Inflation and reheating

— Status and prospects —

L. SRIRAMKUMAR

Harish-Chandra Research Institute

Allahabad, India

IAGRG–25, SINP, Kolkata

January 31, 2009

Recent work and collaborators

The latter part of this talk is largely based on:

- ✦ R. K. Jain, P. Chingangbam and L. Sriramkumar, *On the evolution of tachyonic perturbations at super Hubble scales*, JCAP **0710**, 003 (2007).
- ✦ R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, Punctuated inflation and the low CMB multipoles, JCAP **0901**, 009 (2009).
- ✦ R. K. Jain, P. Chingangbam and L. Sriramkumar, *Reheating in tachyonic inflationary models: Effects on large scale curvature perturbations*, In preparation.

Collaborators:

- ✦ Rajeev Kumar Jain, Harish-Chandra Research Institute, Allahabad, India
- ✦ Pravabati Chingangbam, Korean Institute of Advanced Study, Seoul, Korea
- ✦ Jinn-Ouk Gong, Lorentz Institute for Theoretical Physics, University of Leiden, Leiden, Netherlands
- ✦ Tarun Souradeep, Inter University Centre for Astronomy and Astrophysics, Pune, India

Outline of the talk

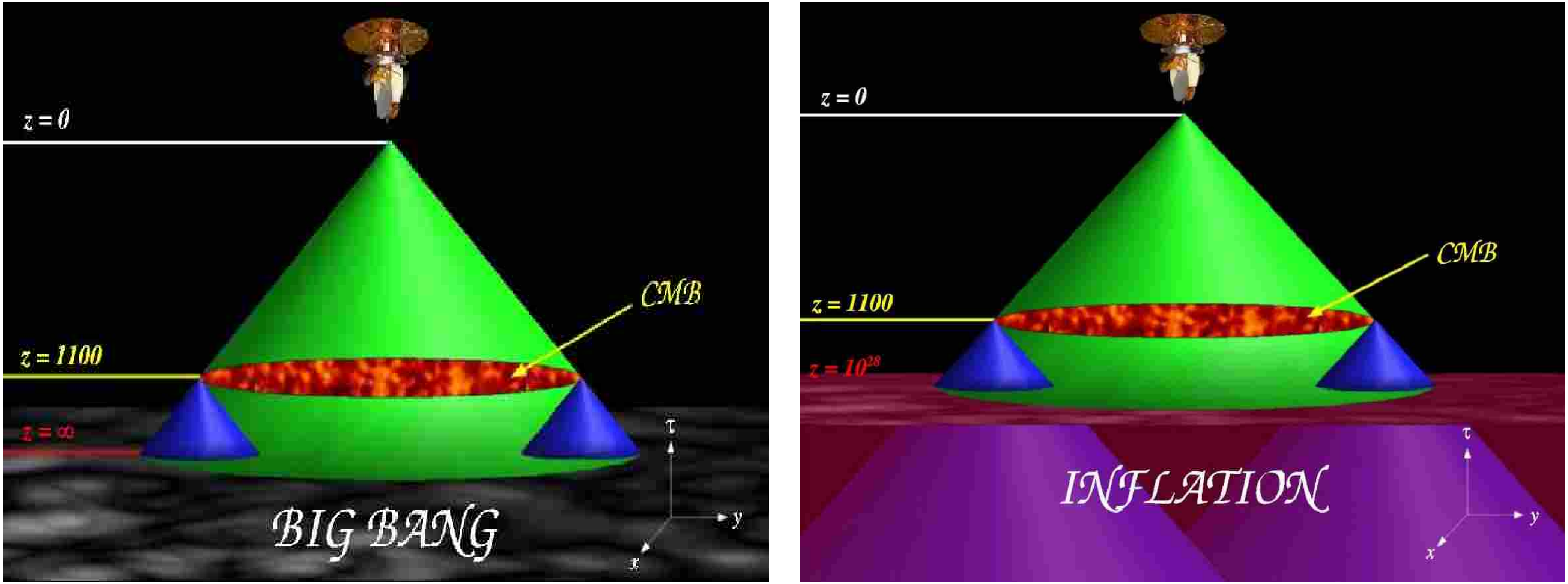
1 Inflation—A quick survey

Background—Essentials

Before proceeding, a couple of words on notation

- We shall set $c = \hbar = 1$, and define the Planck mass to be $M_{_{\mathrm{Pl}}}^2 = (8\,\pi\,G)^{-1}$.
- We shall denote differentiation with respect to the cosmic and the conformal times by an overdot and an overprime, respectively.

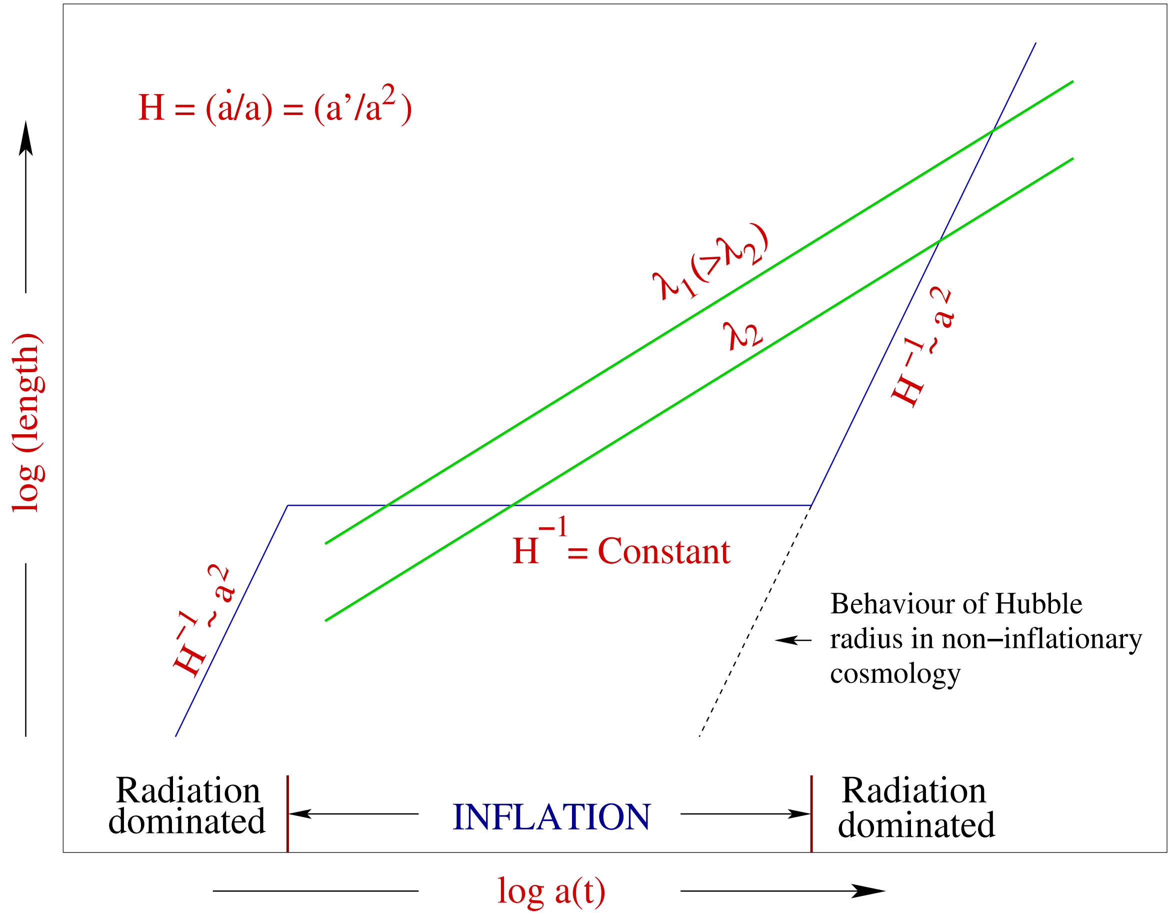
Inflation resolves the horizon problem[a]



Left: The radiation from the Cosmic Microwave Background (CMB) arriving at us from regions separated by more than the Hubble radius at the last scattering surface (which subtends an angle of about 1° today) could not have interacted before decoupling.
Right: An illustration of how inflation resolves the horizon problem.

[a] Images from W. Kinney, astro-ph/0301448.

Bringing the modes inside the Hubble radius[a]



Plots of the physical wavelength $\lambda_{\rm P}$ $[= (\lambda_0\, a)]$ (the green lines) and the Hubble radius $d_{\rm H}$ $(= H^{-1})$ (in blue) illustrating as to how inflation allows us to bring the modes inside the Hubble radius at a suitably early time.

[a] E. W. Kolb and M. S. Turner, *The Early Universe*, (Addison-Wesley Publishing Company, 1990), Fig. 8.4; T. Padmanabhan, *Structure Formation in the Universe* (Cambridge University Press, Cambridge, 1993), Fig. 10.1.

Driving inflation with scalar fields[a]

If we require that $\lambda_{\mathrm{P}} < d_{\mathrm{H}}$ at a sufficiently early time, then we need to have an epoch wherein λ_{P} decreases faster than the Hubble scale *as we go back in time*, i.e. a regime during which

$$-\frac{\mathrm{d}}{\mathrm{d}\,t}\left(\frac{\lambda_{\mathrm{P}}}{d_{\mathrm{H}}}\right) < 0 \quad \rightarrow \quad \ddot{a} > 0.$$

From the Friedmann equations, we then require that, during this epoch,

$$(\rho + 3\,p) < 0.$$

In the case of canonical scalar fields, this condition simplifies to

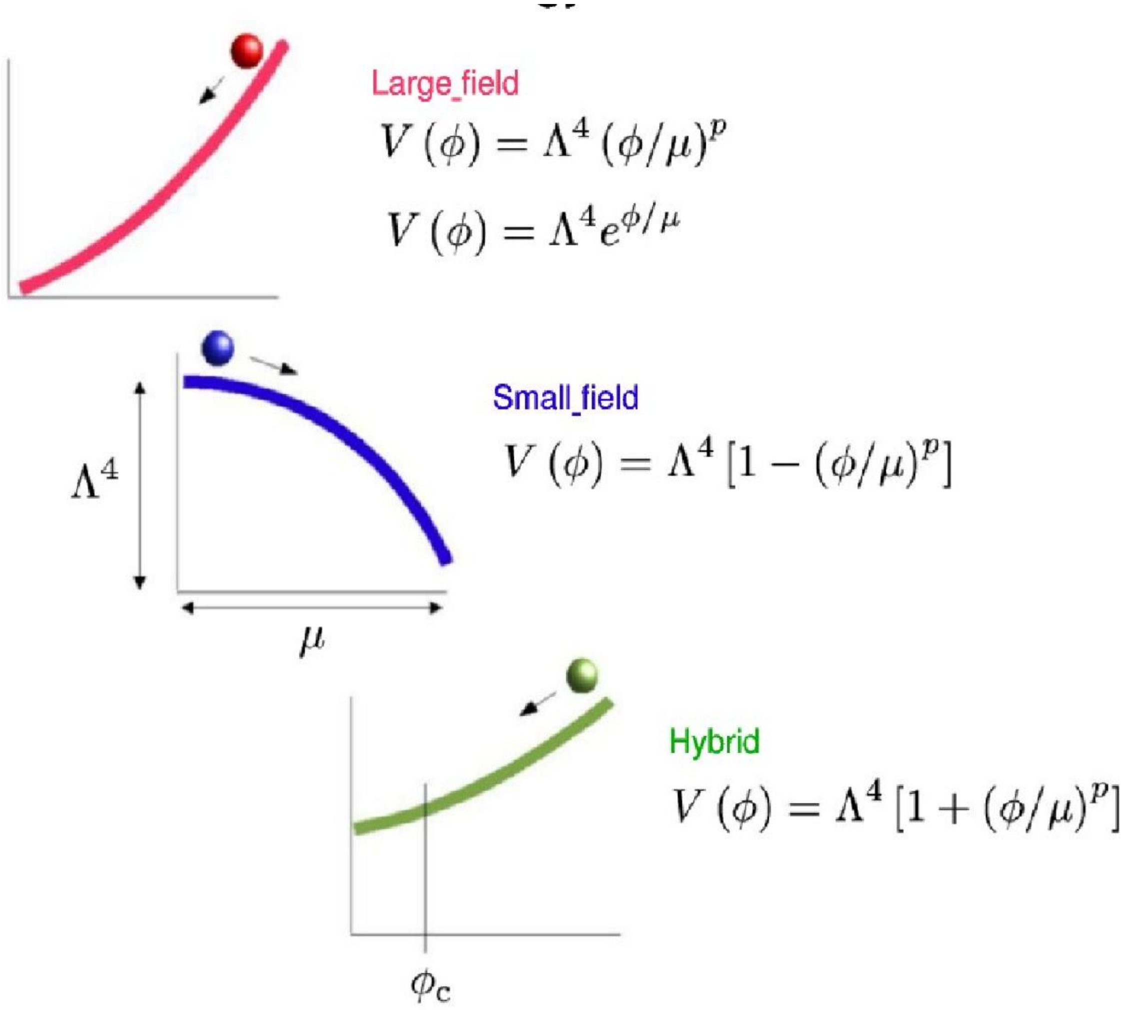
$$\dot{\phi}^2 < V(\phi).$$

This condition can be achieved if the scalar field ϕ is initially displaced from a minima of the potential, and inflation will end when the field approaches a minima with zero or negligible potential energy.

It is the fluctuations in the inflaton field ϕ that act as the seed perturbations that are responsible for the present day inhomogeneities.

[a] For a recent review, see B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

A variety of potentials to choose from[a]



A variety of scalar field potentials have been considered to drive inflation. Often, these potentials are classified as small field, large field and hybrid models.

[a] Image from W. Kinney, astro-ph/0301448.

Perturbations—Key equations, quantities and observational constraints

The perturbation spectra and the tensor-to-scalar ratio[a]

The curvature and the tensor perturbations, say, $\mathcal{R}_k$ and $\mathcal{U}_k$, satisfy the differential equations

$$\mathcal{R}_k'' + 2\,(z'/z)\,\mathcal{R}_k' + k^2\,\mathcal{R}_k = 0 \quad \text{and} \quad \mathcal{U}_k'' + 2\,\mathcal{H}\,\mathcal{U}_k' + k^2\,\mathcal{U}_k = 0,$$

where $z = (a\,\phi'/\mathcal{H})$, with a being the scale factor, ϕ the background inflaton, and $\mathcal{H} = (a'/a)$ is the conformal Hubble parameter.

The scalar and tensor power spectra, viz. $\mathcal{P}_{\rm S}(k)$ and $\mathcal{P}_{\rm T}(k)$, are given by

$$\mathcal{P}_{\rm S}(k) = \left(\frac{k^3}{2\,\pi^2}\right)\,|\mathcal{R}_{\rm k}|^2 \quad \text{and} \quad \mathcal{P}_{\rm T}(k) = \left(\frac{k^3}{2\pi^2}\right)\,|\mathcal{U}_{\rm k}|^2,$$

with the amplitudes $\mathcal{R}_k$ and $\mathcal{U}_k$ evaluated, in general, in the super-Hubble limit.

