Title: Reheating Predictions in Single Field Inflation

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Abstract: <p>One possibility for studying reheating is to link the duration and final temperature after reheating, and its equation of state, to inflationary observables. By restricting the equation of state to lie within a broad physically allowed range, one can bracket an allowed range of n_s and r for models of inflation. The results are similar to, but do a little better, than requiring the length of inflation lie between 50 and 60 efolds. The added constraints can help break degeneracies between inflation models that otherwise overlap in their predictions.</p>

Reheating predictions in single field inflation

Jessica Cook, 1/14/16

work done with Emanuela Dimastrogiovanni, Damien Easson, and Lawrence Krauss

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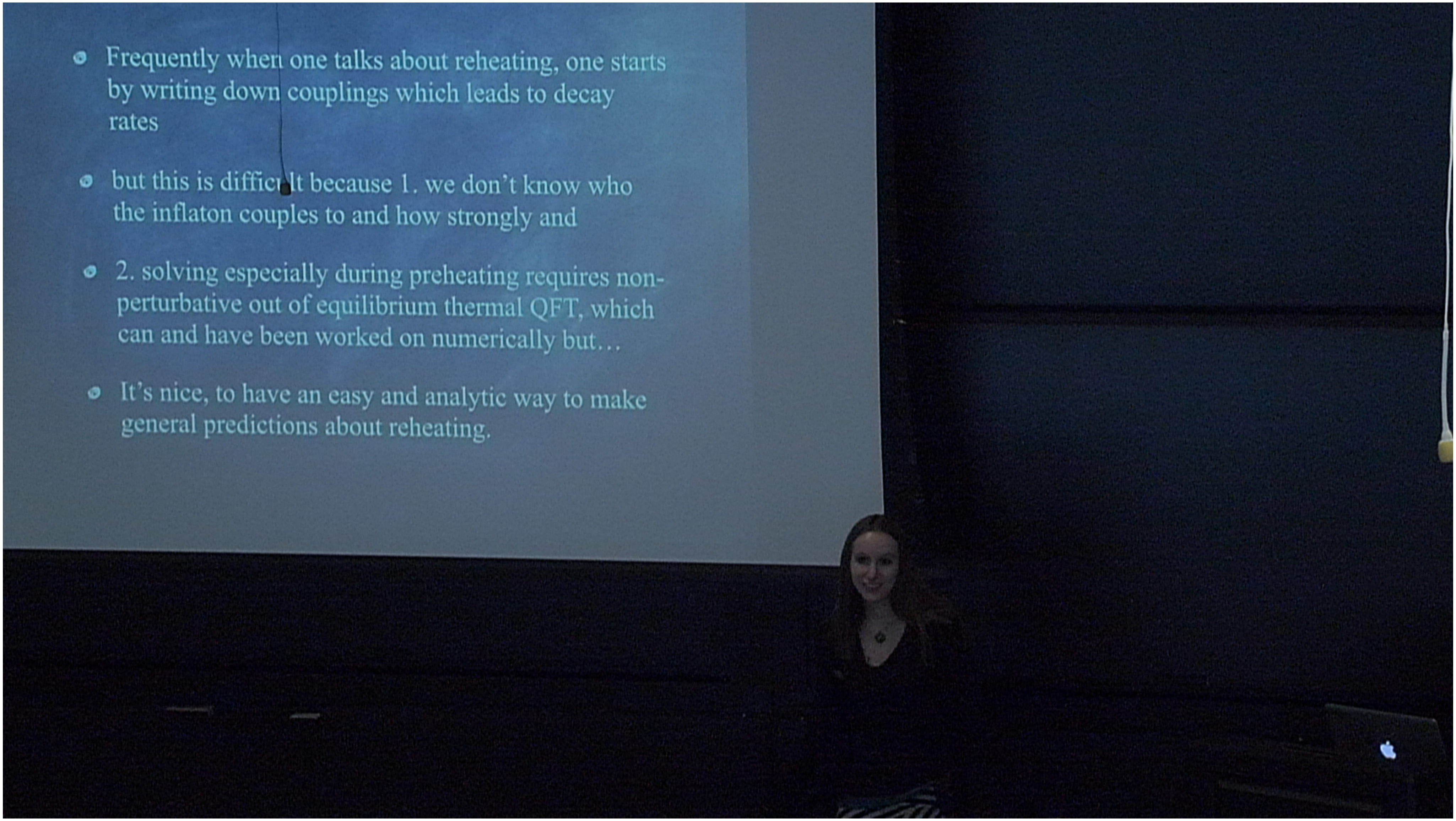
- Frequently when one talks about reheating, one starts by writing down couplings which leads to decay rates
- but this is difficult because 1. we don’t know who the inflaton couples to and how strongly and
- 2. solving especially during preheating requires non-perturbative out of equilibrium thermal QFT, which can and have been worked on numerically but…
- It’s nice, to have an easy and analytic way to make general predictions about reheating.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but this is difficult because 1. we don't know who the inflaton couples to and how strongly and
2. solving especially during preheating requires non-perturbative out of equilibrium thermal QFT, which can and have been worked on numerically but…
It's nice, to have an easy and analytic way to make general predictions about reheating.

