Inflation: String Approach

A REVIEW

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Pune, February 2018

This being a review talk, the references I am giving are to books/review articles

- Inflation and String Theory (CUP)
  Baumann and McAllister

- String Inflation After Planck 2013
  Burgess, Cicoli and Quevedo

- Cosmological Moduli and the Post-Inflationary Universe: A critical review
  Kane, Sinha and Watson

- Options: form the perspective of low energy effective field theory having symmetries or trying to tune the potential.

- Whether they can be realised is a calculable question from the point of the UV complete theory

- For the symmetries, we need to understand the fate of the symmetries in a UV complete theory, the existence of higher dimensional operators that spoil the symmetry.

- For tuning, we need to check if the necessary cancellations can take place by varying the underlying parameters of the UV theory.

- Computing these operators is not easy, but in many cases an estimate suffices.

Outline

- Inflation and string theory
  - Inflation in a UV complete theory
    - Higher dimensional operators
    - Field Ranges of candidate inflatons
  - Moduli dynamics and inflationary predictions

Inflation and String Theory

- Simplest models of inflation involve a scalar field rolling down a potential. To get exponential expansion for a sufficiently long epoch, slow roll conditions need to be satisfied.

$$\epsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'(\varphi)}{V(\varphi)}\right)^2 \ll 1 \qquad \eta \equiv M_{\rm pl}^2\left(\frac{V''(\varphi)}{V(\varphi)}\right) \ll 1$$

- The potential has to be flat in Planck units !

- The vacuum energy is positive. In general, scalar masses are not stable against loop corrections

$$\Delta\eta = \mathcal{O}(1)$$

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- For the symmetries, we need to understand the fate of the symmetries in a UV complete theory, the existence of higher dimensional operators that spoil the symmetry.

- For tuning, we need to check if the necessary cancellations can take place by varying the underlying parameters of the UV theory.

- Computing these operators is not easy, but in many cases an estimate suffices.

$$V = V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}_{\rm in}^2}\left(\frac{3\mathcal{V}_{\rm in}}{4\lambda}\right)^{2/3}\sigma^{4/3}\exp\left[-a_n\left(\frac{3\mathcal{V}_{\rm in}}{4\lambda}\right)^{2/3}\sigma^{4/3}\right].$$

- Various possibilities to realise the standard model sector. In the cases in which, the inflation decays primarily to the SM sector (as one might want for a simple reheating scenario, followed by a standard thermal history). One has a eta problem arising from the coupling

$$\delta V_{1\rm loop} \simeq \frac{1}{\sigma^{2/3}\mathcal{V}^{10/3}}$$

- String theory has no couplings, all couplings are set by vacuum expectation values of fields : Moduli fields.

- At tree level Moduli fields are massless, as long as these flat directions are present, it is impossible to realise inflation.

- Going beyond tree level, moduli fields acquire masses. The potentials generated for them are often flat, moduli are good candidate inflatons.

- Moduli parametrise the shape and size of the extra dimensional geometry e.g. size of a hole in the extra dimensions. Relations between the field ranges.

- Example: Fibre inflation models, in the regime inflation takes place

$$V \simeq \frac{V_0}{\mathcal{V}^{10/3}}\left(3 - 4e^{-k\hat{\varphi}}\right) \quad \text{with} \quad k = \frac{2}{\sqrt{3}}$$

- $\hat{\varphi}$ rolls from higher to lower values. But form of potential very different for larger values of $\hat{\varphi}$. Very difficult to achieve 60 e-foldings.

Inflation, Moduli and Cosmology

- From the very early days of model building in supergravity models in was realised that

inflation + moduli fields

can lead to cosmological timeline distinct from the standard one.

modular cosmology

Cosmology and Moduli

- Starting point of the analysis moduli dynamics during inflation.

- Analysis of dynamics during inflation gives, for $m_\varphi \lesssim H_{\rm infl}$

At the end of inflation the modulus φ has VEV $\hat{\varphi}$,

$$Y = \frac{\hat{\varphi}}{M_{\rm pl}} \lesssim 1$$

Cosmology and Moduli

Thus just after reheating, energy density has two components

- Radiation: To which the inflaton has dumped its energy density.

