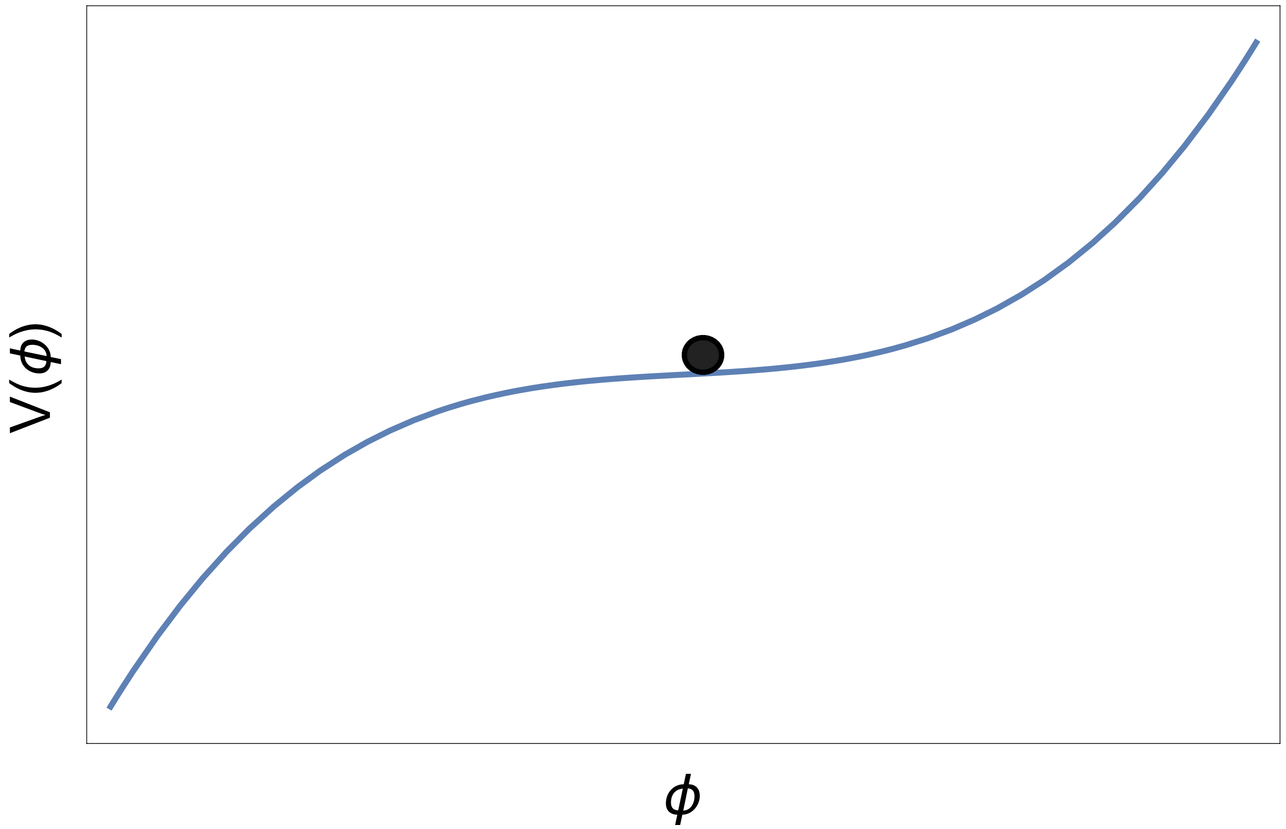
Inflation at criticality

- Small or large field values have been considered in usual inflation models.

  Small fields - graceful exit?

  Large fields - quantum gravity?