- instead of supposing couplings, we ignore all the microphysical details, and instead frame everything in terms of an average equation of state, w_{re}.

- gives simple way of characterizing reheating, while remaining general

- We can require w_{re} to lie within certain reasonable bounds, say -1/3 to 1, or 0 to 1/3, and this puts constraints on what values of inflation observables are consistent with this.

- If one wants to check if a particular inflation potential is viable or not, one can see if there is a spot of the potential that can give the right n_s, and if the height can be adjusted to give the right A_s at that spot.

- But it's not enough that a spot on the potential can give the right n_s. That spot must also allow for a reasonable reheating scenario. Normally this is framed into requiring that the length of reheating fall between 50 and 60 efolds. And generally that does well.

- But the bound should change depending on the model.
- Also, it depends on what assumptions we want to put on reheating. One could be very general and say $-1/3 < w_{re} < 1$, in which case you get a broad range of acceptable inflation observables
- Or if one favors a scenario with slow, inefficient reheating, and an inflaton behaving like matter during reheating, one might suppose $0 < w_{re} < 1/6$ or so.

Martin, Ringeval arvix: 1004.5525

- If one favors a scenario with an efficient preheating phase, one might instead expect w_{re} close to but a little less than 1/3.

arxiv: 0507096
Podolsky, Felder, Kofman and Peloso

- These reheating hypotheses will couple to more precise predictions of inflation observables.

- and it’s important to get the most precise predictions we can from inflation models
- If BICEP doesn’t end up detecting primordial B modes after all…
- Then we’re not going to do that much better in CMB data. Temp data is as good as it’s going to get. There is more that can be done with polarization data, or moving to shorter wavelength modes, more than can be done with LSS…
- but constraints on inflation parameters aren’t likely to change dramatically
- so we should make the most of the data available, but making the predictions of the various inflation models as precise as we can.

- starting from conservation of energy, can relate the energy density at the start of reheating to the energy density at the end:

$$0 = \nabla_\mu T^\mu_0$$

$$\int \frac{1}{\rho} d\rho = -3 \int (1+w) dN \longrightarrow \frac{\rho_{re}}{\rho_{end}} = e^{-3N_{re}(1+\langle w_{re} \rangle)}$$

$$\langle w_{re} \rangle = \frac{1}{N_{re}} \int w \, dN$$

- going to use efolding as unit of time, even though not inflating, still valid unit of time…

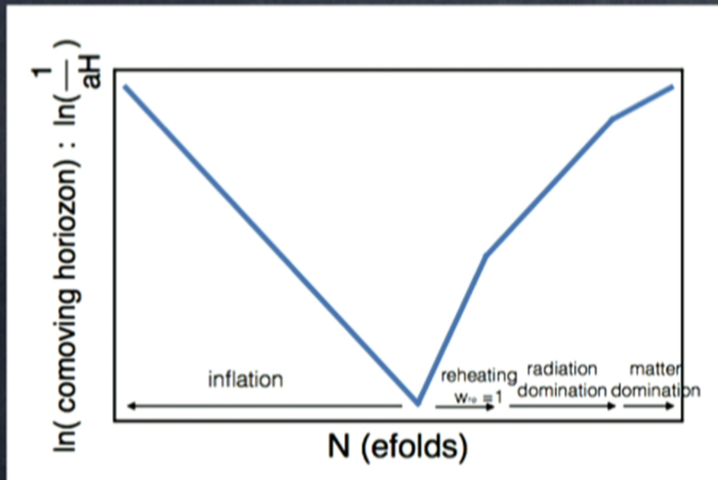
$$a = e^N$$

- if one picks an inflationary model, then know the energy density at the end of inflation

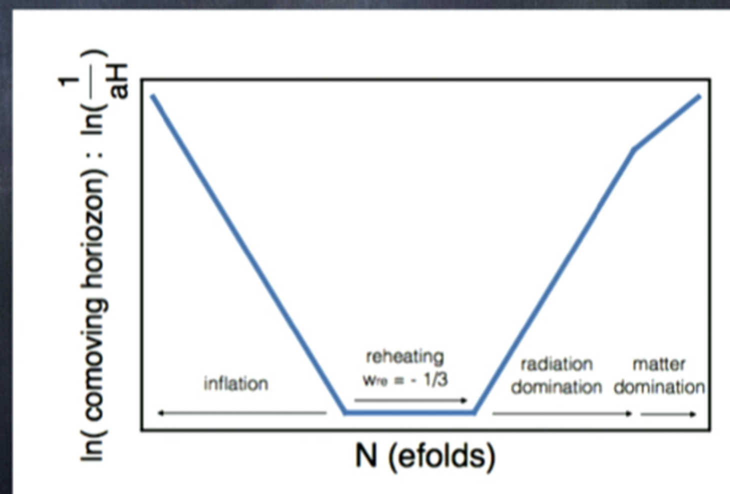
- can relate to the temp at the end of reheating…

$$\rho_{re} = \frac{\pi^2}{30} g_{re} T_{re}^4$$

- so relating details about inflation, but to solve for N_{re} and T_{re} separately, need more information