- Modulus: Potential energy due to displacement.

- As the universe expands time average of energy density falls off as

$$\rho_{\text{modulus}}(t) \propto \frac{1}{a^3(t)}$$

Cosmological evolution of cold moduli particles.

- Quickly dominates over energy density present in the form of radiation
- Modulus domination continues until decay of modulus at

$$\tau_{\text{mod}} \approx \frac{16\pi M_{\text{pl}}^2}{m_\varphi^3}$$

the characteristic lifetime for decay via their Planck suppressed interactions.

Modular Cosmology

Inflation

↓

Reheating

↓

Radiation Domination

↓

Modulus Domination

↓

Reheating (after modulus decay)

↓

Radiation Domination

⋮

Today

Conventional Cosmology

Inflation

↓

Reheating

↓

Radiation Domination

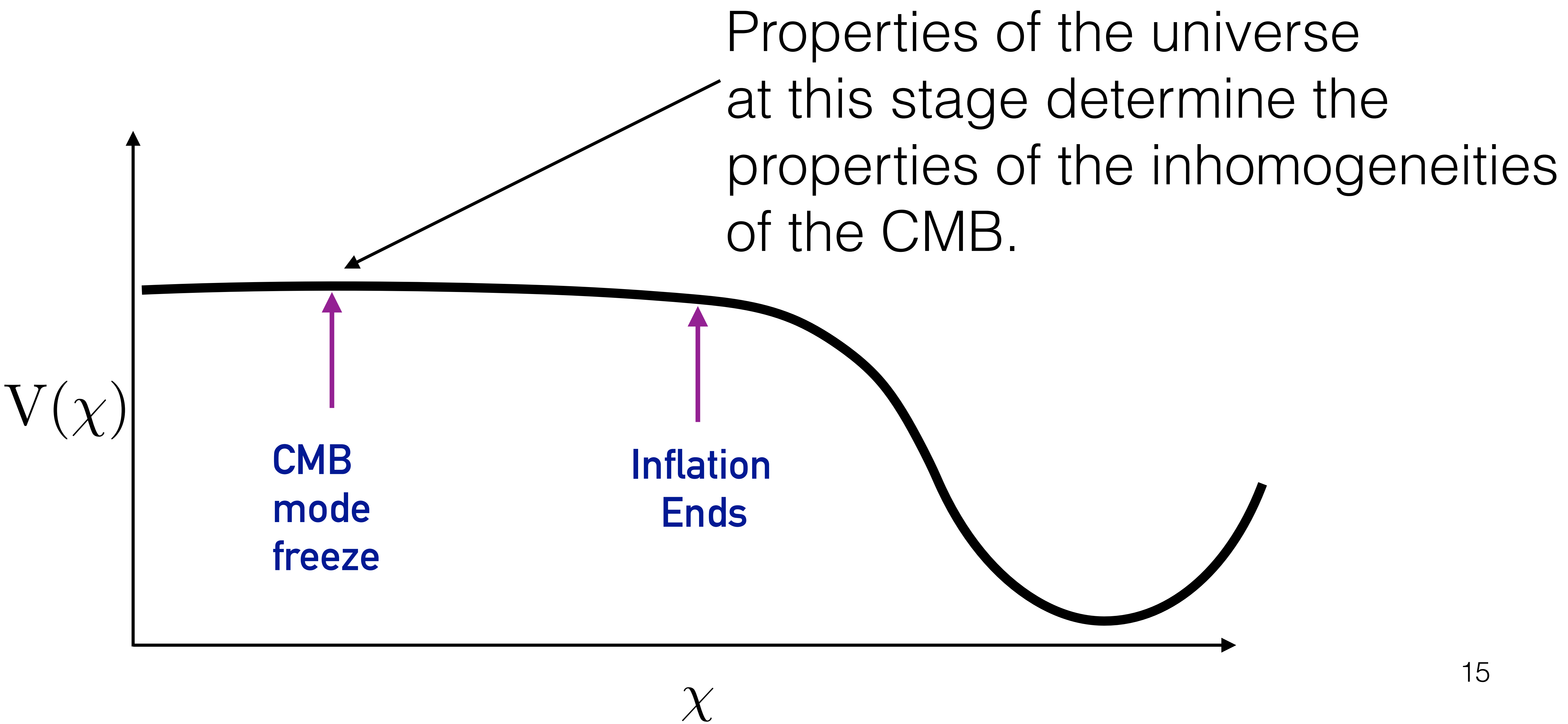
⋮

Today

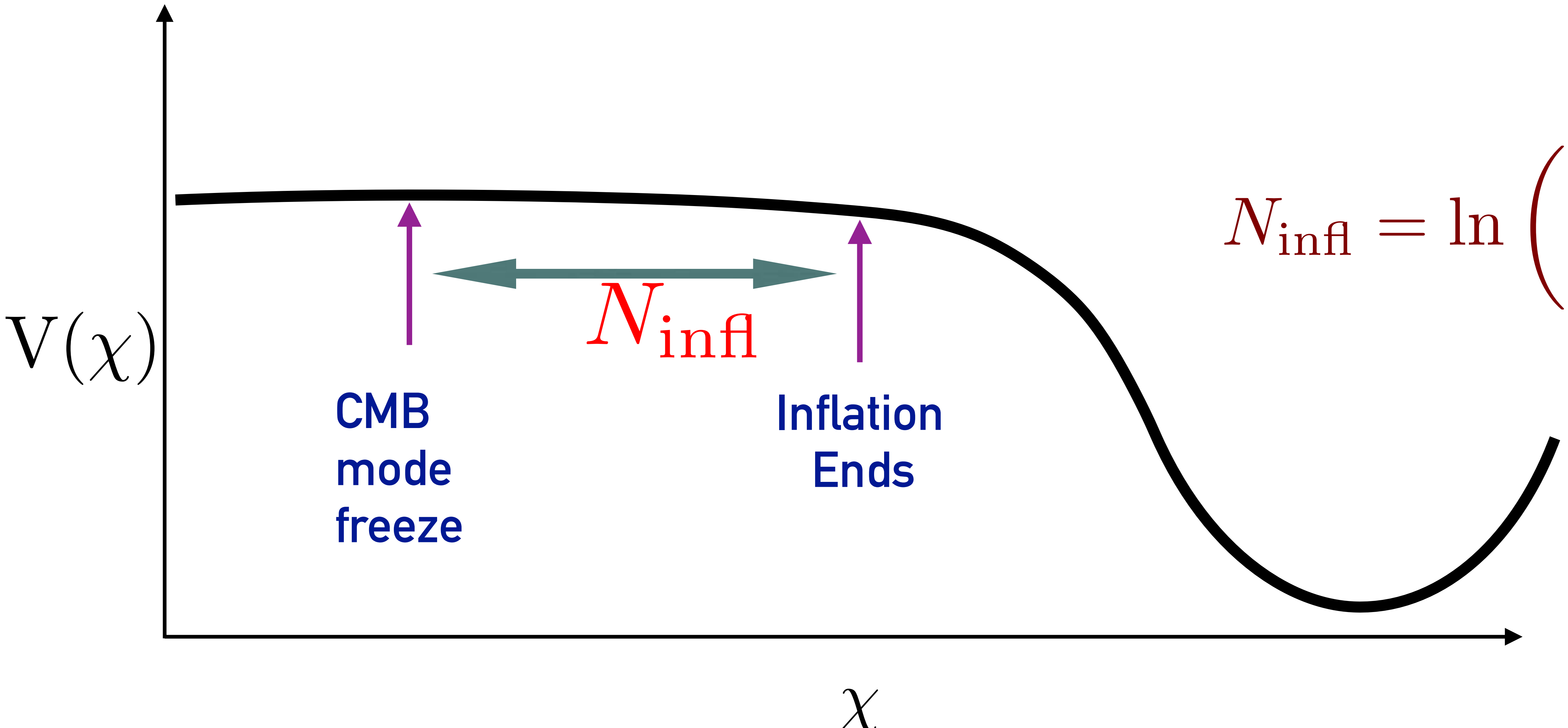
Inflation and Inhomogeneities

- Inhomogeneities are a result of freezing of quantum fluctuations at the time of horizon exit; $k/a \approx H$.