Finally, the tensor-to-scalar ratio r is defined as follows:

$$r \equiv \left(\frac{\mathcal{P}_{\rm T}}{\mathcal{P}_{\rm S}}\right).$$

[a] For a recent review, see B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

The spectral indices and their running[a]

The scalar spectral index and its running are defined as

$$n_{\mathrm{S}} \equiv 1 + \left(\frac{\mathrm{d}\ln \mathcal{P}_{\mathrm{S}}}{\mathrm{d}\ln k}\right) \quad \text{and} \quad \alpha_{\mathrm{S}} \equiv \left(\frac{\mathrm{d}\, n_{\mathrm{S}}}{\mathrm{d}\ln k}\right).$$

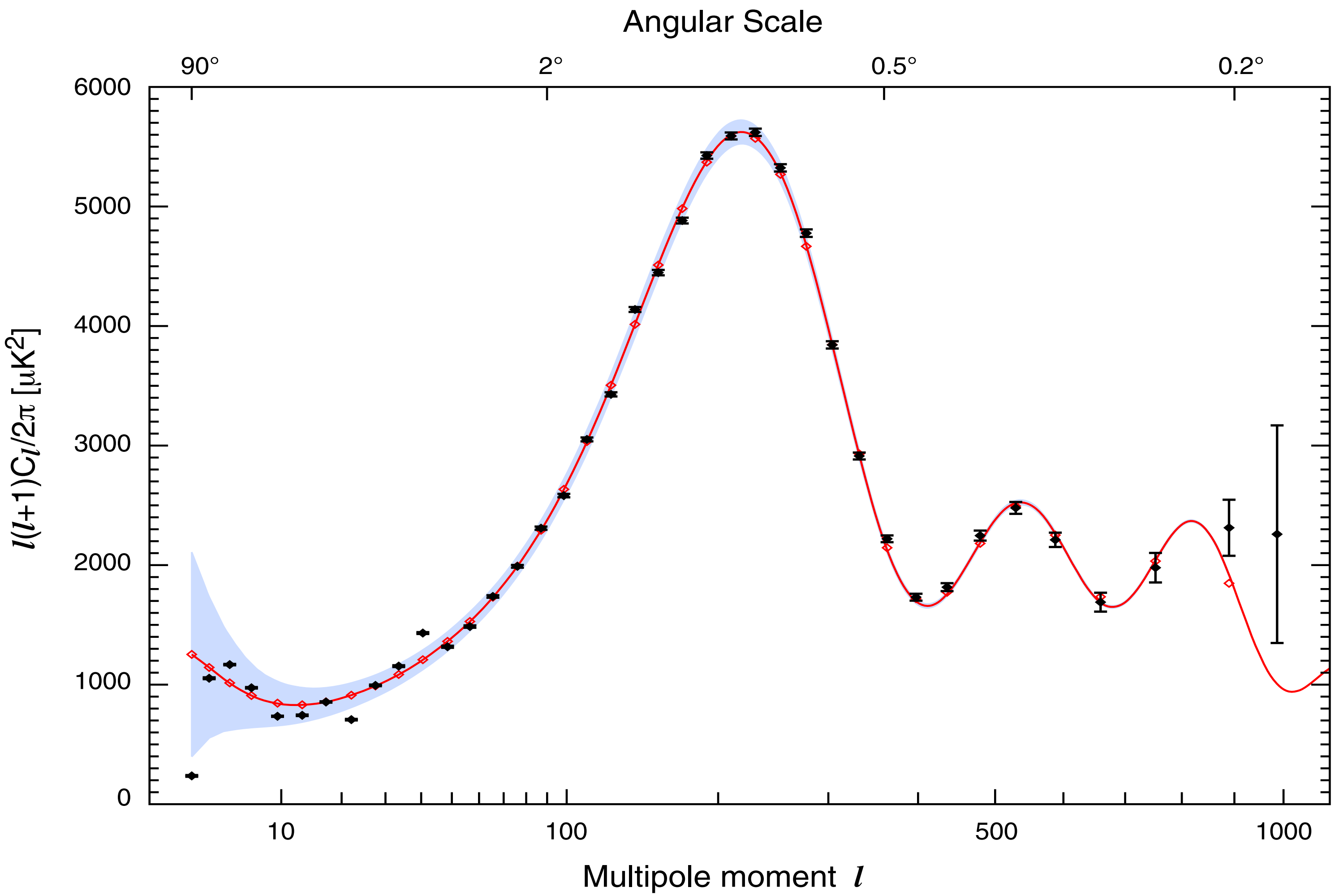
Whereas, the tensor spectral index and its running are given by

$$n_{\mathrm{T}} \equiv \left(\frac{\mathrm{d}\ln \mathcal{P}_{\mathrm{T}}}{\mathrm{d}\ln k}\right) \quad \text{and} \quad \alpha_{\mathrm{T}} \equiv \left(\frac{\mathrm{d}\, n_{\mathrm{T}}}{\mathrm{d}\ln k}\right).$$

[a]For a recent review, see B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

The universe according to WMAP

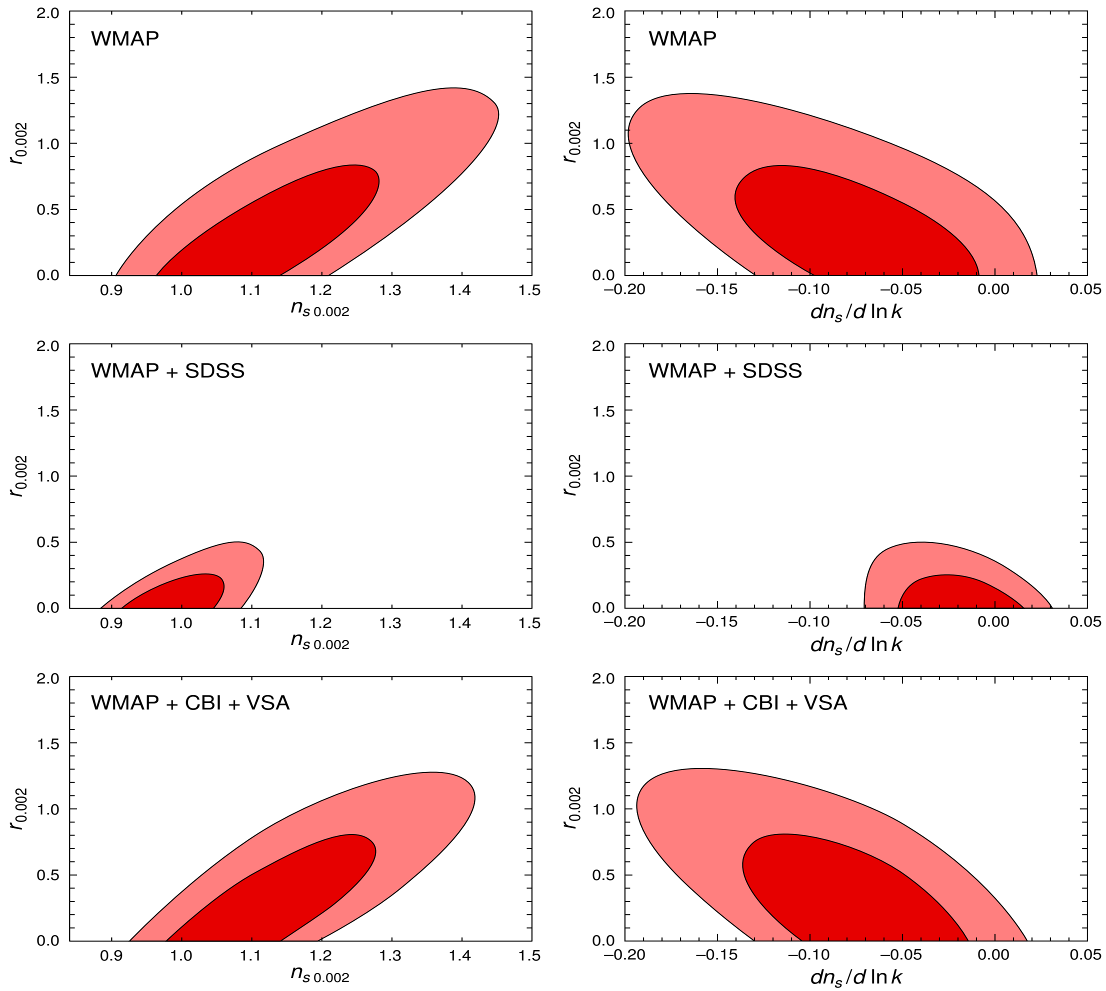
The CMB angular power spectrum from WMAP[a]



The CMB angular power spectrum from the 3-year WMAP data (the black dots with error bars) and the best-fit ΛCDM model with a nearly scale invariant inflationary spectrum (the red curve). The blue band denotes the cosmic variance.

[a] G. Hinshaw et. al., Ap. J. Suppl. **170**, 288 (2007).

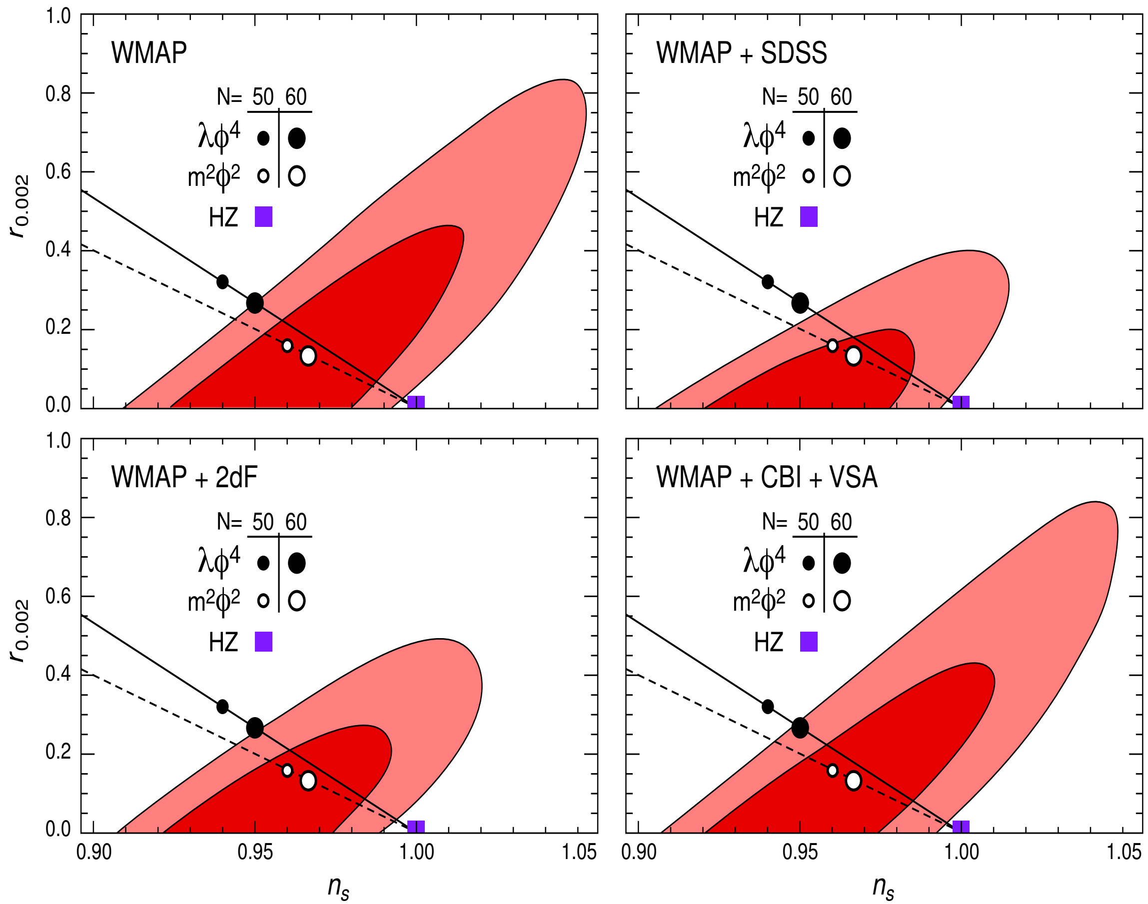
Joint constraints on $n_{\rm s}$, r and α_s[a]



Marginalized contours (at 68% and 95% confidence levels) for the inflationary parameters ($n_{\rm s}$, r) (on the left) and ($\alpha_{\rm s}$, r) (on the right) with the parameters defined at $k = 0.002\ \mathrm{Mpc}^{-1}$.

[a] D. Spergel et. al., Ap. J. Suppl. **170**, 377 (2007).