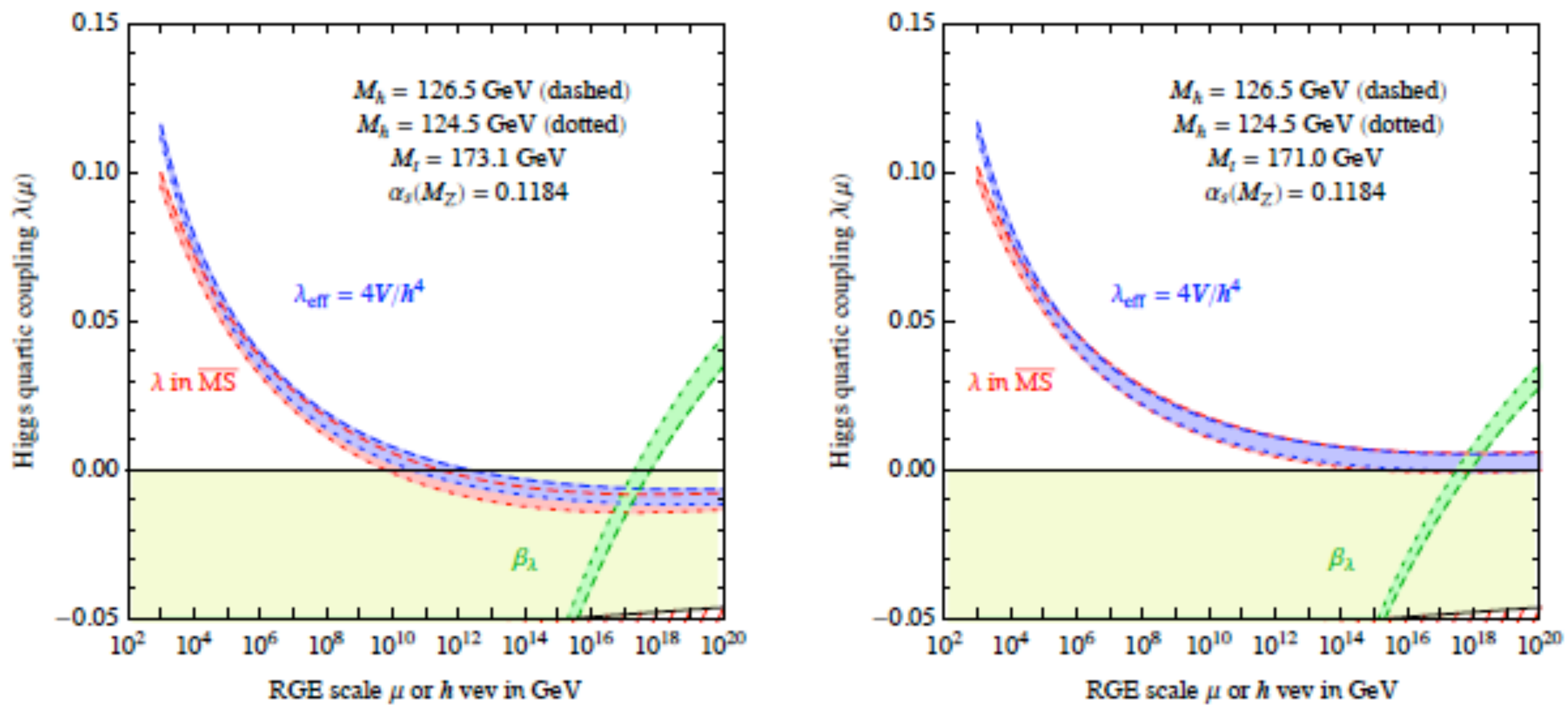
- Symmetry could be enhanced at a certain field space and protect large (quantum) corrections to inflation.



Inflection point inflation?

+ reheating dynamics

Higgs at criticality?



Degrassi et al, 1205.6497

- SM Higgs quartic coupling as well as its beta function might vanish at a similar scale: criticality.

  Inflation at criticality (inflection point)?

cf. Similar models> D-brane inflation: Baumann et al, 0705.3837,
MSSM flat-direction: Allahverdi et al, hep-ph/0605035

Inflation and reheating at inflection point

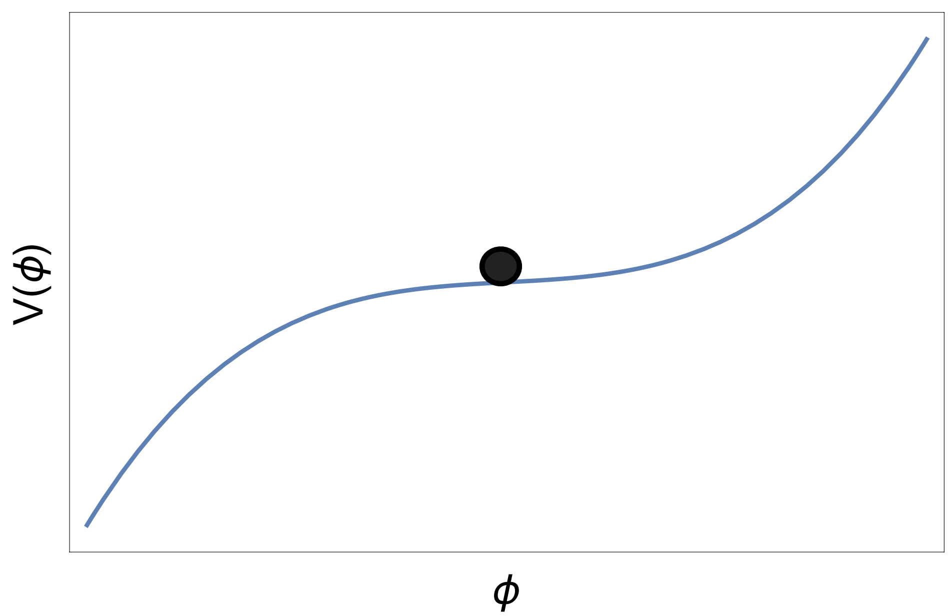
Inflection point inflation

- Expand the inflaton potential near inflection point(IP):

$$V = V_0 + \lambda_1(\phi - \phi_0) + \frac{1}{3!}\lambda_3(\phi - \phi_0)^3 \quad (V_0, \lambda_1, \lambda_3 : \ \text{positive const.})$$

(Suppressed higher order terms for small field excursion or small coefficients.)