Once one chooses a model of inflation, $N_{l=2}$ can be calculated, which tells how many comoving scales left the horizon during inflation. This must = how many comoving scales must have reentered the horizon after inflation -> the horizon problem.



if $w_{re} \neq 1/3$

$$N_{re} = \frac{4}{1-3w_{re}}\left[61.6 - \ln\left(\frac{V_{end}^{\frac{1}{4}}}{H_{pivot}}\right) - N_{pivot}\right]$$

relates reheating parameter

to inflation parameters

$$T_{re} = 2.5 \times 10^{26}\, H_{pivot}\, e^{-N_{pivot}}\, e^{-N_{re}}$$

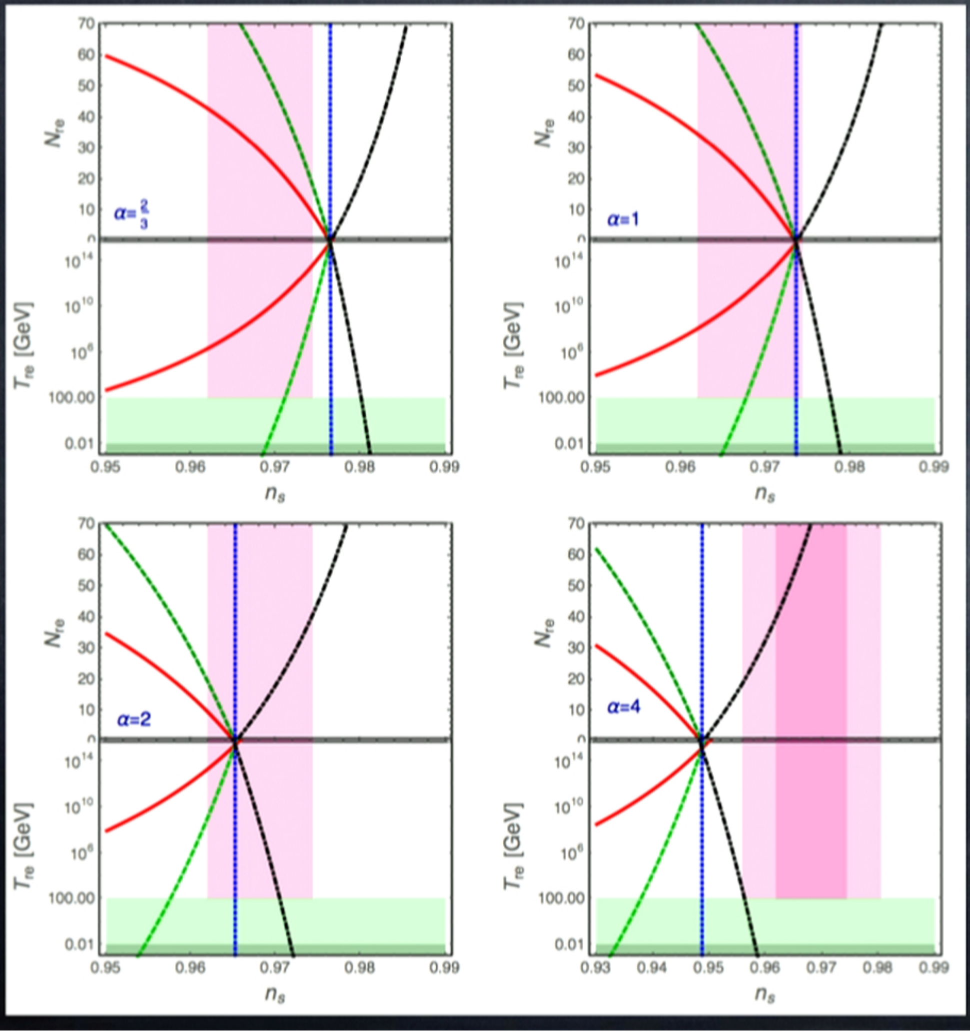
- pick a model and an equation of state, get out predictions for reheating