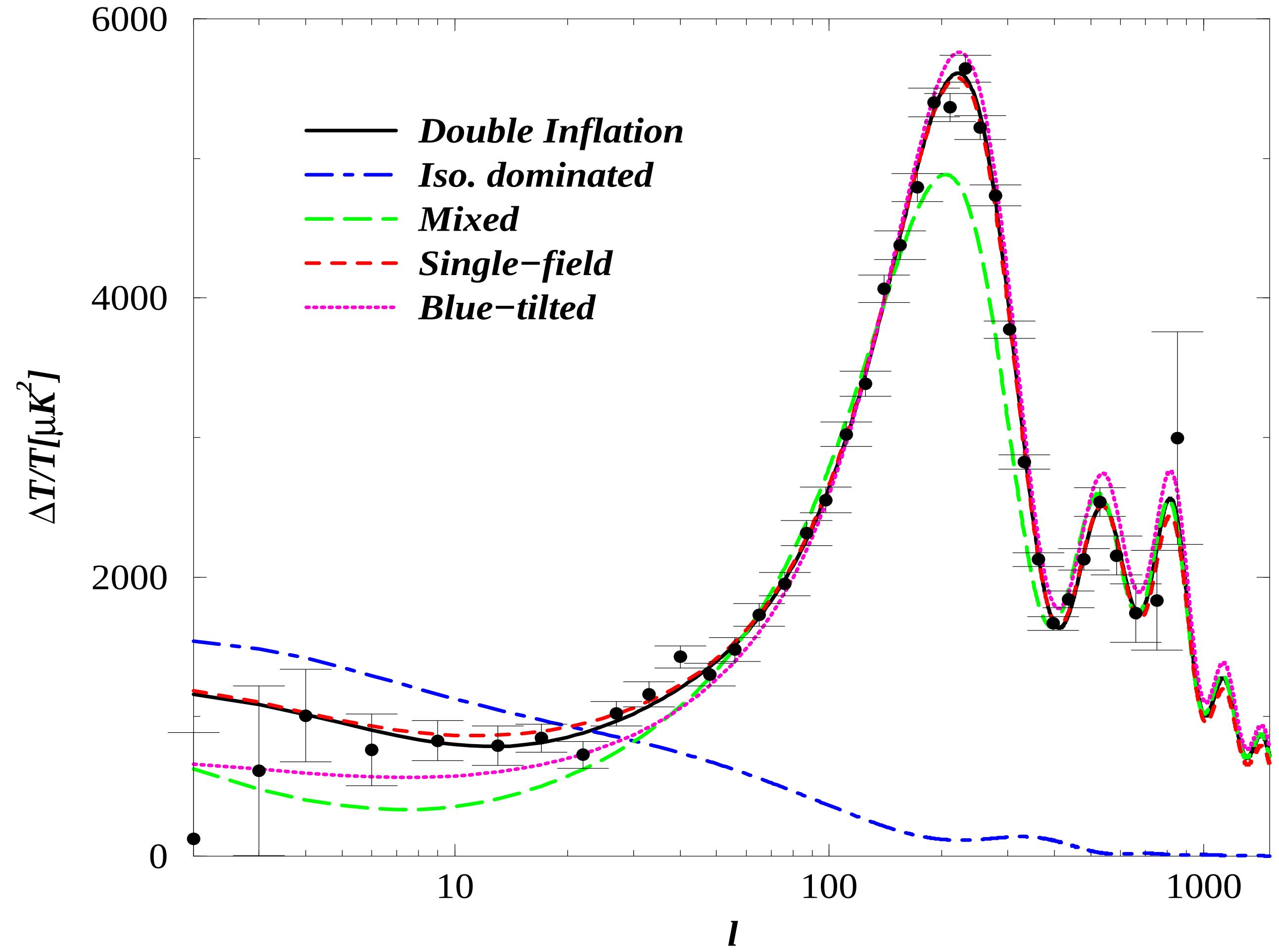
Constraints on large field models[a]



Joint constraints on the inflationary parameters $n_{\rm s}$ and r for large field models with potentials of the form $V(\phi) \propto \phi^n$. The blue rectangle denotes the exactly scale invariant Harrison-Zeldovich (HZ) spectrum. Note that the data prefers the $(m^2\,\phi^2)$ model over both the HZ spectrum and the $(\lambda\,\phi^4)$ model.

[a] D. Spergel et. al., Ap. J. Suppl. **170**, 377 (2007).

Multiple scalar fields and isocurvature perturbations[a]



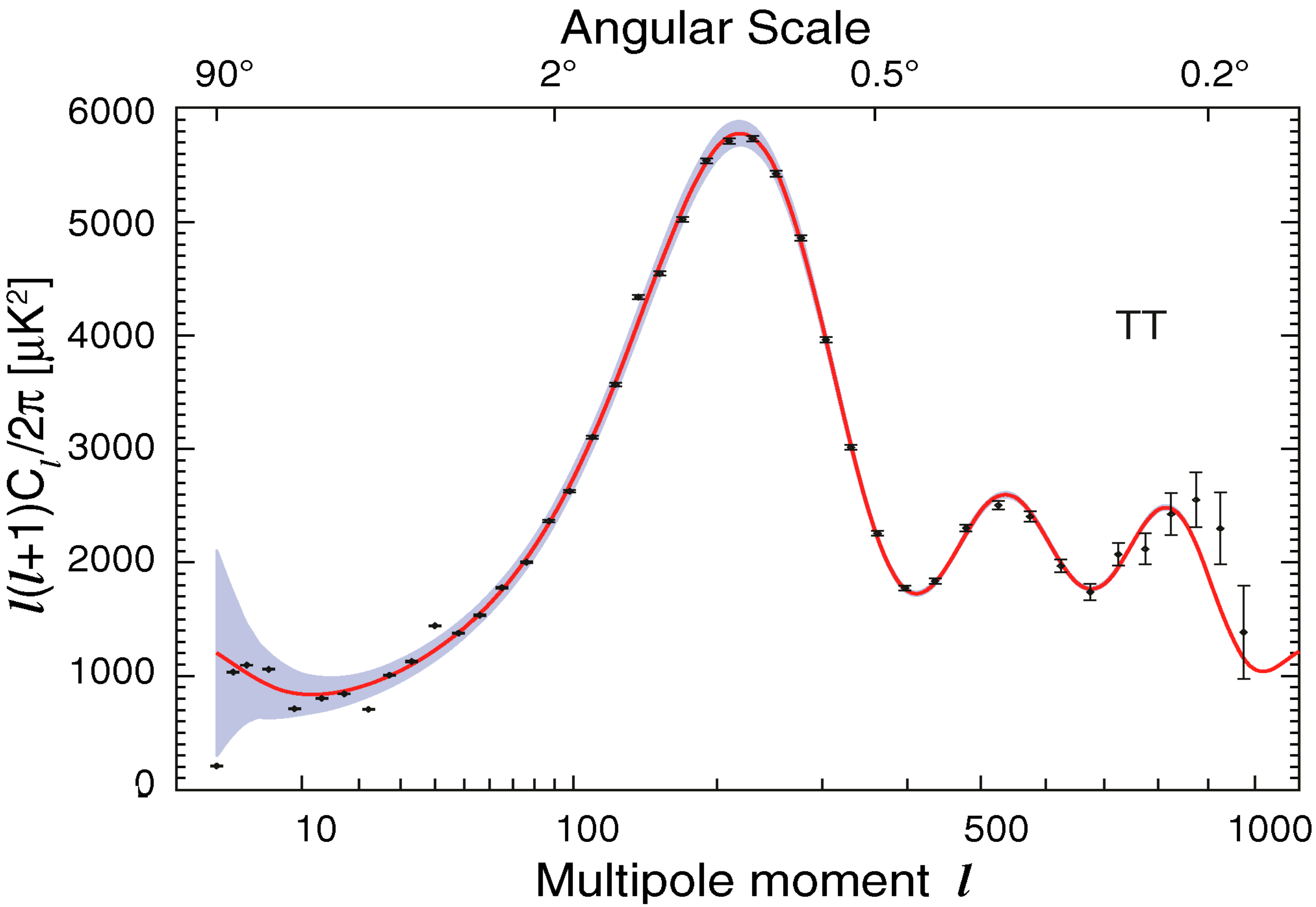
Models involving multiple scalar fields naturally lead to isocurvature (i.e. entropic or non-adiabatic pressure) perturbations. The CMB observations strongly indicate that the primordial perturbations are adiabatic to a large extent.

[a] Figure from B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

2 Does the primordial spectrum contain features?

Do the outliers point to features?

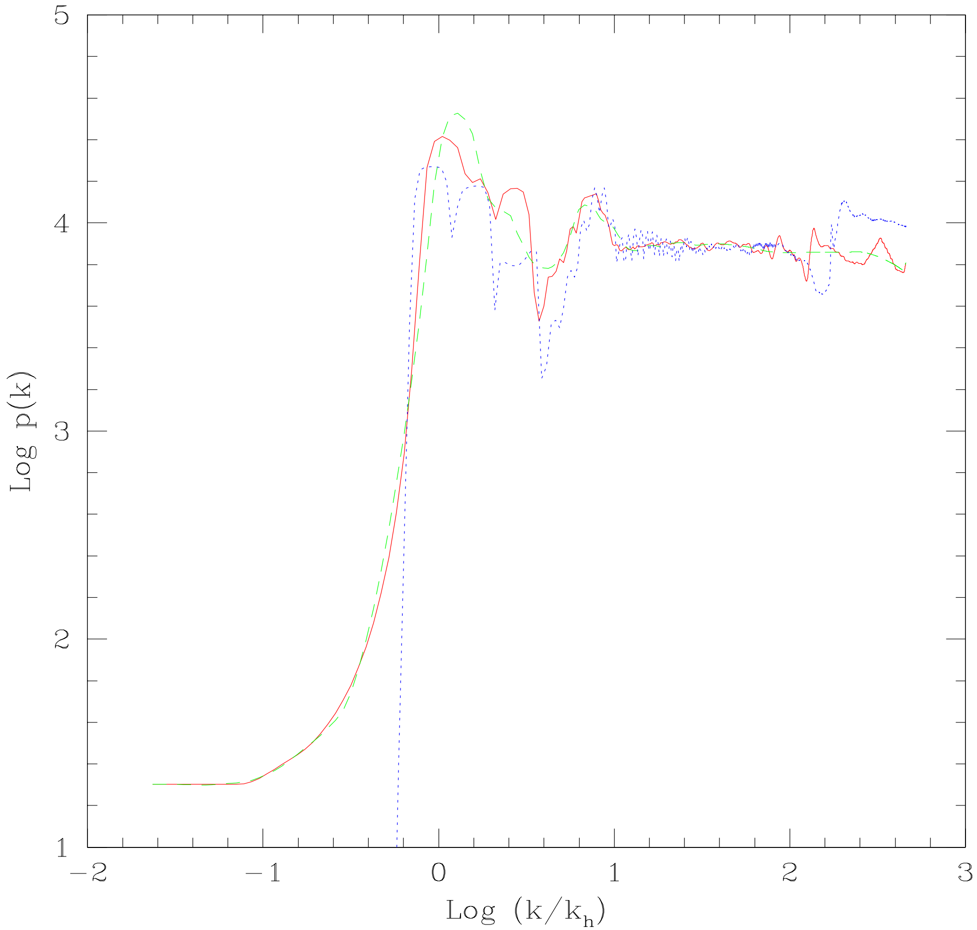
The CMB angular power spectrum from the 5-year WMAP data[a]



The 5-year WMAP data for the CMB angular power spectrum (the black dots with error bars) and the best-fit ΛCDM model with a power law primordial spectrum (the red curve). Note the outliers near the multipoles $\ell = 2$, 22 and 40.

[a] G. Hinshaw *et. al.*, arXiv:0803.0732.

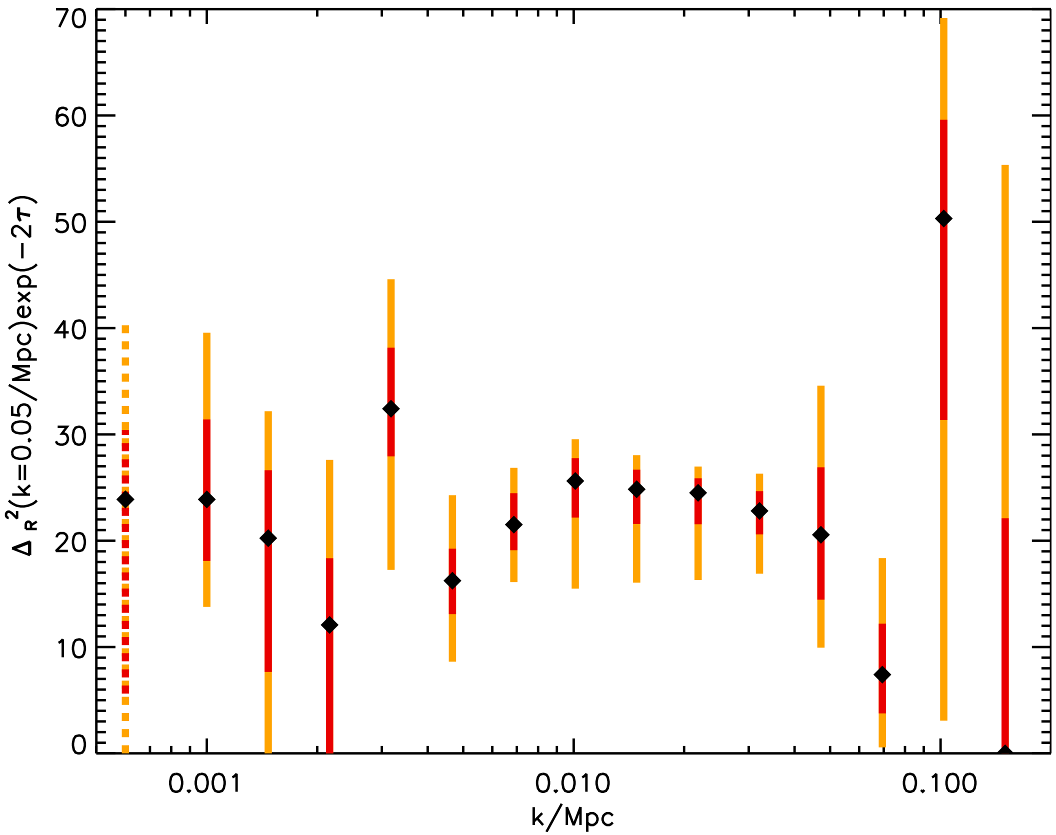
Do we require lower power at large scales?



The 'recovered' primordial spectrum (the blue dotted line), assuming the standard background ΛCDM model. The recovered spectrum improves the fit to the 3-year WMAP data by $\Delta\chi^2_{\rm eff} = 15.93$, with respect to the best fit power law spectrum[a].

[a] A. Shafieloo, T. Souradeep, P. Manimaran, P. K. Panigrahi and R. Rangarajan, Phys. Rev. D **75**, 123502 (2007).

Does the primordial spectrum contain other features?

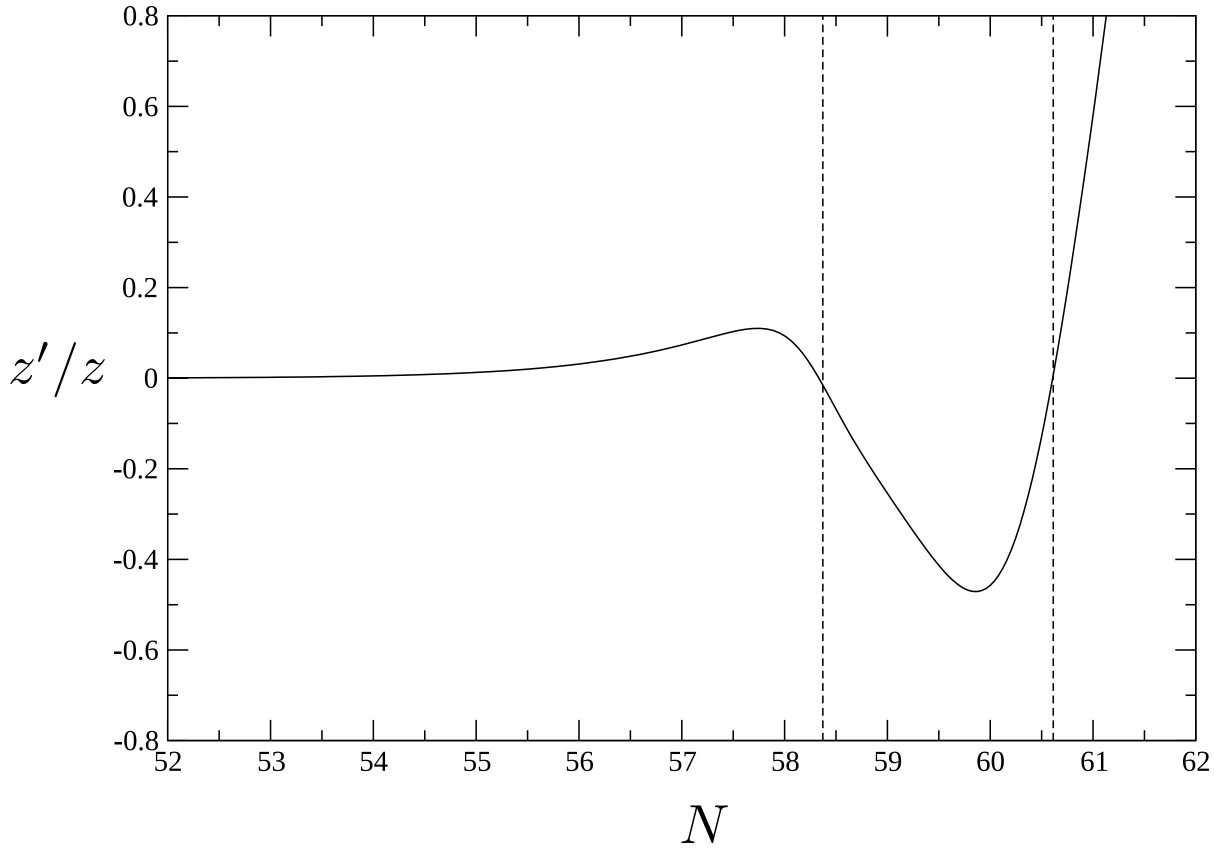


A primordial spectrum 'reconstructed' in 15 bins between $k = 0$ and $k = 0.15\ \mathrm{Mpc}^{-1}$ using the 3-year WMAP data. The vertical bars indicate the 68% (in red) and 95% (in orange) constraints, about the peak likelihood values (marked as black diamonds). Such a spectrum was found to improve the fit to the 3-year WMAP data by $\Delta\chi^2_{\mathrm{eff}} = 22$[a].