$k \approx 0.05 \ \ \mathrm{Mpc}^{-1}$ for CMB observations by the PLANCK satellite.



It is conventional to keep track of the point of freezing by the number of e-folding between freezing and end of inflation.



$$N_{\rm infl} = \ln\left(\frac{a(t_{\rm end})}{a(t_{\rm freeze})}\right)$$

For e.g. $m^2\chi^2$ potential (similar expressions for all models)

$$n_s = 1 - 2/N \qquad r = 8/N$$

Given a potential we need the value of $N_{\rm infl}$ to extract predictions

Inflation and Inhomogeneities

- How is $N_{\rm infl}$ determined ?

Observed Inhomogeneties ⟷ INFLATION ⟷ Energy Density at an early time

- More precisely,

$$A_s = \frac{2}{3\pi^2 r}\left(\frac{\rho}{M_{\rm pl}^4}\right)$$

- ρ - Energy density of universe at the time of horizon exit of mode relevant for CMB observations.

- r - Strength of gravity waves.

Inflation, Inhomogeneities and Energy Densities

- An early time and today's energy densities known. This implies a consistency condition

Any history we ascribe must be such that the early time energy density evolves to the energy density today.

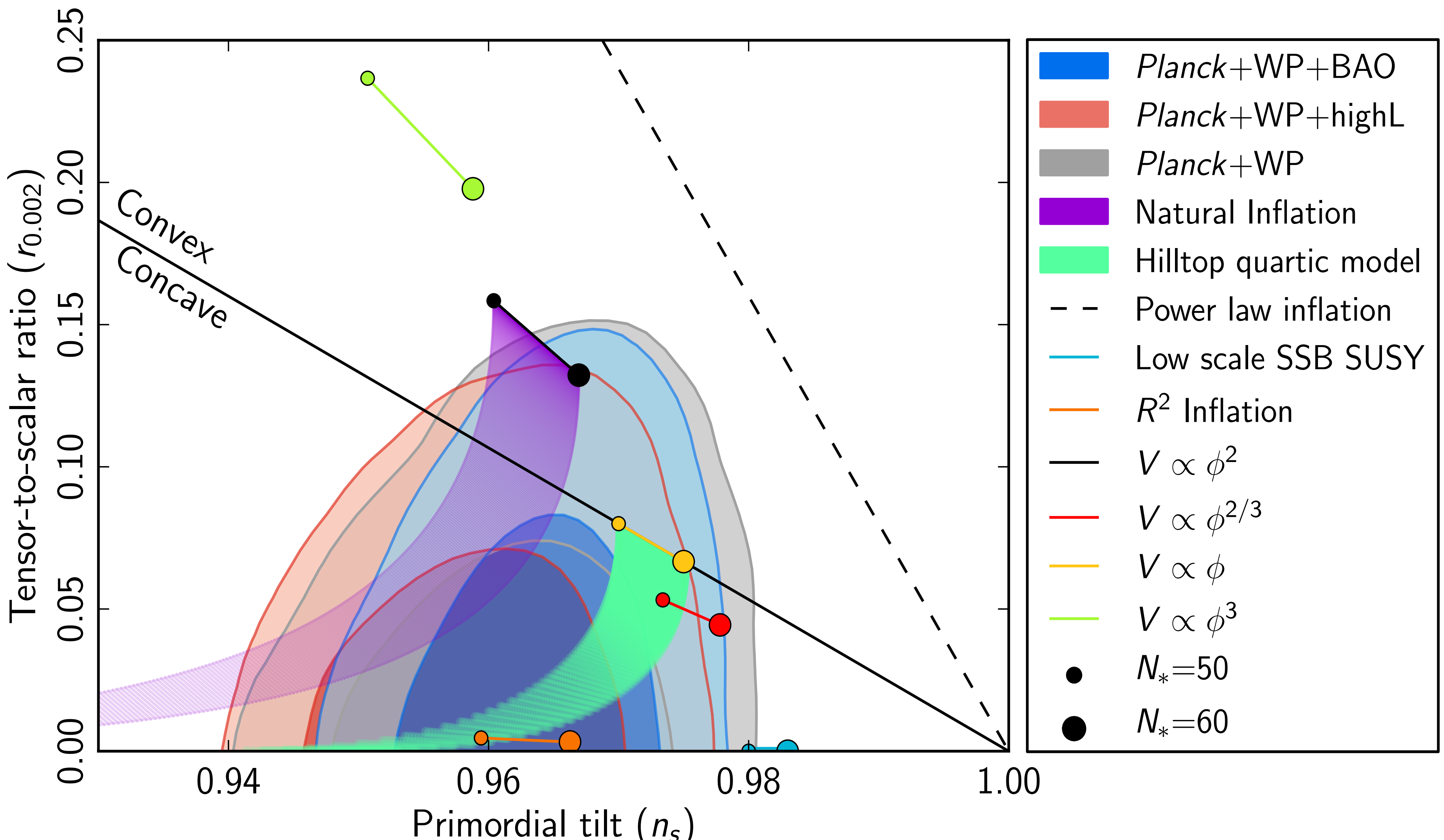
Energy density at horizon exit, ρ_k (from inhomogeneities).