if $w_{re} = 1/3$

$$61.6 = \ln\left(\frac{V_{end}^{\frac{1}{4}}}{H_{pivot}}\right) + N_{pivot}$$

gives precise prediction for n_s

polynomial inflation, φ^α



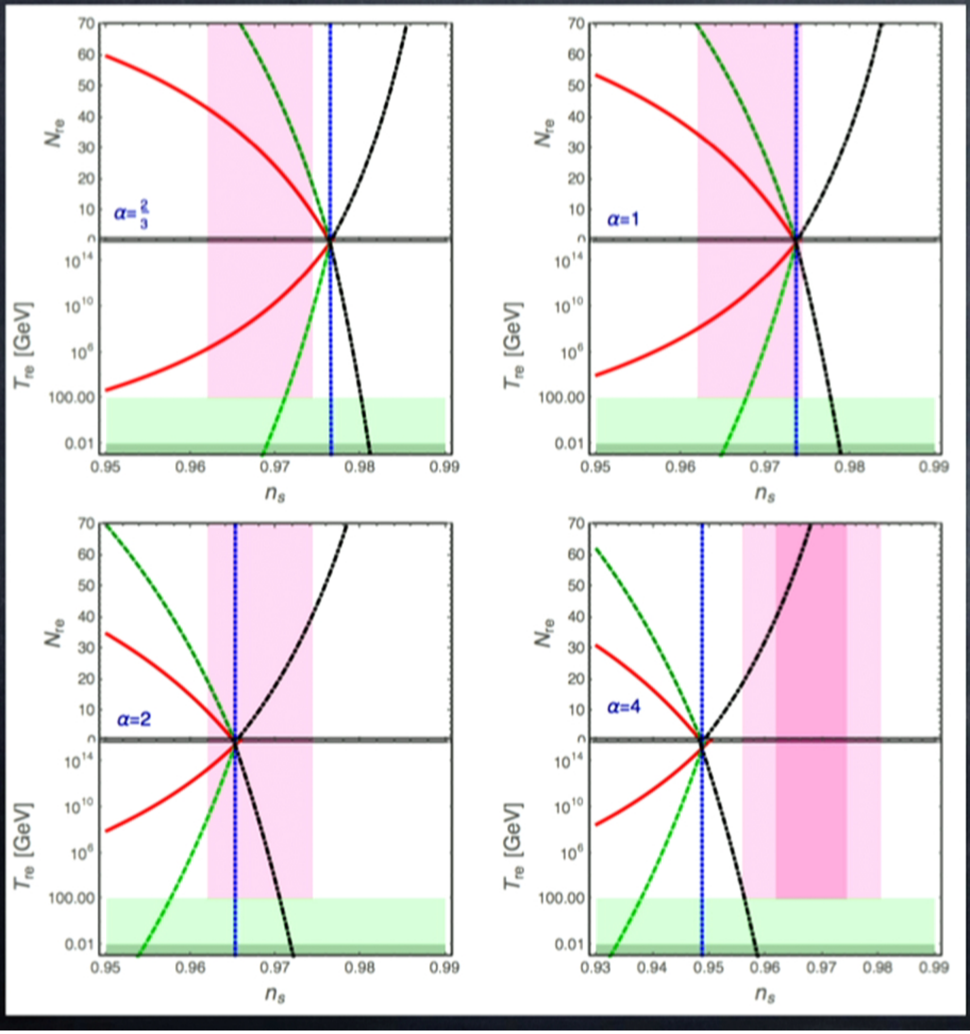
$\omega_{re} = -1/3$

$\omega_{re} = 0$

$\omega_{re} = 1/3$

$\omega_{re} = 1$

polynomial inflation, φ^α



$w_{re} = -1/3$

$w_{re} = 0$

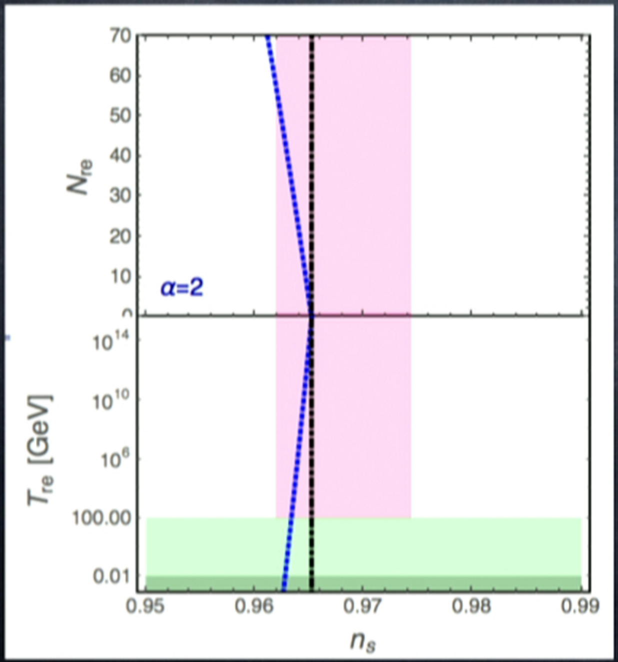
$w_{re} = 1/3$

$w_{re} = 1$

- note if there was an efficient preheating phase with the inflation decaying into radiation…
- studies that have considered inflation with short preheating phase, tend to predict w_{re} shooting up to close to 1/3 very quickly and then slowly increasing the rest of way to 1/3.

arxiv: 0507096

Podolsky, Felder, Kofman and Peloso



then you get especially precise predictions for n_s

$w_{re} = 0.22$

$w_{re} = 1/3$

if $w_{re} \approx 1/3$,
$n_s \approx 0.965$

- a lot of the work using these methods has focused on $w_{re} = 0$, especially to give bounds on T_{re}.