[a] D. Spergel *et. al.*, Astrophys. J. Suppl. **170**, 377 (2007).

Deviations from slow roll inflation and features in the primordial spectrum

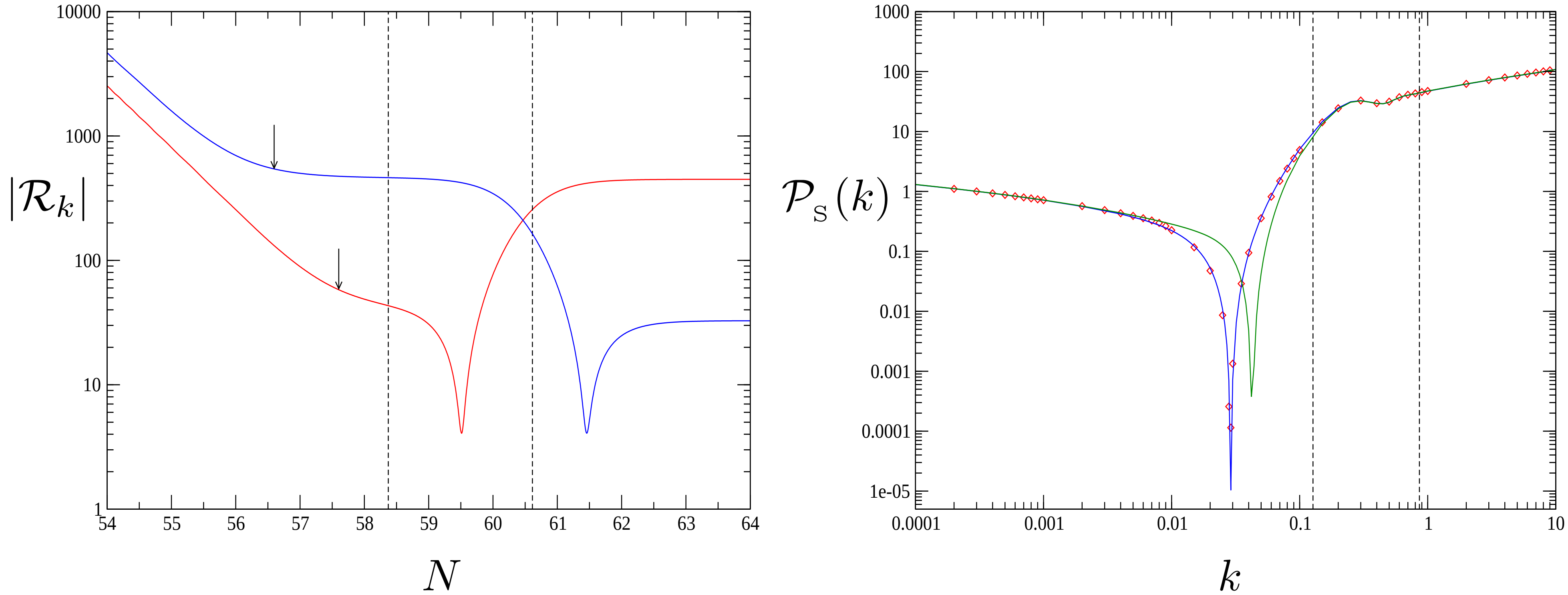
A specific example[a]



The evolution of the quantity (z'/z) plotted as a function of the number of e-folds N in a particular tachyonic inflationary model. The vertical lines delineate the regime where (z'/z) is negative. Note that it remains negative for a little less than three e-folds between N of 58 and 61.

[a] R. K. Jain, P. Chingangbam and L. Sriramkumar, JCAP **0710**, 003 (2007).

Evolution of the curvature perturbations and the power spectrum[a]



Left: The evolution of the curvature perturbations plotted as a function of the number of the number of e-folds N for two modes that leave the Hubble radius just before the fast roll. The arrows indicate the time at which the modes leave the Hubble radius.
Right: The resulting scalar power spectrum. The vertical lines indicate the modes that leave the Hubble scale during the period of fast roll.

[a] R. K. Jain, P. Chingangbam and L. Sriramkumar, JCAP **0710**, 003 (2007).

Fitting the low quadrupole

Suppressing power at large scales

- Within the inflationary scenario, a variety of single and two field models have been constructed to produce such a drop in power at the large scales[a].
- However, in single field inflationary models, in order to produce such a spectrum, many of the scenarios either assume a specific pre-inflationary regime, say, a radiation dominated epoch[b], or special initial conditions for the background scalar field, such as an initial period of fast roll[c], or special initial states for the perturbations[d].

---

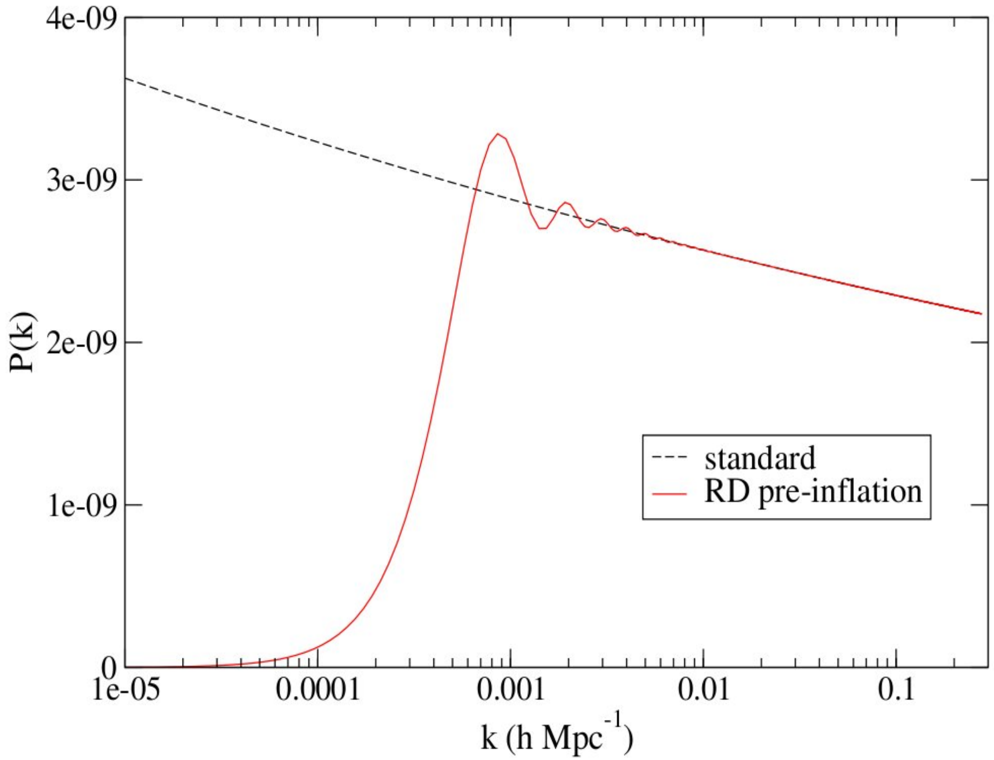
[a] See, for instance, B. Feng and X. Zhang, Phys. Lett. B **570**, 145 (2003); R. Sinha and T. Souradeep, Phys. Rev. D **74**, 043518 (2006).

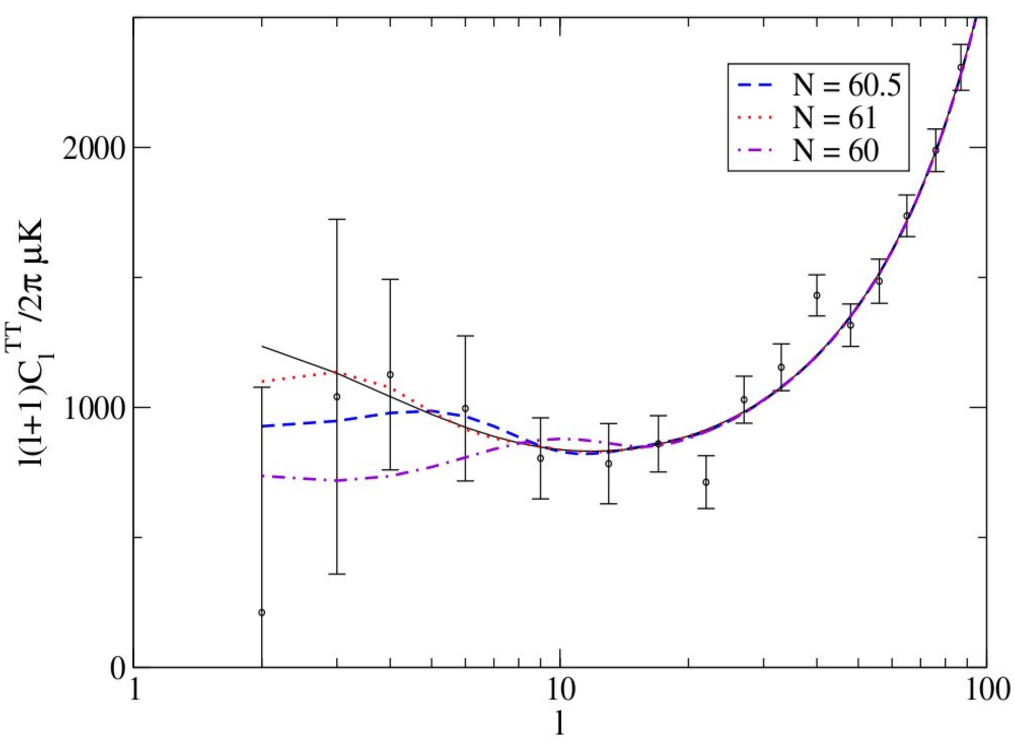
[b] See, for example, D. Boyanovsky, H. J. de Vega and N. G. Sanchez, Phys. Rev. D **74**, 123006 (2006); *ibid* **74**, 123007 (2006); B. A. Powell and W. H. Kinney, Phys. Rev. D **76**, 063512 (2007).

[c] See, for instance, C. R. Contaldi, M. Peloso, L. Kofman and A. Linde, JCAP **0307**, 002 (2003); J. M. Cline, P. Crotty and J. Lesgourgues, JCAP **0309**, 010 (2003).

[d] L. Sriramkumar and T. Padmanabhan, Phys. Rev. D **71**, 103512 (2005).

Spectrum due to a pre-inflationary, radiation dominated phase[a]

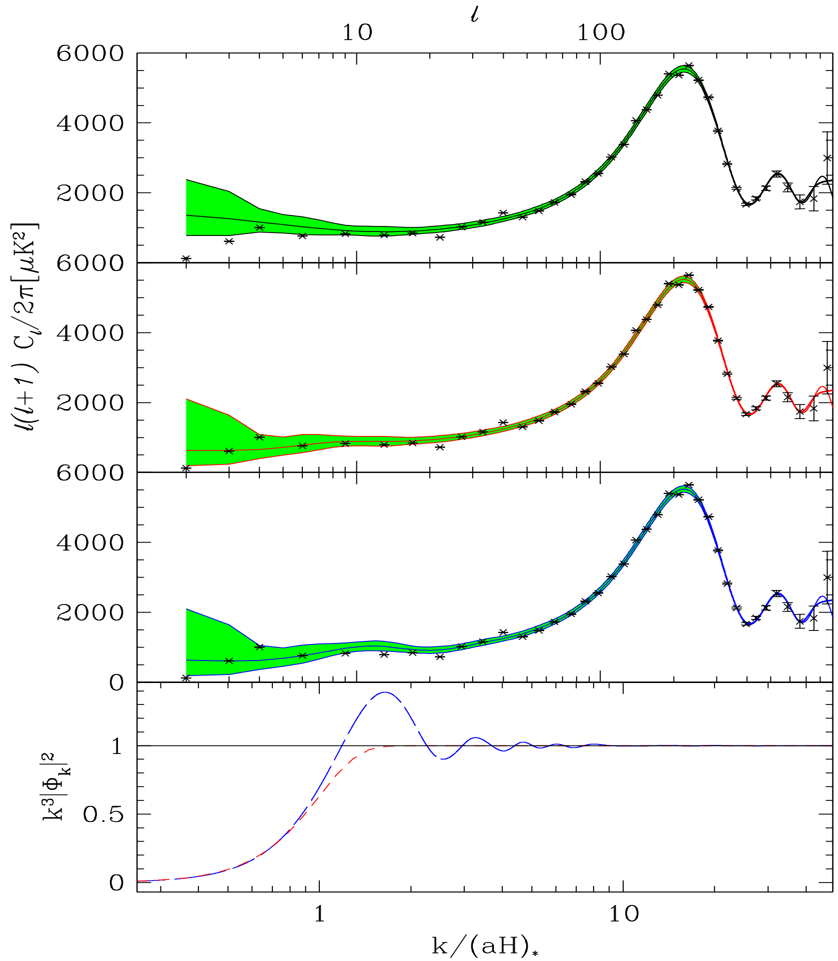




The scalar power spectrum in a model with a pre-inflationary radiation dominated epoch (on the left) and the corresponding CMB angular power spectrum (on the right).

[a] B. A. Powell and W. H. Kinney, Phys. Rev. D **76**, 063512 (2007).