Energy density today, ρ_0

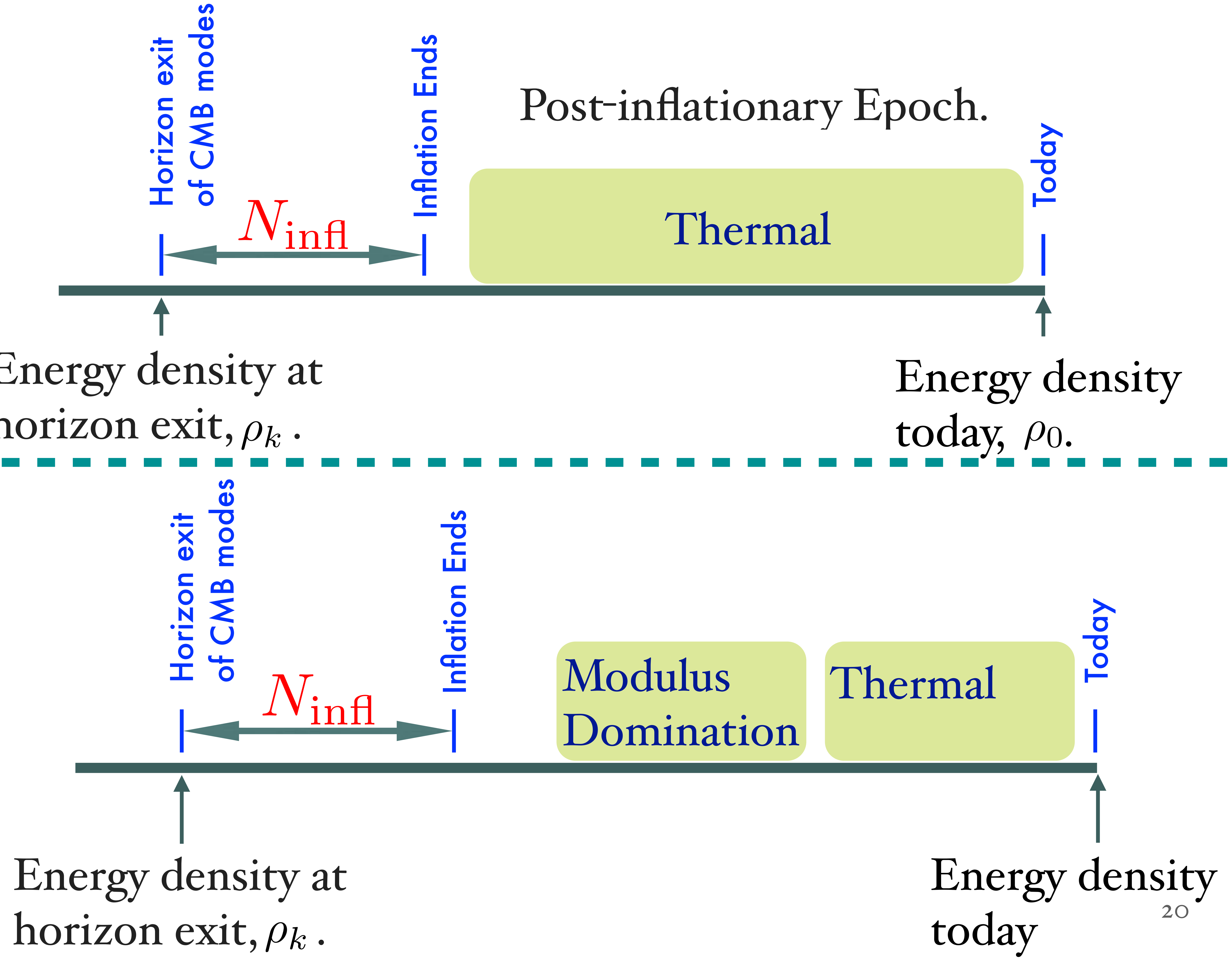
Post-inflationary Epoch consists of reheating followed by thermal history in conventional cosmologies.