- Think main reason for this: if you do simplest case, ignore preheating, and write inflaton equation with constant decay rate, then find the average w_{re} can come out close to 0.

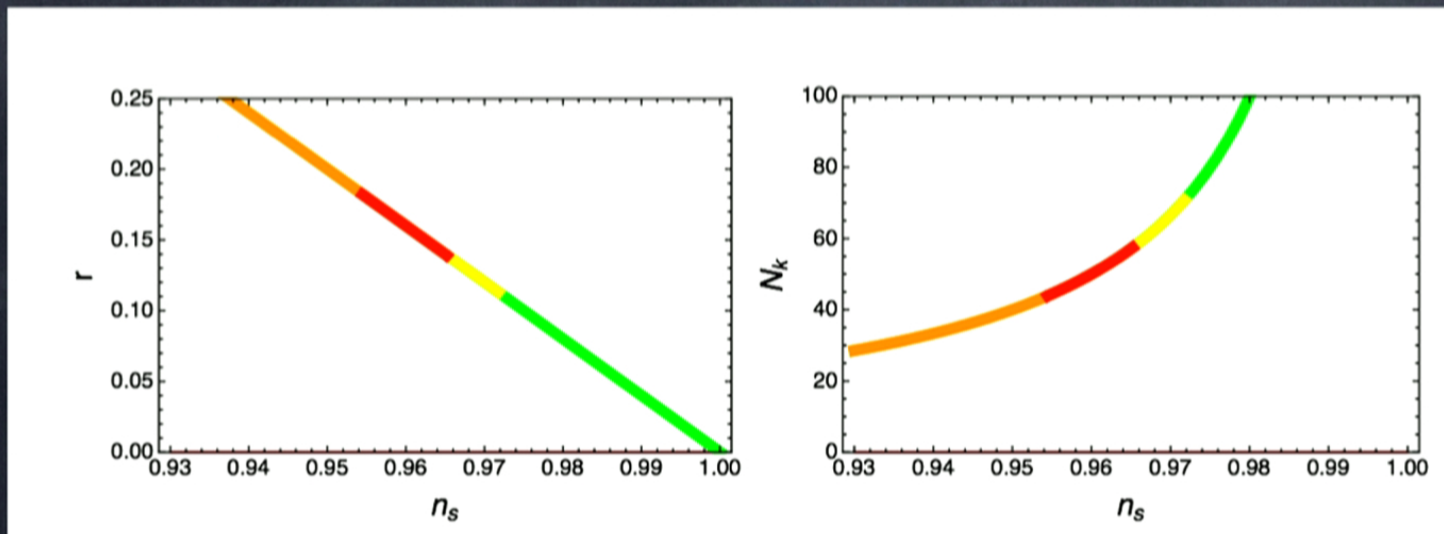
Martin, Ringeval
arvix: 1004.5525

- Think if your model allows for efficient preheating phase, w_{re} near 1/3 might be more accurate. In which case you get a very precise prediction for n_s.

- Think that is the main strength of this technique is not to constrain reheating, but to use reasonable reheating bounds to constrain inflation.

φ^2

(everything evaluated at Planck's pivot, l ~ 686)



$w_{re} > 1$

$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

so a solution with $0 < w_{re} < 1/3$ would fall in the red region

$0.14 < r < 0.18$

$44 < N_k < 57$

$r > 0.11$

note 2 σ limit from joint BICEP/Planck analysis: r < 0.12

Starobinsky model

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} (R + \alpha R^2) + \mathcal{L}_{matter} \right]$$

apply a conformal transformation:

$$\tilde{g}_{\mu\nu} = (1 + 2\alpha R) g_{\mu\nu}$$

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{M_P^2}{2} \left[\tilde{R} - \frac{1}{4\alpha} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \right)^2 \right] - \frac{1}{2} (\tilde{\partial}\phi)^2 + e^{-2\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \mathcal{L}_{matter} \right]$$

end up with single field model with potential

$$V = \frac{M_P^2}{8\alpha} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \right)^2$$