Spectrum in an initially fast rolling inflationary model[a]



The scalar power spectrum in the chaotic inflation model with an initial period of fast roll (bottom panel) and the corresponding CMB angular power spectrum (the second panel from the bottom).

[a] C. R. Contaldi, M. Peloso, L. Kofman and A. Linde, JCAP **0307**, 002 (2003).

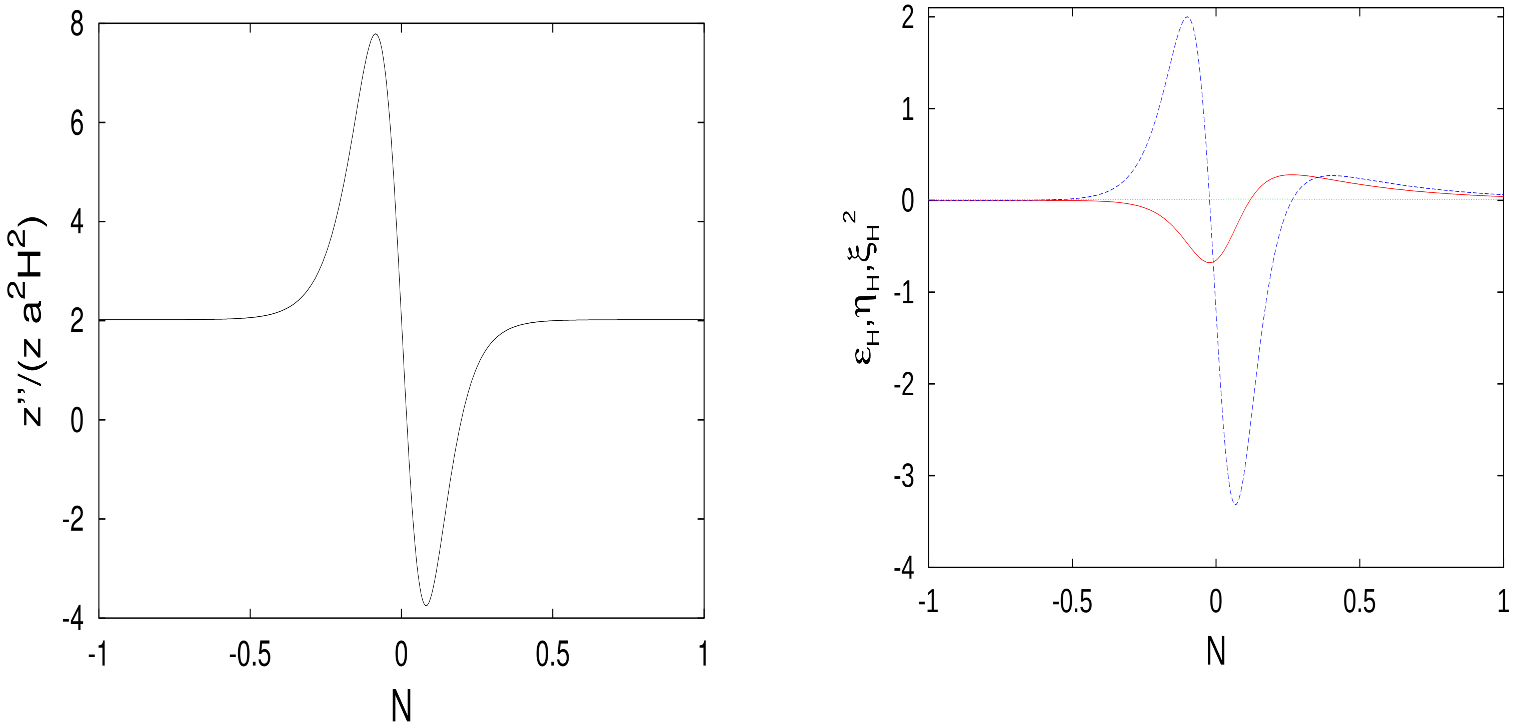
Drawbacks of these approaches

- ✦ Evidently, these models assume either a specific pre-inflationary phase or special initial conditions for the inflaton.
- ✦ Also, these models impose the initial conditions on the perturbations when the largest scales are outside the Hubble radius during the pre-inflationary or the fast roll regime.
- ✦ Moreover, though a very specific pre-inflationary phase such as the radiation dominated epoch may allow what can be considered as natural (i.e. Minkowski-like) initial conditions for the perturbations even at super-Hubble scales, choosing to impose initial conditions for a small subset of modes when they are outside the Hubble radius, while demanding that such conditions be imposed on the rest of the modes at sub-Hubble scales, is highly unsatisfactory.

Ideally, it would be preferable to produce the desired power spectrum during an inflationary epoch without invoking any specific pre-inflationary phase or special initial conditions for the inflaton. Also, one would like to impose the standard Bunch-Davies initial conditions on *all* the modes when they are well inside the Hubble radius.

Fitting the outliers at $\ell = 22$ and 40

Inducing fast roll in the chaotic inflation model

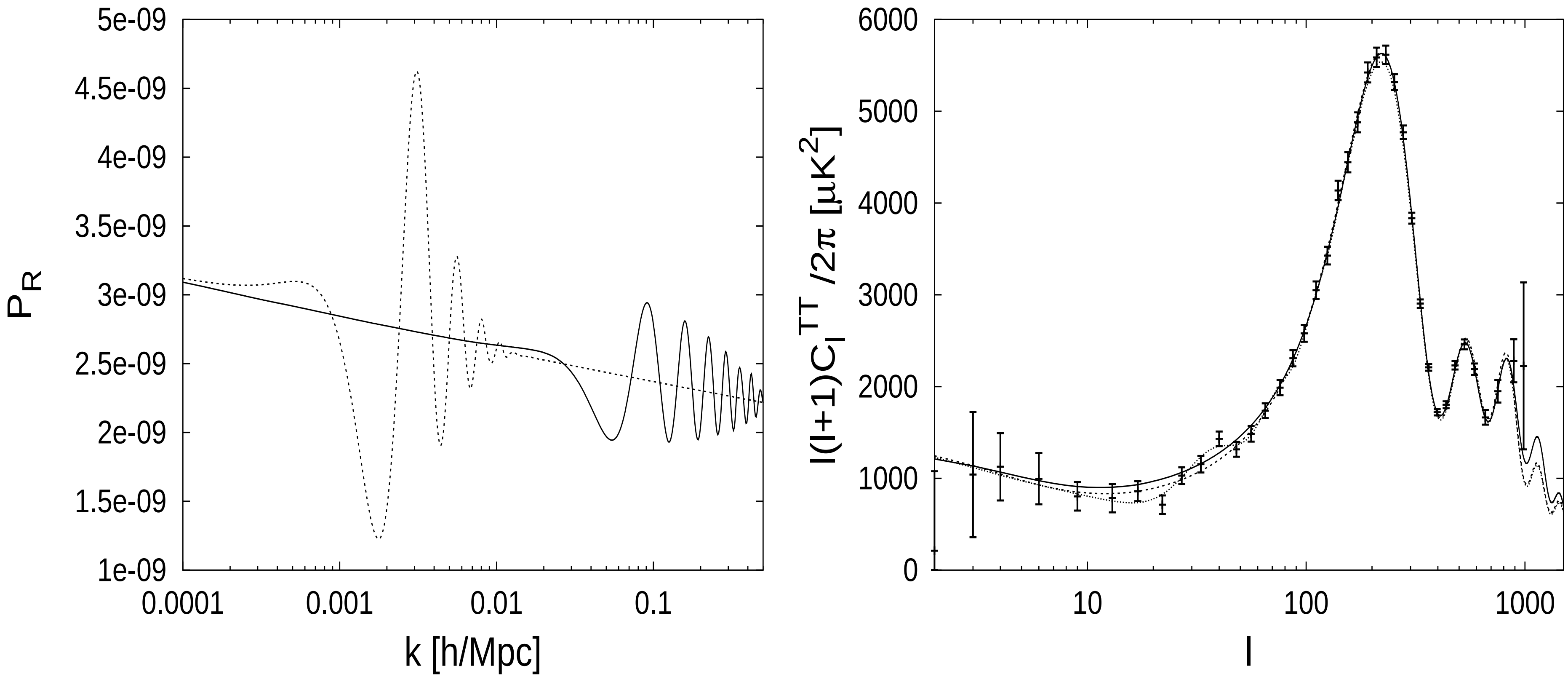


The evolution of the quantity $(z''/z\,\mathcal{H}^2)$ (on the left) and the first three Hubble slow roll parameters (on the right) in the following 'modified' chaotic inflation potential[a]:

$$V(\phi) = \left(\frac{m^2\,\phi^2}{2}\right)\,\left[1 - c\,\tanh\left(\frac{\phi - b}{d}\right)\right].$$

[a] L. Covi, J. Hamann, A. Melchiorri, A. Slosar and I. Sorbera, Phys. Rev. D **74**, 083509 (2006); J. Hamann, L. Covi, A. Melchiorri and A. Slosar, Phys. Rev. D **76**, 023503 (2007).

The scalar and the CMB angular power spectrum



The CMB angular spectrum (on the right) resulting from the primordial spectrum with features (on the left)[a]. The dashed line (on the right) corresponds to the spectrum arising from the standard power law model and the solid line refers to best fit model which improves the fit by $\Delta\chi^2_{\rm eff} = 7$ with respect to the standard model.

[a] L. Covi, J. Hamann, A. Melchiorri, A. Slosar and I. Sorbera, Phys. Rev. D **74**, 083509 (2006).

Punctuated inflation and the low CMB multipoles

Motivations and the model

- Our aim is to consider a single field model of inflation that leads to a suppression of the power on large scales without the need for any special initial conditions on either the background or the perturbations.

- Also, we would like to arrive at the desired power spectrum using an inflaton potential that does not contain any ad hoc, sharp feature.

The effective potential that we shall consider is given by[a]

$$V(\phi) = \left(m^2/2\right)\, \phi^2 - \left(\sqrt{2\,\lambda\,(n-1)}\, m/n\right)\, \phi^n + (\lambda/4)\, \phi^{2(n-1)},$$

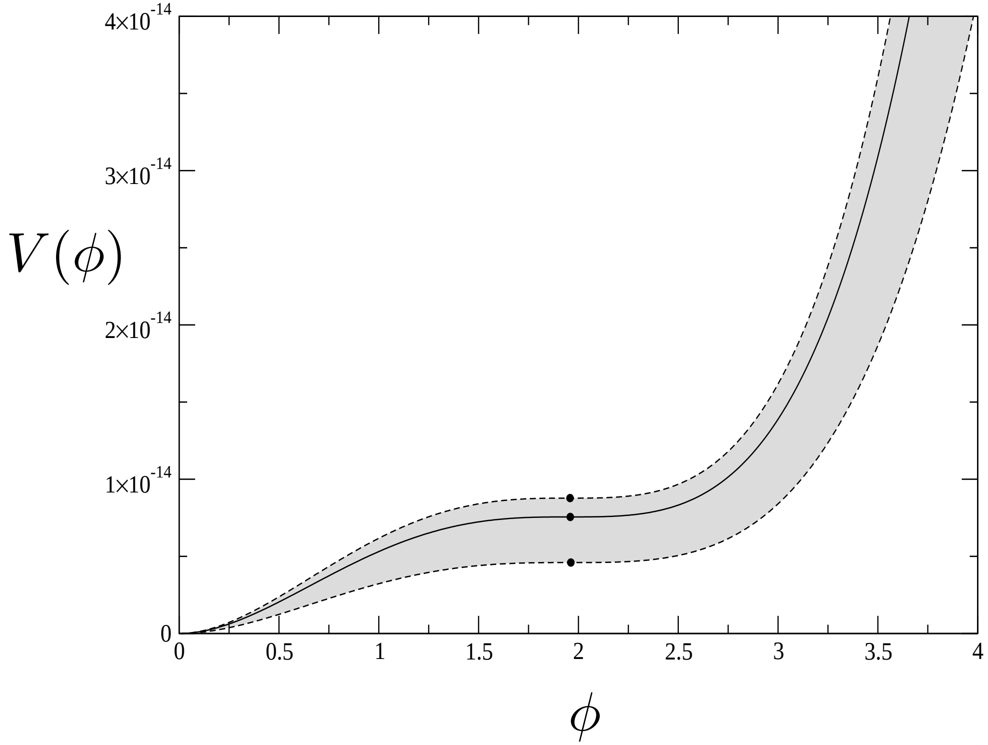
where $n > 2$ is an integer. The two parameters m and λ are chosen so that the potential has a point of inflection at

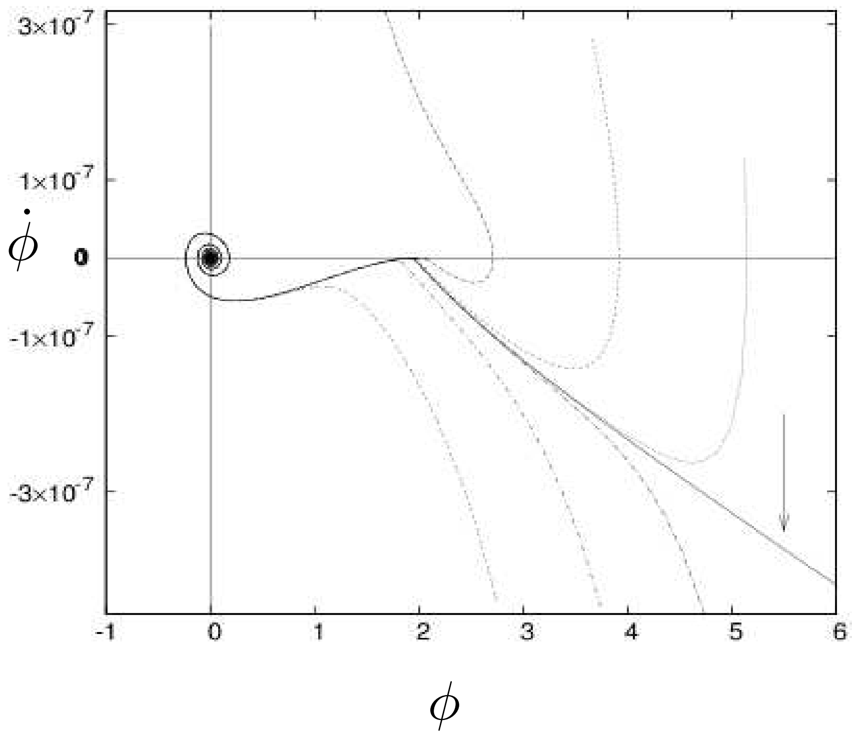
$$\phi_0 = \left[\frac{2\, m^2}{(n-1)\,\lambda}\right]^{\frac{1}{2\,(n-2)}}.$$

These large field models allow a period of fast roll sandwiched between two stages of slow roll inflation.