$\lambda_1 > 0$
ensures graceful exit.



e.g. Baumann et al, 0705.3837
(warped D-brane inflation)

Slow-roll parameters:

$$\epsilon \simeq \frac{1}{2}\left(\frac{\lambda_1 + \frac{1}{2}\lambda_3(\phi - \phi_0)^2}{V_0}\right)^2,$$

$$\eta \simeq \frac{\lambda_3}{V_0}(\phi - \phi_0).$$

Number of efoldings:

$$N_* = \frac{N_{\rm max}}{\pi}\left(\arctan\left(\frac{N_{\rm max}}{2\pi}\eta_*\right) - \arctan\left(\frac{N_{\rm max}}{2\pi}\eta_{\rm end}\right)\right)$$

$$N_{\rm max} \equiv \int_{-\infty}^{+\infty}\frac{d\phi}{\sqrt{2\epsilon}} = \pi V_0\sqrt{\frac{2}{\lambda_1\lambda_3}}.$$

$N_{\rm max} \gtrsim 2N_*$

$$\frac{V_0}{\sqrt{\lambda_1\lambda_3}} \ll 1 :$$ necessary condition for large N.

Inflation conditions

- Sufficient number of efoldings

$$\frac{V_0}{\sqrt{\lambda_1 \lambda_3}} \ll 1$$

- Slow-roll or small tensor mode

$$\lambda_1 \ll V_0$$

- Small vs large field excursions + above two

$V_0 \lesssim \lambda_3$: sub-Planckian $\Longrightarrow$ $\lambda_1 \ll V_0 \lesssim \lambda_3$

$V_0 \gtrsim \lambda_3$: trans-Planckian $\Longrightarrow$ $\lambda_3 \ll \lambda_1 \ll V_0$

IP inflation vs Planck

- Spectral index and tensor-to-scalar ratio are given by

$$n_s = 1 - 3\left(\frac{\lambda_1}{V_0}\right)^2 + \frac{4\pi}{N_{\rm max}} \tan\left(\pi \frac{N_*}{N_{\rm max}} + \arctan\left(\frac{N_{\rm max}}{2\pi}\eta_{\rm end}\right)\right),$$

$$r = 8\left(\frac{\lambda_1}{V_0}\right)^2.$$

Planck TT, TE, EE + low P

$$\boxed{\begin{array}{r} n_s = 0.9652 \pm 0.0047 \\ r < 0.10 \text{ at } 95\ \%\ \text{C.L.} \end{array}}$$

- CMB normalization fixes one parameter while the other two are to be determined by n_s (or N_{max}) and r.

$$A_s = \frac{1}{24\pi^2}\frac{V_*}{\epsilon_*} \simeq 2.196 \times 10^{-9} \quad \text{at } k = 0.05\,\text{Mpc}^{-1}$$

$$\Rightarrow \quad V_0 = 3.25 \times 10^{-9}\left(\frac{r}{0.10}\right), \quad \lambda_3 = 3.98 \times 10^{-11}\left(\frac{120}{N_{\rm max}}\right)^2\left(\frac{r}{0.10}\right)^{1/2}$$

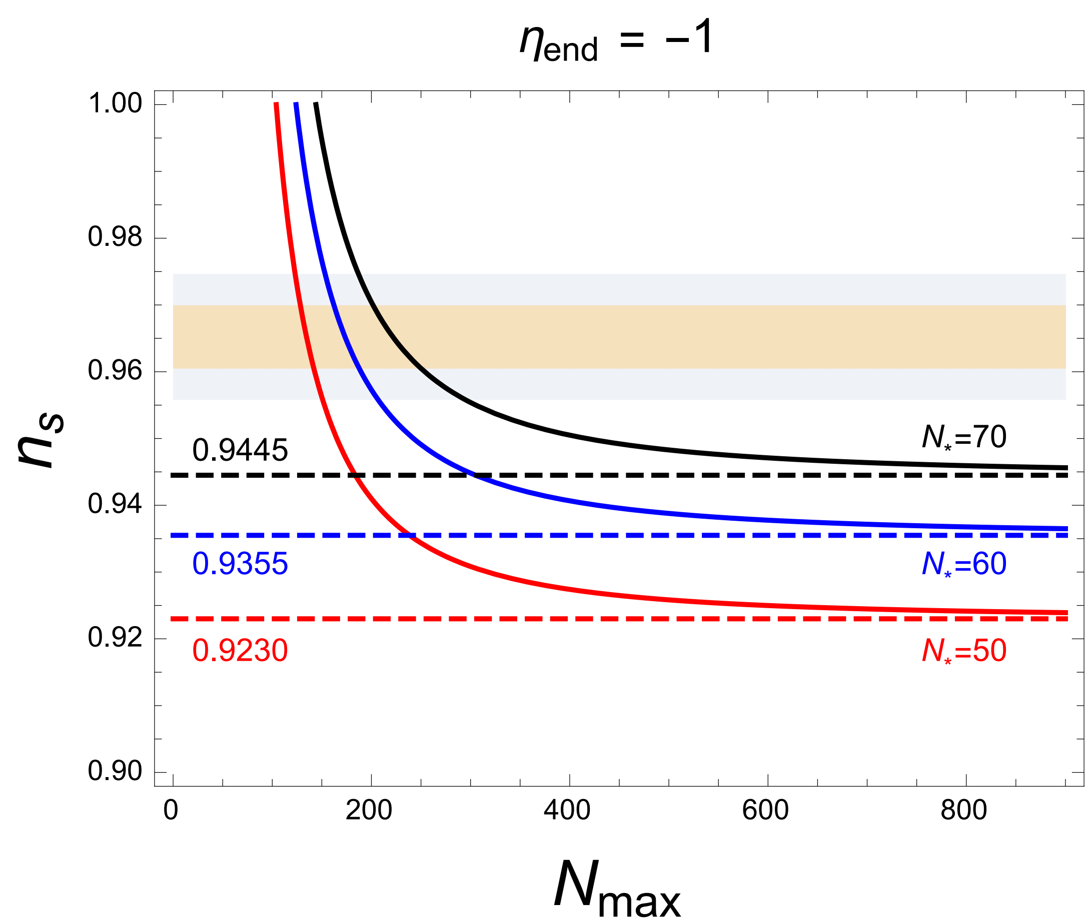
$$r = 0.10\left(\frac{\lambda_1}{3.63 \times 10^{-10}}\right)^{2/3}$$