Higgs Inflation:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R\left(1 + 2\xi\frac{H^\dagger H}{M_P^2}\right) + \mathcal{L}_{matter}\right]$$

same idea… apply conformal transformation…

$$\tilde{g}_{\mu\nu} = \left(1 + 2\xi\frac{H^\dagger H}{M_P^2}\right) g_{\mu\nu}$$

then rewrite in terms of new canonically normalizable field, and using a few approximations…

end up with a canonically normalized field $\bar{h}$ (function of the SM higgs) evolving under a potential:

$$V = \frac{\lambda M_p^4}{4\xi^2}\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\bar{h}}{M_P}}\right)^2$$

same potential as the R^2 case

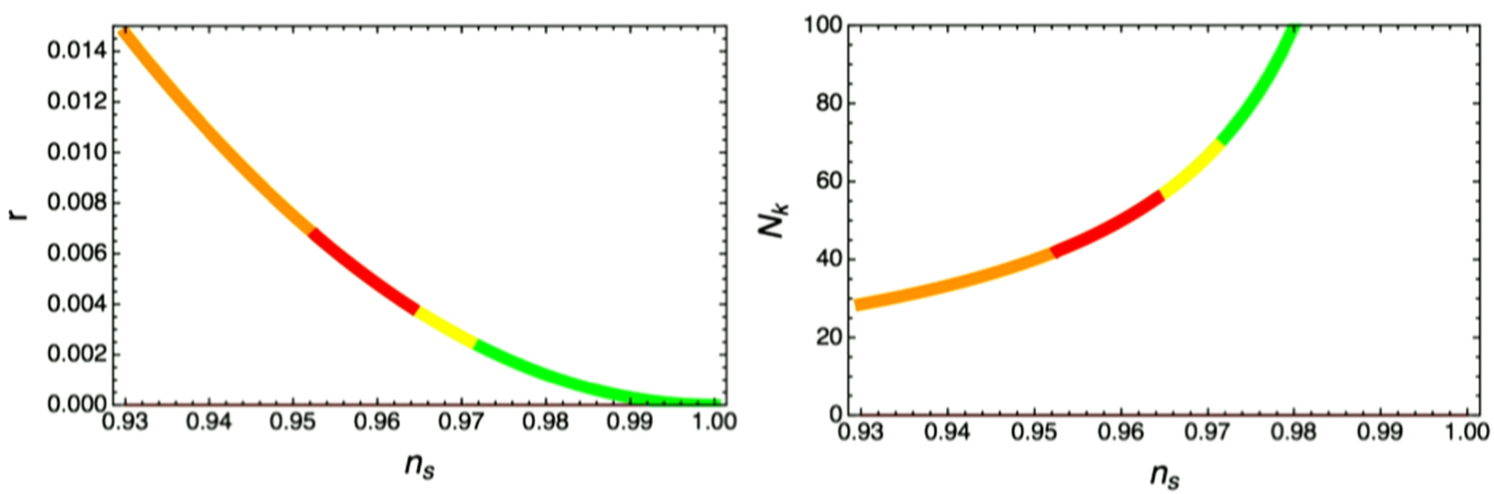
- Potential not the same at low scales, but it same at inflation scales. So expect if one modeled exact reheating dynamics, would get different behavior.

- But said reheating predictions using the average equation of state just depends on inflation predictions…

- so since at inflation scales have same potential, find same predictions for reheating parameter space when parametrized in terms of an average equation of state).

- Idea is, the allowed parameter space as a function of w_{re} is the same, but the most likely w_{re} for each model is likely different.

Starobinsky/ Higgs inflation model



$w_{re} > 1$

$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

and solution with $0 < w_{re} < 1/3$ would fall in the red region

$0.953 < n_s < 0.964$

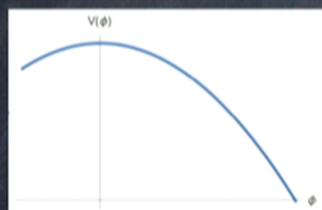
$0.004 < r < 0.007$

$42 < N_k < 56$

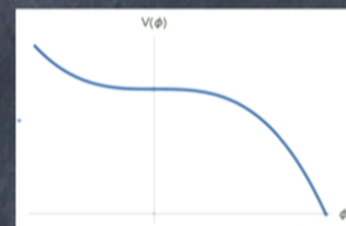
- Also considered hilltop model...

$$V = M^4 \left[1 - \left(\frac{\phi}{\mu} \right)^p \right]$$

if p even, looks like:

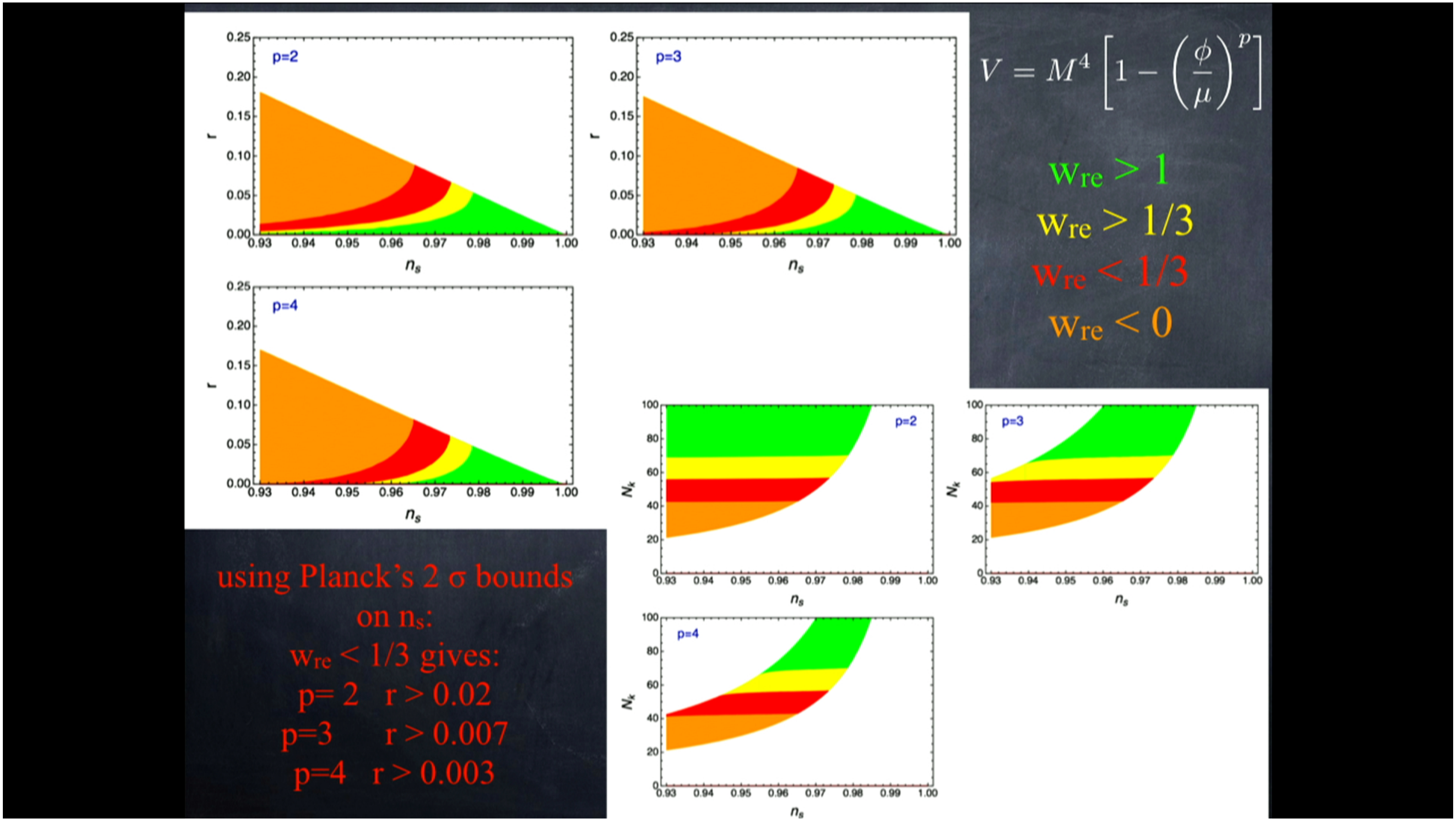


if p odd, looks like:



so potential starts very flat, gets steeper

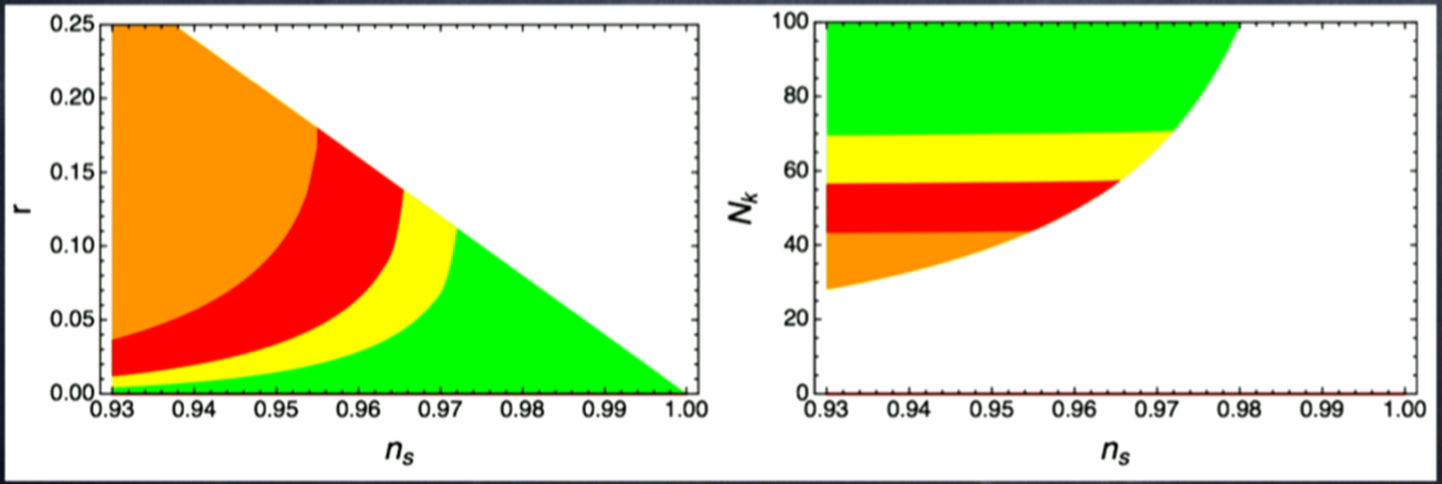
note 2 free parameters now, will draw out shape instead of line in n_s vs. r plane