[a] See, for example, R. Allahverdi, K. Enqvist, J. Garcia-Bellido, A. Jokinen and A. Mazumdar, JCAP **0706**, 019 (2007).

The effective potential and the phase portrait[a]



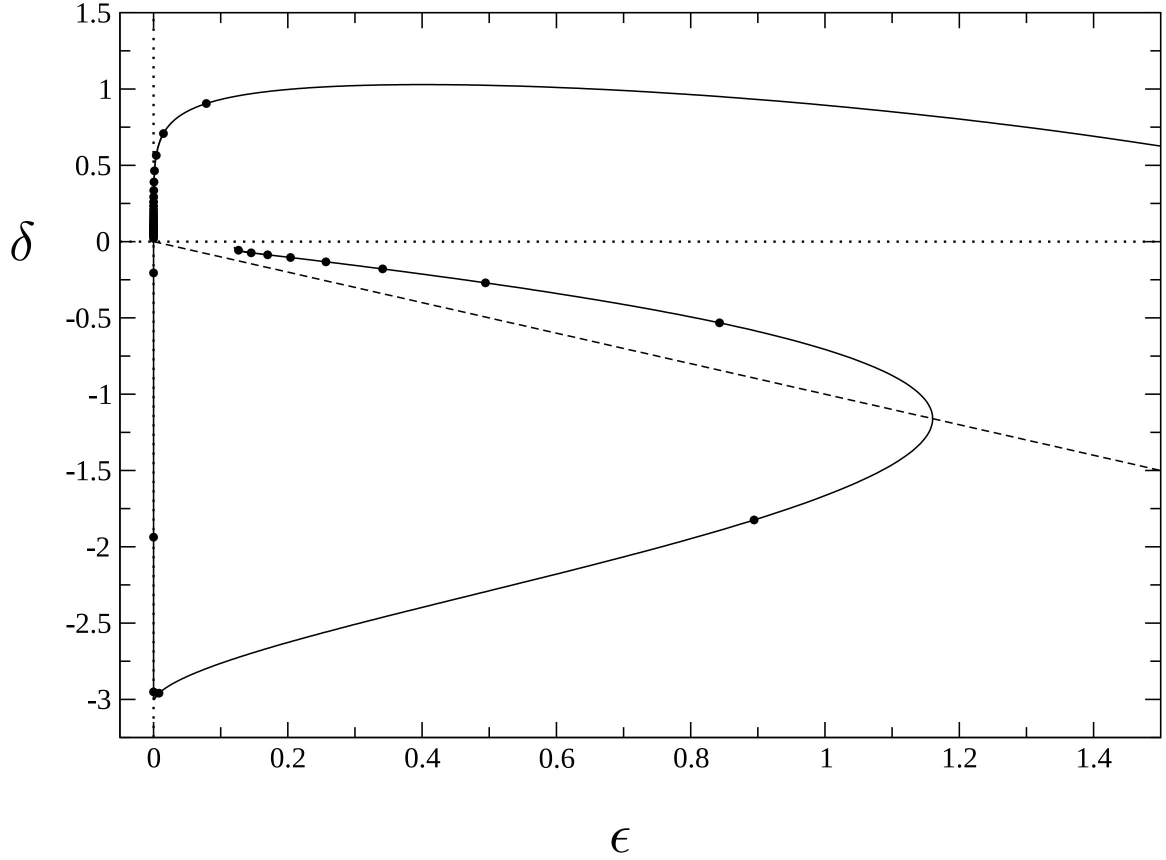


Left: The inflaton potential for the case of $n = 3$. The solid line corresponds to the values for the potential parameters that provide the best fit to the 5-year WMAP data, and the black dot denotes the point of inflection.

Right: The corresponding phase portrait of the scalar field. The arrow points to the attractor. Note that all the trajectories quickly approach the attractor.

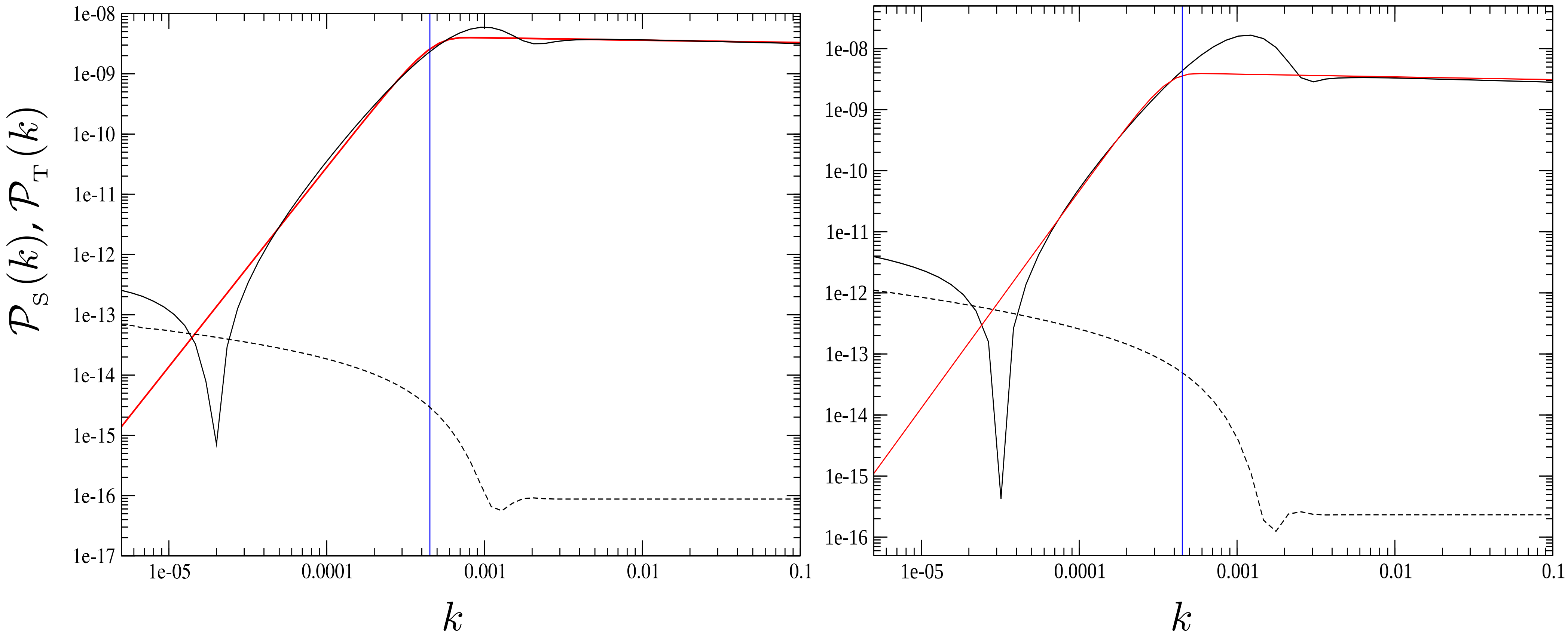
[a] R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **0901**, 009 (2009).

Evolution in the ϵ-δ plane



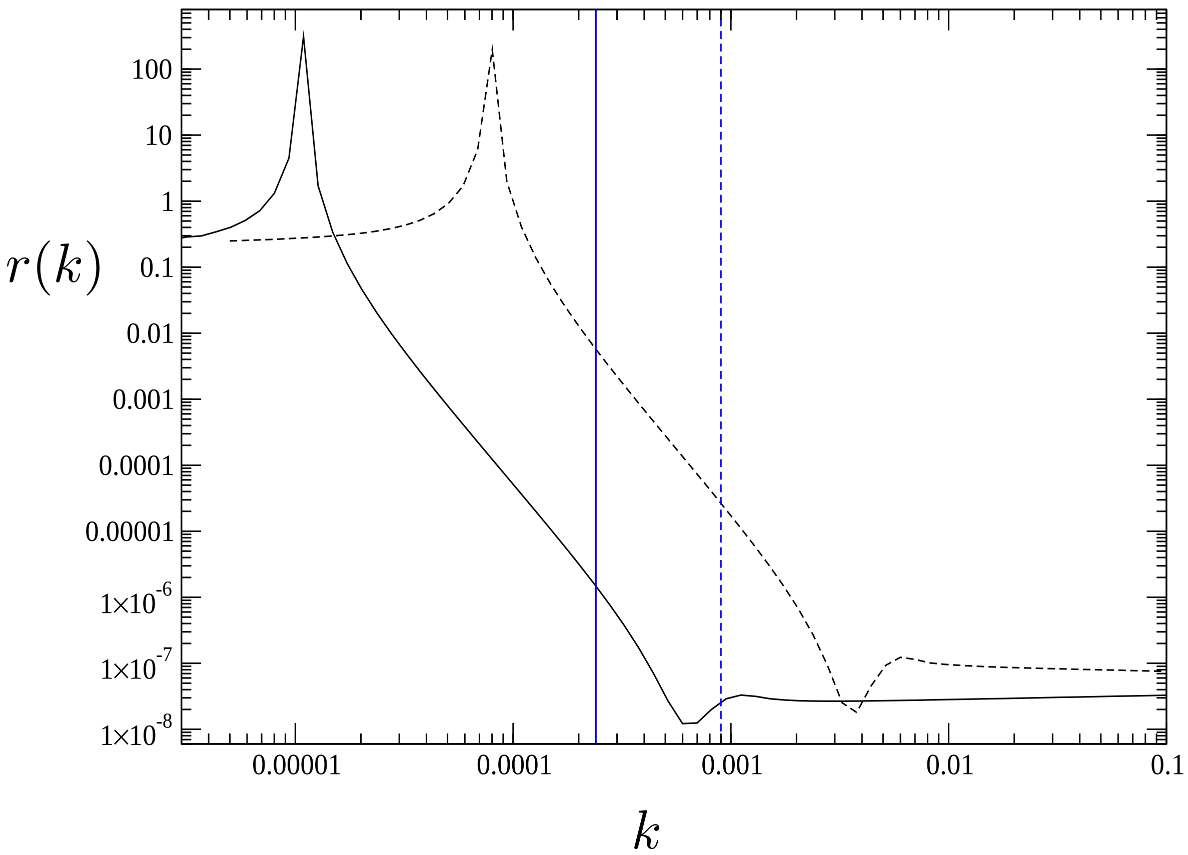
The evolution of the scalar field has been plotted (as the solid black line) in the plane of the first two Hubble slow roll parameters ϵ and δ in the case of $n = 3$. The black dots have been marked at intervals of one e-fold, while the dashed line corresponds to $\epsilon = -\delta$. Note that $\epsilon > 1$ during $8 < N < 9$. In other words, during fast roll, inflation is actually interrupted for about a e-fold.

Power spectra for the $n = 3$ and $n = 4$ cases



The scalar power spectrum $\mathcal{P}_{\rm S}(k)$ (the solid line) and the tensor power spectrum $\mathcal{P}_{\rm T}(k)$ (the dashed line) have been plotted as a function of the wavenumber k for the cases of $n = 3$ (on the left) and $n = 4$ (on the right). We have chosen the same values for the potential parameters as in the earlier figures. Moreover, we should emphasize that we have arrived at these spectra by imposing the standard, Bunch-Davies, initial condition on *all* the modes.

The tensor-to-scalar ratio



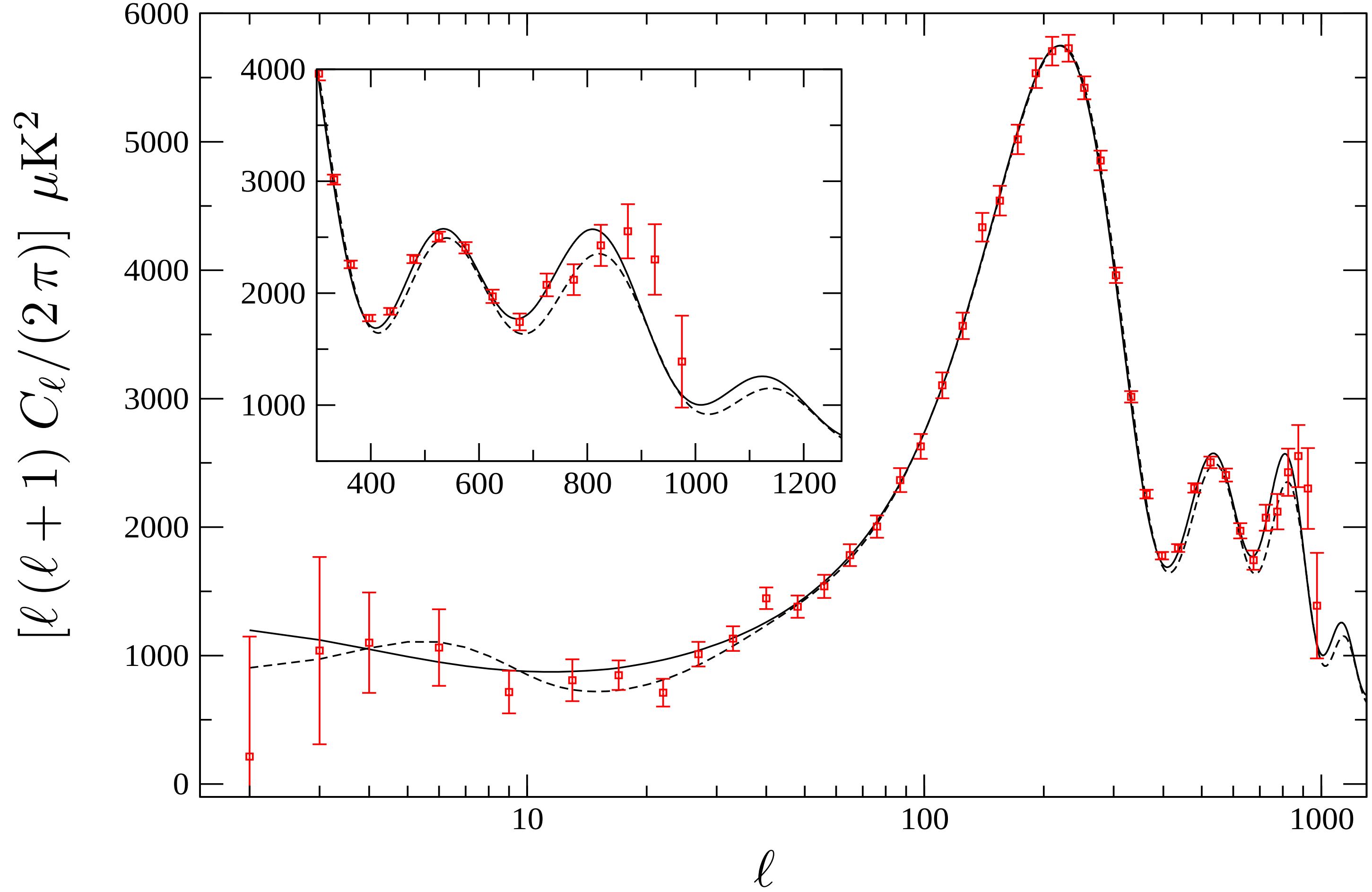
The tensor-to-scalar ratio r for the cases of $n = 3$ (the solid line) and $n = 4$ (the dashed line) plotted as a function of the wavenumber k. These plots have been drawn for the same choice of parameters as in the earlier figures. Note that, in spite of the rise at larger wavelengths, the tensor-to-scalar ratio remains smaller than 10^{-4} for modes of cosmological interest.