Small-field case

Baumann et al, 0706.0360

- Perturbative regime: $\lambda_1 \ll V_0 \lesssim \lambda_3$

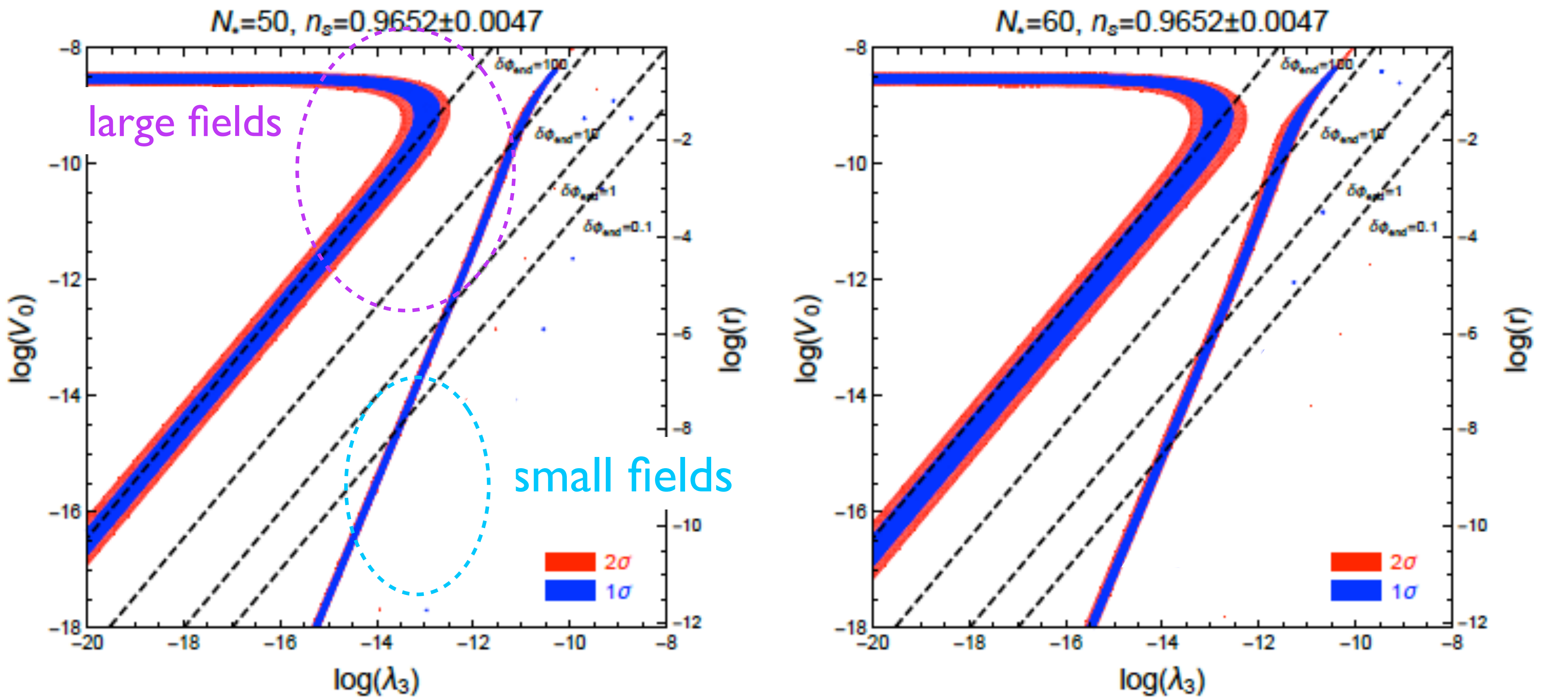
$$N_{\max} = \pi V_0 \sqrt{\frac{2}{\lambda_1 \lambda_3}} \sim 200$$



- Tensor-to-scalar ratio is very small.

$$\frac{V_0}{\lambda_3} = \left(\frac{N_{\max}}{120}\right)^2 \left(\frac{r}{1.50 \times 10^{-5}}\right)^{1/2} \Longrightarrow \boxed{r \lesssim 10^{-6}}$$

Large field case



- Trans-Planckian field could lead to a large r ~ 0.1.
- Higher order terms?

$$V = V_0 + \lambda_1 \delta\phi + \frac{\lambda_3}{3!}(\delta\phi)^3 + \boxed{\frac{\lambda_4}{4!}(\delta\phi)^4} + \cdots$$

$\delta\phi \sim 100$

$\Rightarrow$ $\lambda_4 < 0.04\lambda_3$?