$$N_{\rm infl} + \frac{1}{4}(1-3w_{\rm rh})N_{\rm rh} \approx 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_{\bf k}}{\rho_{\rm end}}\right)$$

This motivates the usual range of 50-60 for $N_{\rm infl}$



Modular Cosmology



We obtain

$$N_{\rm infl} + \frac{1}{4}N_{\rm modulus} + \frac{1}{4}(1-3w_{\rm rh1})N_{\rm rh1} + \frac{1}{4}(1-3w_{\rm rh2})N_{\rm rh2} \approx 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right)$$

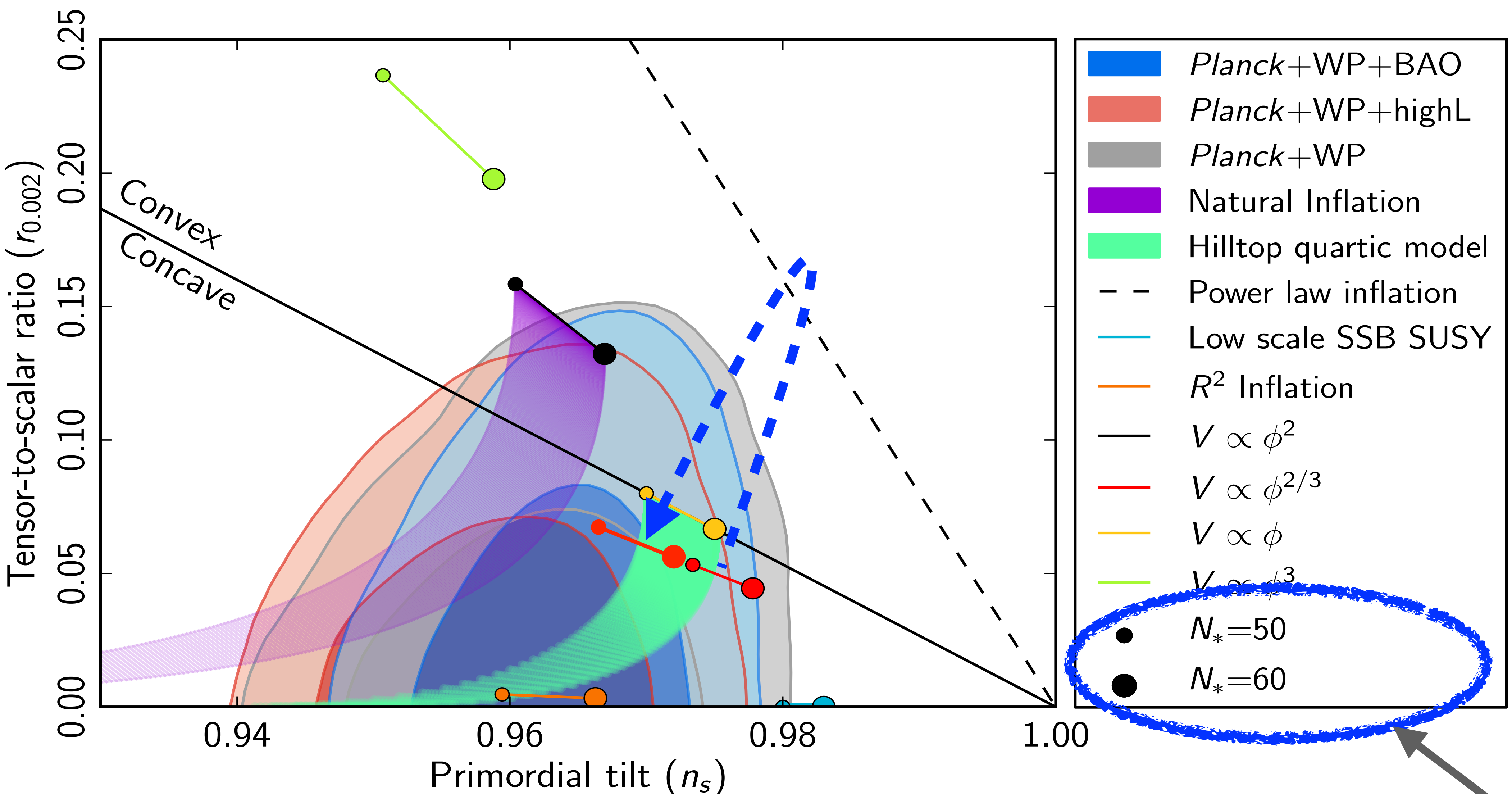
The number of e-folding during modulus domination.