The best-fit values of the parameters in the $n = 3$ case

Parameter	Reference model	Our model
$\Omega_{\mathrm{b}}\, h^2$	$0.02242^{+0.00155}_{-0.00127}$	$0.02146^{+0.00142}_{-0.00108}$
$\Omega_{\mathrm{c}}\, h^2$	$0.1075^{+0.0169}_{-0.0126}$	$0.12051^{+0.02311}_{-0.02387}$
θ	$1.0395^{+0.0075}_{-0.0076}$	$1.03877^{+0.00979}_{-0.00931}$
τ	$0.08695^{+0.04375}_{-0.03923}$	$0.07220^{+0.04264}_{-0.02201}$
$\log\,\left[10^{10}\, A_{\mathrm{S}}\right]$	$3.0456^{+0.1093}_{-0.1073}$	—
n_{S}	$0.9555^{+0.0394}_{-0.0305}$	—
$\log\,\left[10^{10}\, m^2\right]$	—	$-8.3509^{+0.1509}_{-0.1473}$
ϕ_0	—	$1.9594^{+0.00290}_{-0.00096}$
a_0	—	$0.31439^{+0.02599}_{-0.02105}$

The mean values and the 1-σ constraints on the various parameters that describe the reference model and our model. We find that the $n = 3$ case provides a much better fit to the data than the reference model with an improvement in χ^2_{eff} of 6.62.

The CMB angular power spectrum for the best fit values



The CMB angular power spectrum for the best fit values in the $n = 3$ case (the dashed line) and the best fit power law, reference model (the solid line). Visually, it is evident that our model fits the data much better than standard power law case at the lower multipoles.

3 Post-inflationary dynamics—A rapid overview

Post-inflationary dynamics and effects on perturbations

Inflation is expected to be immediately followed by a period of (p)reheating. Post-inflationary dynamics that are known to affect the perturbations are:

- ✦ Preheating: A mechanism that transfers the energy from the inflaton to radiation through an 'explosive' production of quanta corresponding to an intermediate scalar field can have a 'large' effect on the perturbations[a].
- ✦ The curvaton scenario: In this scenario, while the inflationary epoch still remains the source of the perturbations, these fluctuations are amplified after inflation because of the presence of isocurvature perturbations[b].
- ✦ Modulated/inhomogeneous reheating: In this extreme case, inflation is essentially required to resolve the horizon problem, whereas the perturbations are generated due to an inhomogeneous decay rate when the energy is being transferred from the inflaton and (or through) other fields to radiation[c].

In contrast, it is often assumed that the simpler process of reheating does affect the evolution of the perturbations.

[a] See, for example, F. Finelli and R. Brandenberger, Phys. Rev. D **62**, 083502 (2000).
[b] See, for instance, D. H. Lyth and D. Wands, Phys. Letts. B **524**, 5 (2002).
[c] See, for example, L. Kofman, arXiv:astro-ph/0303614.

4 Reheating and effects on large scale curvature perturbations

Reheating in canonical scalar field models

Background dynamics

Background equations in the presence of energy transfer

Recall that the first Friedmann equation and the equation governing the conservation of the total energy density ρ are given by

$$H^2 = (8\,\pi\,G/3)\;\rho \quad \text{and} \quad \dot{\rho} + 3\,H\;(\rho + p) = 0,$$

where $H = (\dot{a}/a)$ denotes the Hubble parameter, and p the total pressure.

When multiple components of matter are present so that $\rho = \sum_\alpha \rho_\alpha$ and $p = \sum_\alpha p_\alpha$, then, in the absence of interactions, each of the components satisfy the above energy conservation equation separately.

On the other hand, when the different components interact, the continuity equation for the individual components can be expressed as[a]

$$\dot{\rho}_\alpha + 3\,H\;(\rho_\alpha + p_\alpha) = Q_\alpha,$$

where Q_α is the rate at which the energy density is transferred to the component α.

The conservation of energy of the complete system then leads to the following constraint on the total rate of transfer of the energy densities: $\sum_\alpha Q_\alpha = 0$.

[a] See, for example, K. A. Malik and D. Wands, JCAP **02**, 007 (2005).

Canonical scalar field interacting with a perfect fluid

Let us now consider the case of a canonical scalar field that is interacting with a perfect fluid described by the equation of state $w_{\rm F} = (p_{\rm F}/\rho_{\rm F})$.

If we now assume that $Q_{\rm F} = (\Gamma\,\dot{\phi}^2)$, then the continuity equation for the perfect fluid is given by

$$\dot{\rho}_{\rm F} + 3\,H\,\left(1+w_{\rm F}\right)\,\rho_{\rm F} = \left(\Gamma\,\dot{\phi}^2\right),$$

while the standard equation describing the field scalar ϕ is modified to

$$\ddot{\phi} + 3\,H\,\dot{\phi} + \Gamma\,\dot{\phi} + V_{\phi} = 0,$$

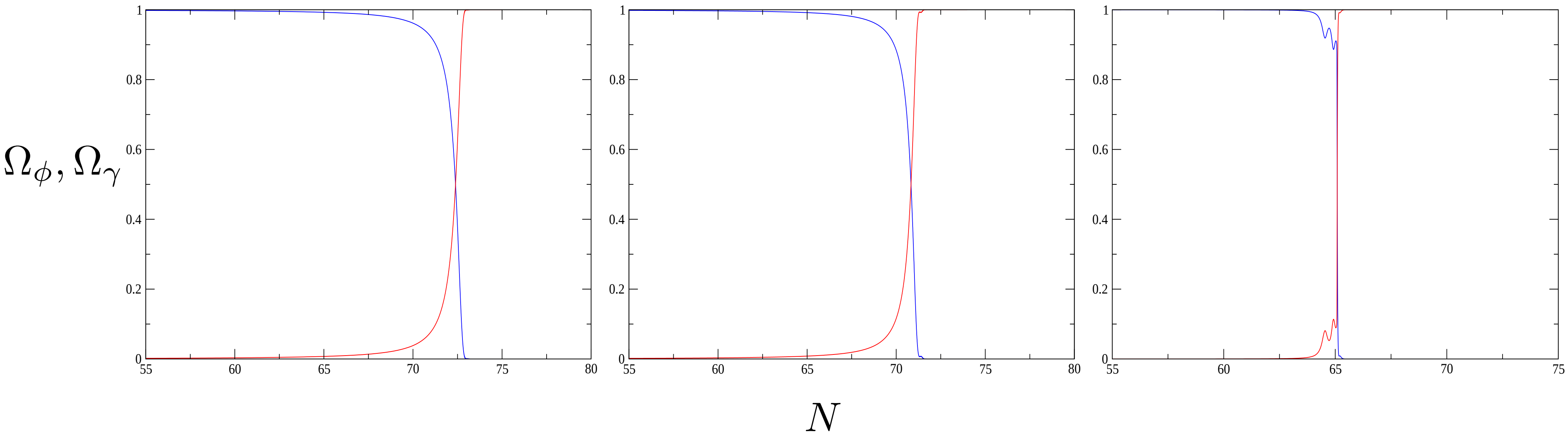
where $V_{\phi} = ({\rm d}V/{\rm d}\phi)$.

Such a transfer of energy is assumed to describe—albeit, in a course grained fashion—the perturbative decay of the inflaton into particles that constitute the perfect fluid. The quantity Γ represents the corresponding decay rate and, as we shall discuss below, it can either be a constant, depend on the inflaton, or depend explicitly on time[a].

In what follows, we shall work with the potential $V(\phi) = (m^2\,\phi^2/2)$.

[a] S. Matarrese and A. Riotto, JCAP **0308**, 007 (2003).

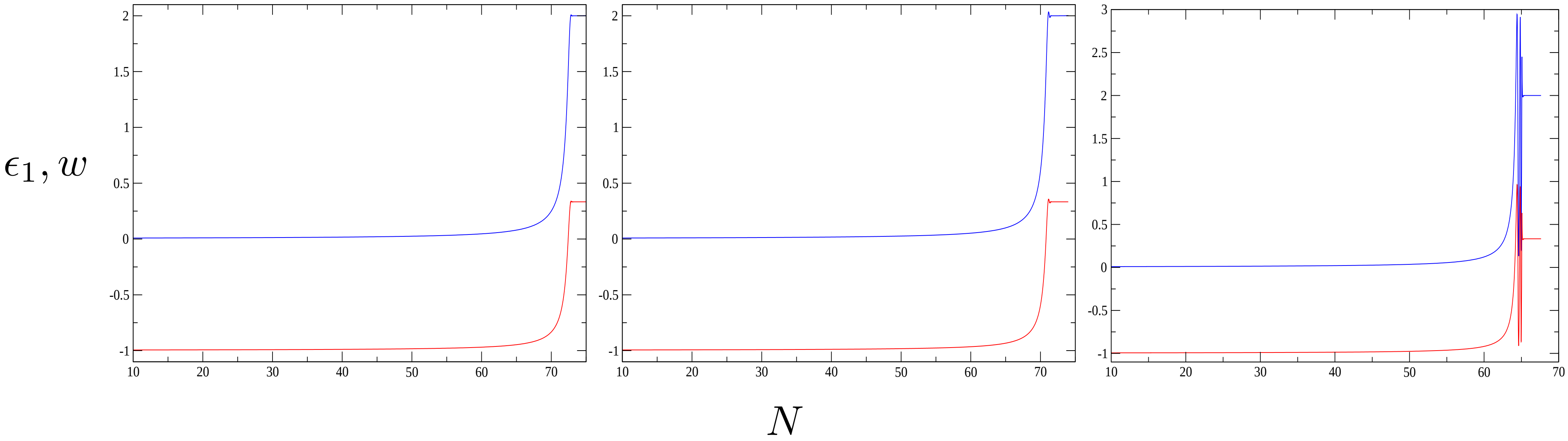
Transfer of energy from the scalar field to radiation



The evolution of the quantities $\Omega_\phi = (\rho_\phi/\rho)$ (in blue) and $\Omega_\gamma = (\rho_\gamma/\rho)$ (in red) have been plotted as a function of the number of e-folds N for the following three cases: (i) $\Gamma =$ constant (on the left), (ii) $\Gamma(\phi)$ (in the middle), and (iii) $\Gamma(t)$ (on the right). The transition to radiation domination evidently occurs in these cases roughly between e-folds of 62 and 75.

Note that $\Gamma(t)$ describes a situation wherein the inflaton first decays into particles corresponding to an intermediate field before further decaying into radiation.

The first slow roll parameter and the effective equation of state

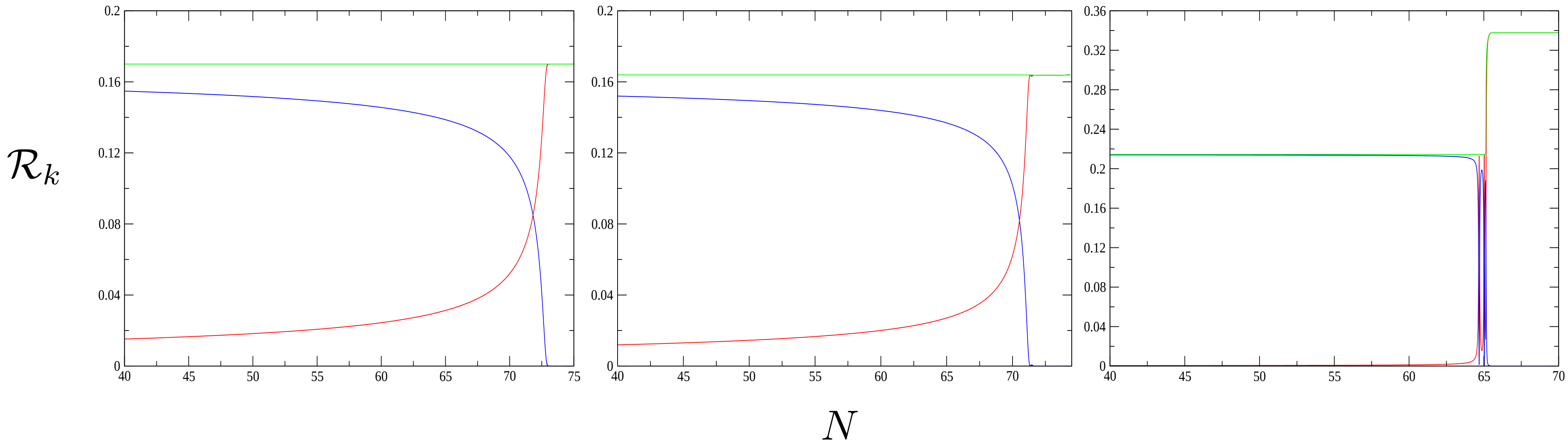


The evolution of the first slow roll parameter $\epsilon = -(\dot{H}/H^2)$ (in blue) and the effective equation of state $w = (p/\rho)$ (in red) have been plotted as a function of the number of e-folds N for the three different cases of Γ considered in the previous figure.

Note that we have chosen the different parameters in such a fashion that there is no intermediate regime wherein $w = 0$.

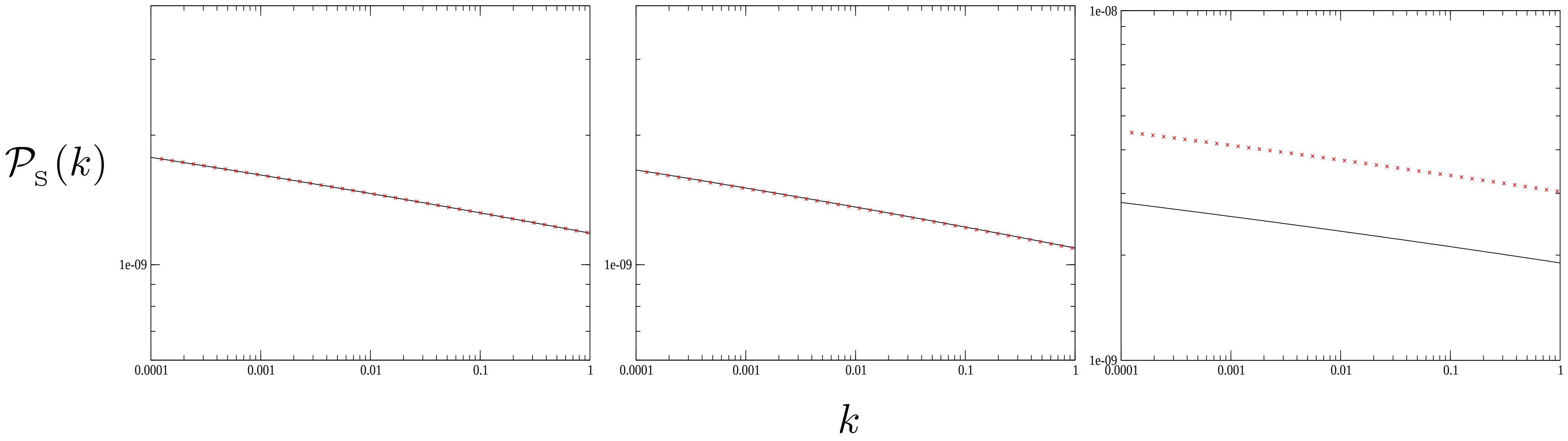
Evolution of the large scale curvature perturbations

Evolution of the curvature perturbations during reheating



The evolution of the curvature perturbation $\mathcal{R}_k$ for a typical cosmological mode has been plotted as a function of the number of e-folds N for the three different cases of Γ. Note that while reheating does not affect the amplitude of the curvature perturbation when Γ is a constant or a function of the inflaton, the amplitude of the curvature perturbation is altered when the decay rate explicitly depends on time.