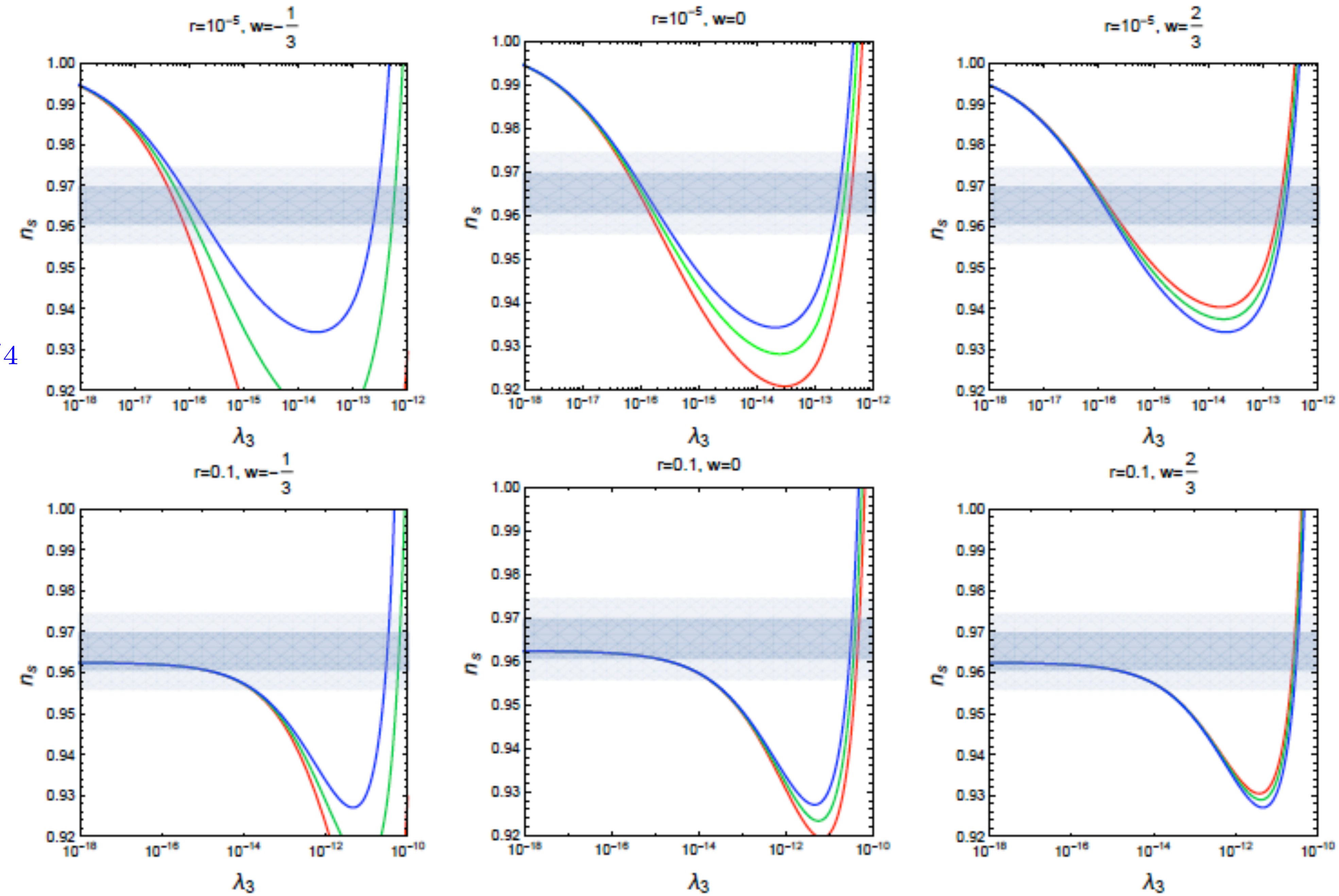
Reheating & effective coupling

$T_{\rm rh} = 10^3\,{\rm GeV}$

$T_{\rm rh} = 10^9\,{\rm GeV}$

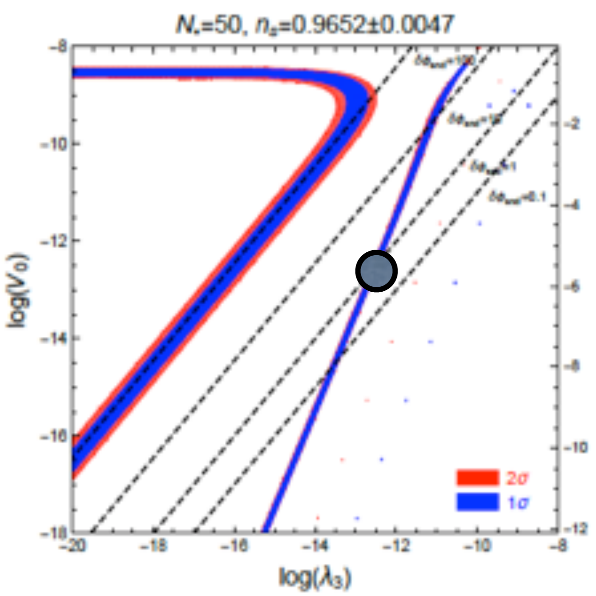
$T_{\rm rh} = T_{\rm max}$

$= 8.5 \times 10^{14} (r/10^{-5})^{1/4}$

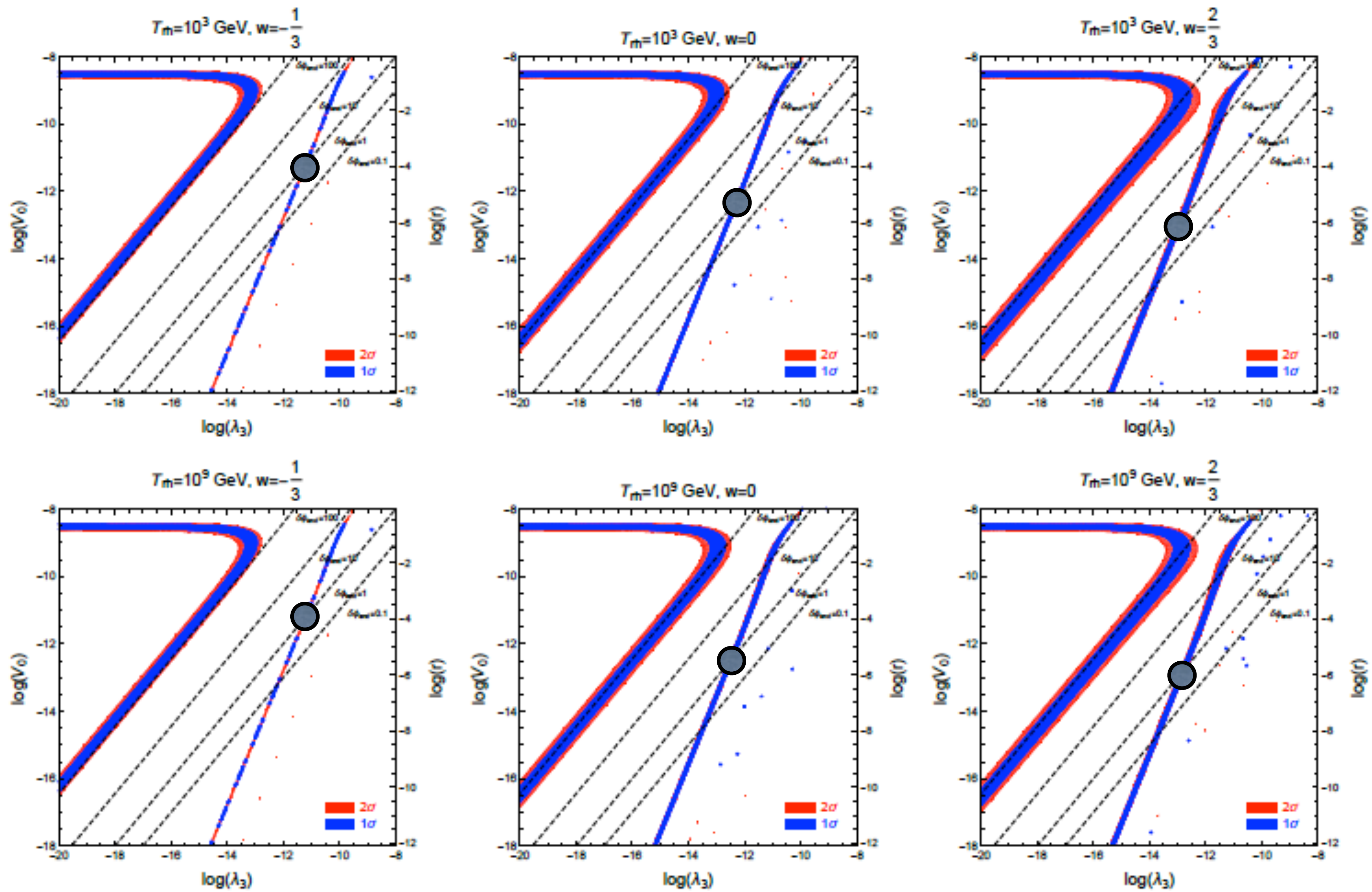


- w<1/3 (smaller N_*): the lower $T_{\rm rh}$, the smaller λ_3.
- w>1/3 (larger N_*): the lower $T_{\rm rh}$, the larger λ_3.

Reheating & tensor mode



(No RH effect)



- In perturbative regime, tensor-to-scalar ratio is 10^{-6} -10^{-4}, getting larger for w<1/3.