$V = M^4 \left[1 - \left(\frac{\phi}{\mu} \right)^p \right]$
$w_{re} > 1$
$w_{re} > 1/3$
$w_{re} < 1/3$
$w_{re} < 0$
using Planck's 2 σ bounds on n_s:
$w_{re} < 1/3$ gives:
p= 2 r > 0.02
p=3 r > 0.007
p=4 r > 0.003
p=2
p=3
p=4
r
n_s
N_k

natural inflation

$$V = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

again have 2 free parameters



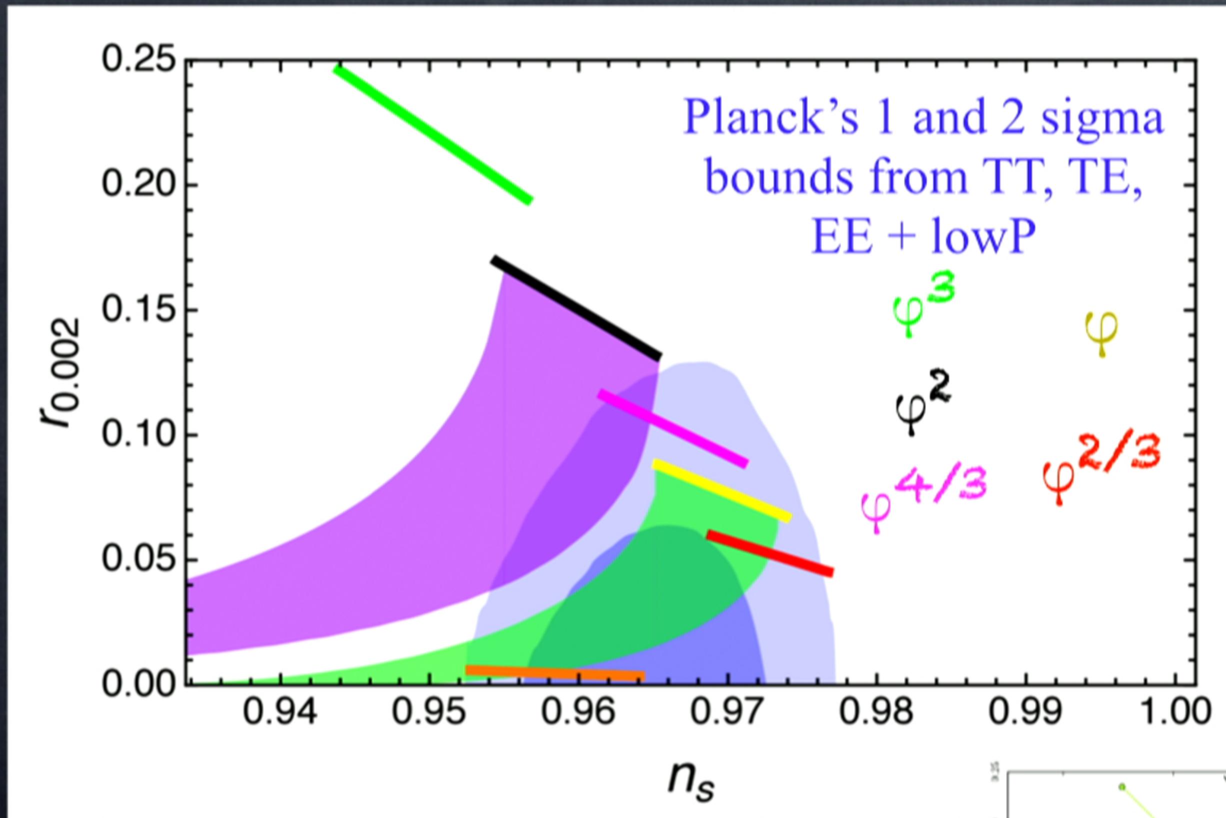
$w_{re} > 1$

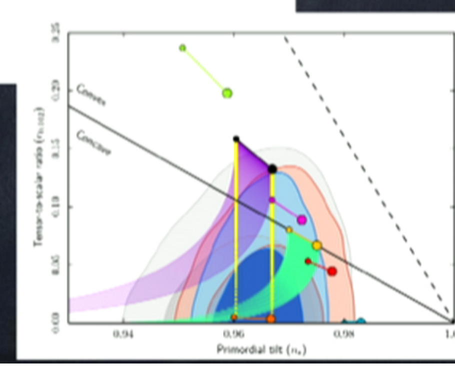
$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

$w_{re} < 1/3$ gives $r > 0.05$
and favors $n_s <$ Planck's central value





R^2
natural
quartic hilltop