$$N_{\rm modulus} \approx \frac{4}{3}\ln\left(\frac{\sqrt{16\pi}M_{\rm pl}Y^2}{m_\varphi}\right)$$

$Y = \frac{\hat{\varphi}}{M_{\rm pl}}$ The initial displacement in Planck Units (generic estimate from EFT $Y \simeq \mathcal{O}(1)$)

m_φ The post-inflationary mass of the modulus

Since the dependence is on $\ln(M_{\rm pl}/m_\varphi)$ this can significantly bring down the value of $N_{\rm infl}$.



Modulus mass input for inflationary predictions

Change the 50 - 60 range

$N_{\rm infl}$

$$N_{\rm infl} + \frac{1}{4} N_{\rm modulus} + \frac{1}{4}(1 - 3w_{\rm rh1}) N_{\rm rh1} + \frac{1}{4}(1 - 3w_{\rm rh2}) N_{\rm rh2} \approx \mathbf{57} + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right)$$

Moduli stabilisation gives the necessary inputs

- The initial displacement of the modulus.
- The inflaton width.

Carrying this out for Kahler Moduli Inflation.

$$N_{\text{infl}} \approx 45$$

Exhibits the importance of moduli dynamics for making inflationary predictions. To confront the next generation experiments we need to know N_{infl} with accuracy:

$$\Delta N \approx 5 \qquad m_\varphi \simeq 10^{13} \ \text{GeV}$$

Having an era of early matter domination also

- The initial displacement of the modulus.
- The inflaton width.

Carrying this out for Kahler Moduli Inflation.

$$N_{\rm infl} \approx 45$$

Exhibits the importance of moduli dynamics for making inflationary predictions. To confront the next generation experiments we need to know $N_{\rm infl}$ with accuracy:

$$\Delta N \approx 5$$

Modular cosmology also has implications for dark matter.

- Thermal overproduction before the epoch of early matter domination.

- Dilution upon reheating

The dilution factor is given by $\left(\frac{H(t_{\mathrm{r}})}{H(t_{\mathrm{m}})}\right)^{1/2}$ thus is directly related to the shift in N_{infl}

Conclusions

Constructing models of inflation in string theory poses many challenges

- Higher dimensional operators
- Field Ranges

Can lead to rich connections:

Scale of inflation   Initial field displacement N_{infl}

Moduli masses   Field Ranges   Nature of dark matter