Higgs inflation at criticality

SM Higgs inflation

- Near criticality, the effective Higgs quartic and its beta function is vanishingly small.

$$V(h) = \frac{1}{4}\lambda(h)h^4\,, \qquad \lambda(h) = \lambda_{\rm cr} + b\left(\ln\frac{h}{h_{\rm cr}}\right)^2,\ \ b = 10^{-5},\ \ h_{\rm cr} \sim 1.$$

$\Rightarrow$ Effective parameters near IP:

$$\begin{aligned} V_0 &= \frac{1}{24}b\left(\frac{37}{12} - 7\sqrt{\frac{25}{144} - \frac{\lambda_{\rm cr}}{b}}\right)h_0^4, \\ \lambda_1 &= \frac{2}{3}b\left(\frac{1}{3} - \sqrt{\frac{25}{144} - \frac{\lambda_{\rm cr}}{b}}\right)h_0^3, \\ \lambda_3 &= 6b\sqrt{\frac{25}{144} - \frac{\lambda_{\rm cr}}{b}}\,h_0 \end{aligned}$$

Here, IP condition:

$$\ln\frac{h_0}{h_{\rm cr}} = -\frac{7}{12} + \sqrt{\frac{25}{144} - \frac{\lambda_{\rm cr}}{b}}$$

- Small slope: $\lambda_1 \ll V_0$ $\Rightarrow$ $\lambda_{\rm cr} \approx \dfrac{b}{16}\,, \qquad h_0 \approx e^{-\frac{1}{4}}\,h_{\rm cr}.$

$V_0 \approx \dfrac{1}{24}bh_0^4\,, \qquad \lambda_3 \approx 2bh_0$ $\Rightarrow$ $N_{\rm max} \sim 0.5\,h_0^{1/2}$: too small.

Higgs with non-minimal coupling

- Non-minimal coupling makes Higgs potential flat, even near inflection point located at $\gtrsim 1/\sqrt{\xi}$.
- Effective Higgs potential with non-minimal coupling:

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}(1+\xi h^2)R - \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{4}\lambda(h^2-v^2)^2\right)$$

$$\Rightarrow \quad S = \int d^4x\sqrt{-g_E}\left(\frac{1}{2}R - \frac{1}{2}(\partial_\mu \chi)^2 - V_E\right), \qquad \frac{d\chi}{dh} = \frac{\sqrt{1+\xi(1+6\xi)h^2}}{1+\xi h^2},$$

$$V_E = \frac{1}{4}\lambda\varphi^4, \qquad \varphi \equiv \frac{h}{\sqrt{1+\xi h^2}}, \qquad \lambda(\varphi) = \lambda_{\rm cr} + b\left(\ln\frac{\varphi}{\varphi_{\rm cr}}\right)^2.$$

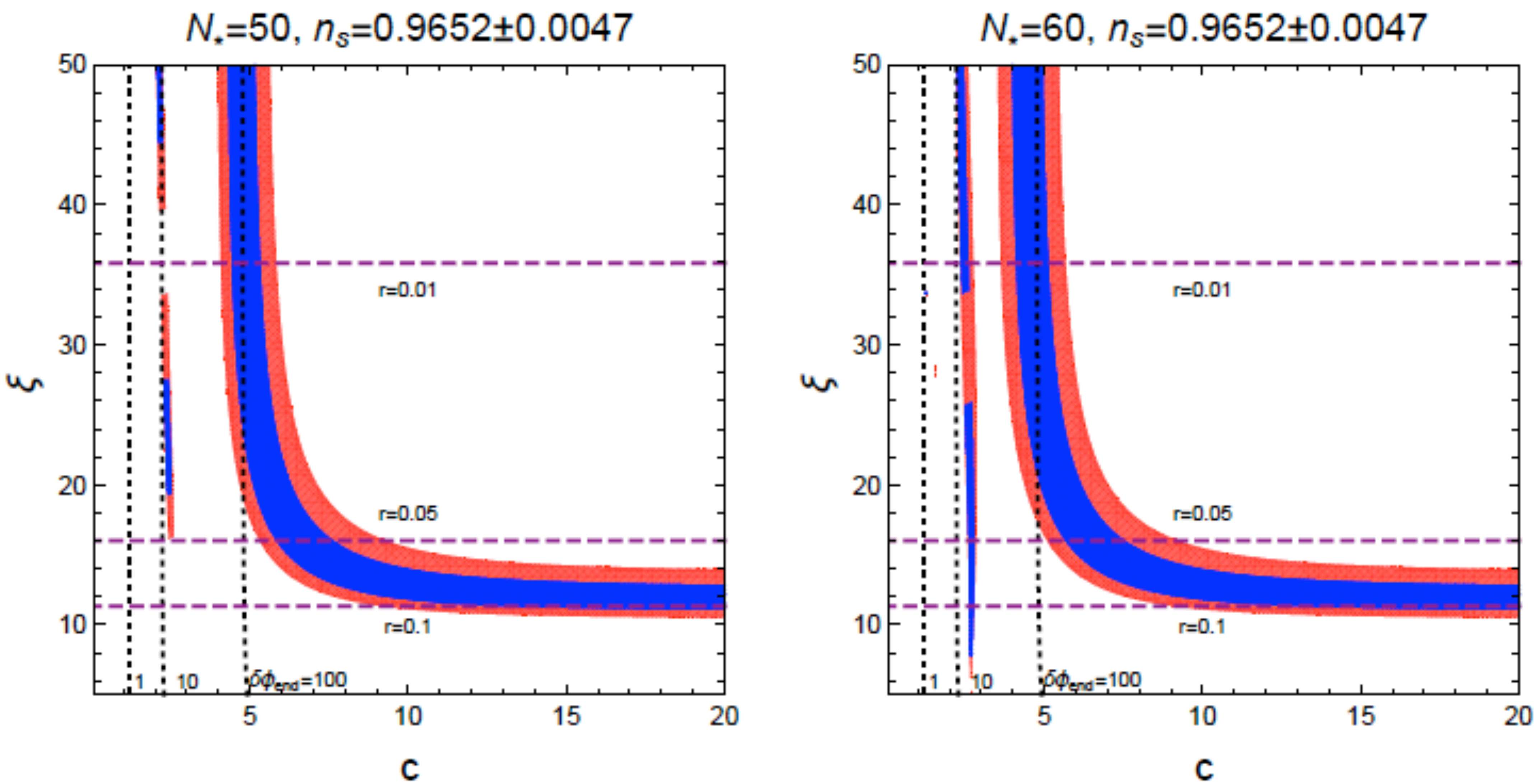
- Derivative wrt canonical Higgs is suppressed:

$$\frac{d}{d\chi} = \frac{dh}{d\chi}\frac{d\varphi}{dh}\frac{d}{d\varphi} \sim \frac{h}{\sqrt{6}}\cdot\frac{1}{\xi^{3/2}h^3}\cdot\frac{d}{d\varphi} \sim \frac{1}{\sqrt{6}\xi^{3/2}h^2}\frac{d}{d\varphi}$$

$\Rightarrow$ higher derivatives are naturally small.

Results

$$h_0 \equiv \frac{c}{\sqrt{\xi}}$$



- Tensor-to-scalar ratio is in a testable range.
- Canonical Higgs field is trans-Planckian, but higher order terms are suppressed by $(\xi^{3n/2}c^{2n})^{-1}$.

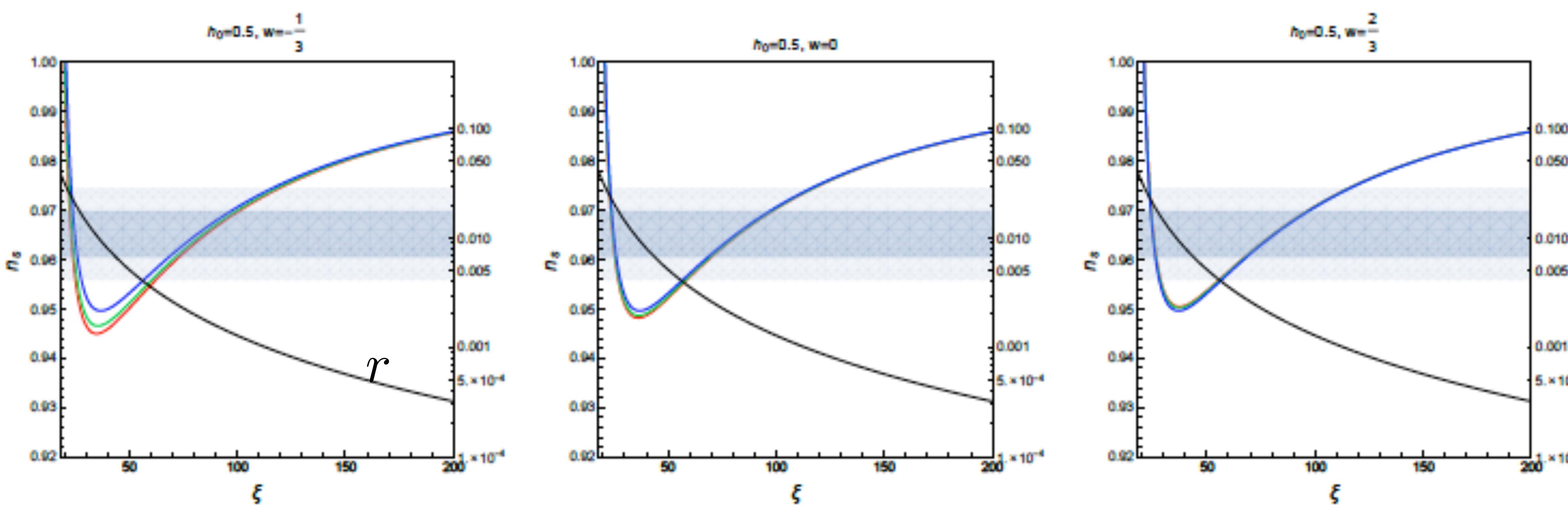
Reheating by Higgs

- Higgs couples to the SM particles with sizable interactions.

  ⟹ Reheating temperature is typically high.

  e.g. classical Higgs inflation: $T_{\rm rh} = 3 \times 10^{13} - 1.5 \times 10^{14}\,{\rm GeV}$

- Taking reheating temperature of similar order, the reheating effects on N* are mild.



$T_{\rm rh} = T_{\rm max}$ $\qquad$ $T_{\rm rh} = 3 \times 10^{13}\,{\rm GeV}$ $\qquad$ $T_{\rm rh} = 1.5 \times 10^{14}\,{\rm GeV}$

Conclusions

- We have got the general results for the effective inflation near inflection point and the reheating dynamics in both small and large field regimes.
- New large field regimes could be consistent, if there is a suppression mechanism for higher order terms, such as enhanced symmetry.
- Determination of effective parameters or tensor-to-scalar ratio depends on reheating dynamics.
- Higgs inflation at criticality belongs to a trans-Planckian inflection-point inflation but higher order terms are suppressed due to a sizable non-minimal coupling.