The scalar spectrum before and after reheating[a].



The scalar power spectrum $\mathcal{P}_{\rm S}(k)$ has been plotted as a function of the wavenumber k before and after reheating in the three different possibilities discussed earlier.

[a] R. K. Jain, P. Chingangbam and L. Sriramkumar, In preparation.

Reheating in tachyonic inflation

Evolution of the background

Tachyon interacting with a perfect fluid

Let us now consider the system of a tachyon (which we shall denote as T) that is interacting with a perfect fluid.

We shall assume that the rate at which the energy density is transferred to the perfect fluid, viz. $Q_{_F}$, is given by $Q_{_F} = (\Gamma\ \dot{T}^2\,\rho_{_T})$, where $\rho_{_T}$ is the energy density of the tachyon[a]. In such a case, $\rho_{_T}$ satisfies the continuity equation

$$\dot{\rho}_{_T} + 3\,H\ (\rho_{_T} + p_{_T}) = -\left(\Gamma\,\dot{T}^2\,\rho_{_T}\right),$$

where $p_{_T}$ is the pressure associated with the tachyon.

Given a potential $V(T)$ describing the tachyon, the corresponding energy density $\rho_{_T}$ and pressure $p_{_T}$ are given by

$$\rho_{_T} = \left(V(T)/\sqrt{1-\dot{T}^2}\right) \qquad \text{and} \qquad p_{_T} = -V(T)\,\sqrt{1-\dot{T}^2}.$$

On substituting these two expressions in the above continuity equation, we arrive at the following equation of motion for the tachyon[b]:

$$[\ddot{T}/(1-\dot{T}^2)] + 3\,H\,\dot{T} + \Gamma\,\dot{T} + (V_{_T}/V) = 0, \quad \text{where} \quad V_{_T} \equiv (\mathrm{d}V/\mathrm{d}T)\,.$$

[a] V. H. Cardenas, Phys. Rev. D **73**, 103512 (2006).

[b] R. Herrera, S. del Campo and C. Campuzano, JCAP **0610**, 009 (2006).

The tachyonic potentials

We shall consider the following tachyonic potential to describe the inflaton[a]:

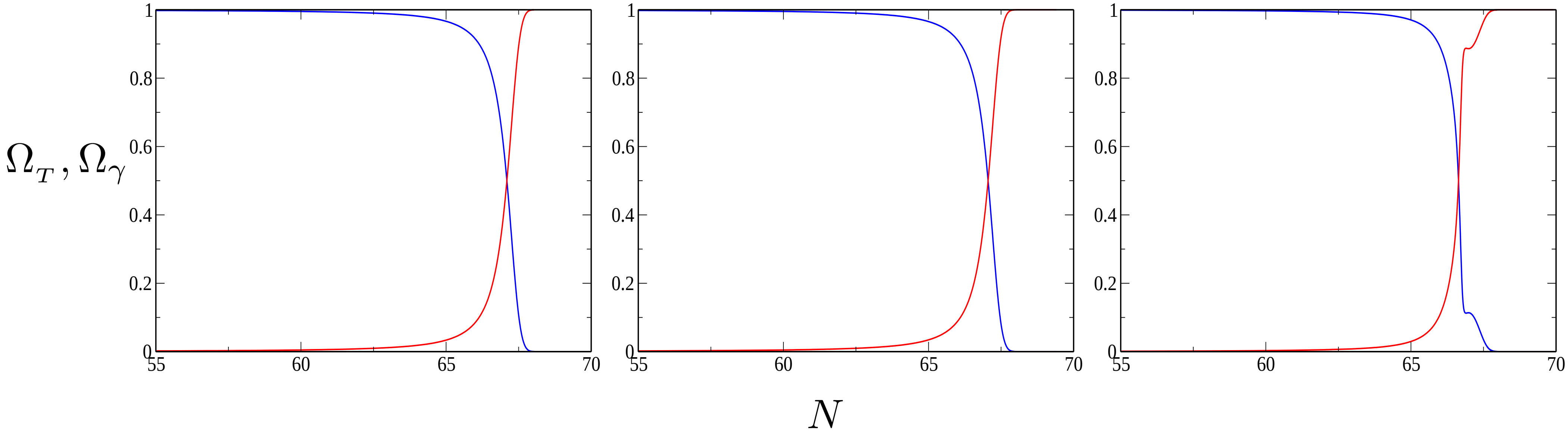
$$V(T) = \left(\frac{\lambda}{\cosh\left(T/T_{_0}\right)}\right).$$

In order to achieve the necessary amount of inflation and the correct amplitude for the scalar perturbations, suitable values for the two parameters λ and $T_{_0}$ that describe the above potentials can be arrived at as follows:

- ✦ Firstly, one finds that, in these potentials, inflation typically occurs around $T \simeq T_{_0}$ corresponding to an energy scale of about $\lambda^{1/4}$.
- ✦ Secondly, it turns out that, the quantity $(\lambda\, T_{_0}^2/M_{_{\rm Pl}}^2)$ has to be much larger than unity for the potential slow roll parameters to be small and thereby ensure that, at least, 60 e-folds of inflation takes place. The COBE normalization condition for the scalar perturbations essentially constrains the value of λ. We shall then choose a sufficiently large value of $(\lambda\, T_{_0}^2/M_{_{\rm Pl}}^2)$, thereby determining the value of $T_{_0}$.

[a] A. Sen, JHEP **04**, 048 (2002); JHEP **07**, 065 (2002); D. A. Steer and F. Vernizzi, Phys. Rev. D **70**, 043527 (2004).

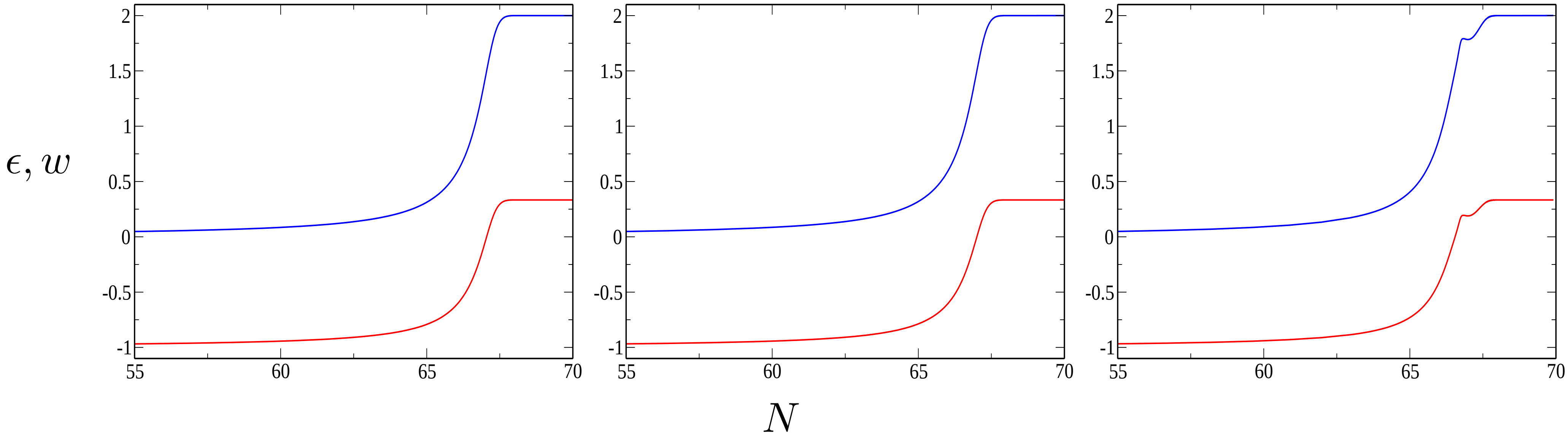
Transfer of energy from the tachyon to radiation



The evolution of the quantities $\Omega_T = (\rho_T/\rho)$ (in blue) and $\Omega_\gamma = (\rho_\gamma/\rho)$ (in red) have been plotted (on the left) as a function of the number of e-folds N for the following three cases: (i) $\Gamma =$ constant (on the left), (ii) $\Gamma(T)$ (in the middle), and (iii) $\Gamma(t)$ (on the right).

Broadly, the transition from tachyon driven inflation to the radiation dominated epoch occurs as in the case of the canonical scalar field.

The first slow roll parameter and the effective equation of state



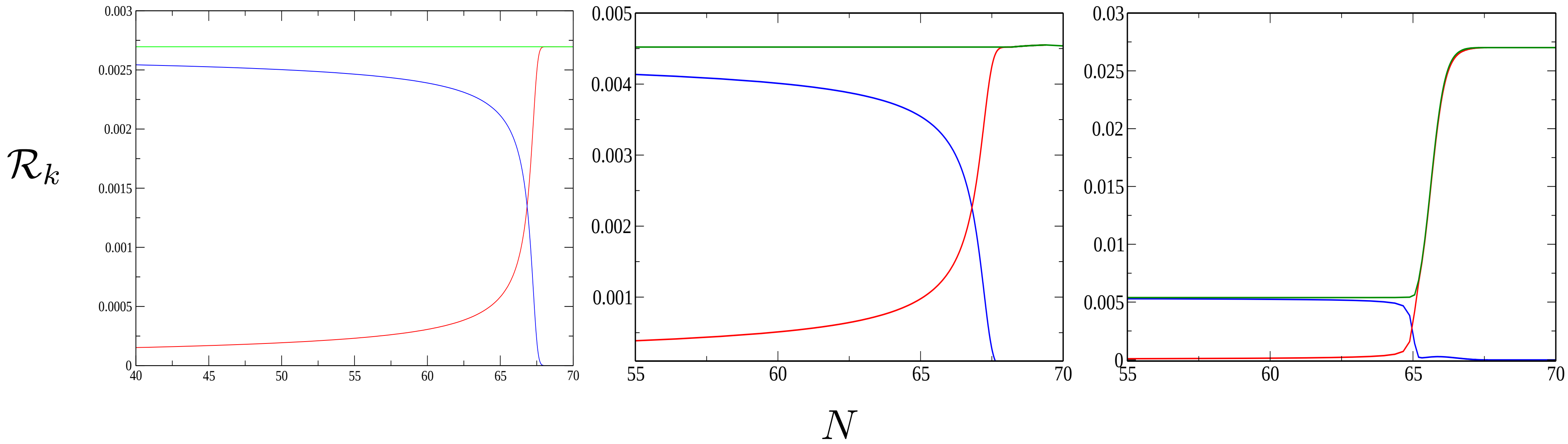
The evolution of the first slow roll parameter $\epsilon = -(\dot{H}/H^2)$ (in blue) and the effective equation of state $w = (p/\rho)$ (in red) have been plotted as a function of the number of e-folds N for the three different cases of Γ considered in the previous figure.

When the coupling to radiation is absent, at the end of tachyonic inflation, typically, there arises a regime wherein $w = 0$. There was a concern that, at the end of tachyonic inflation, caustics may form thereby prolonging an epoch of a 'matter dominated' regime[a]. Evidently, explicitly coupling to radiation resolves such a problem.

[a] G. Felder, L. Kofman and A. Starobinsky, JHEP **0209**, 026 (2002).

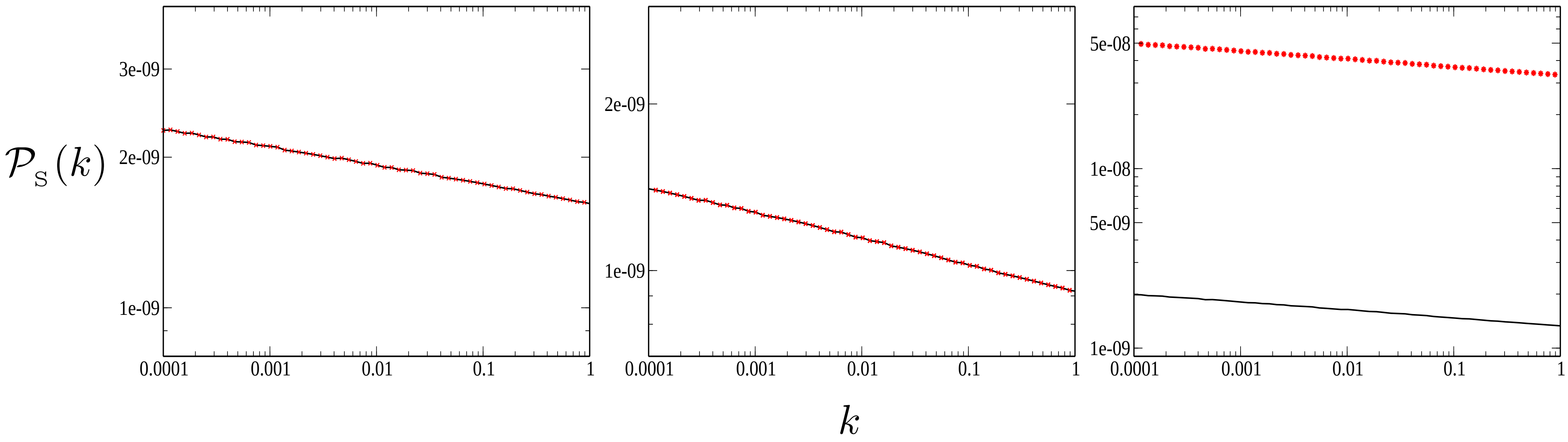
Effects on large scale perturbations

Evolution of the curvature perturbations during reheating



The evolution of the curvature perturbation $\mathcal{R}_k$ for a typical cosmological mode has been plotted as a function of the number of e-folds N for the three different possibilities of the decay rate Γ.

The scalar spectrum before and after the transition[a]



The scalar power spectrum $\mathcal{P}_{\rm S}(k)$ has been plotted as a function of the wavenumber k before and after reheating for the three cases of Γ discussed earlier.

[a] R. K. Jain, P. Chingangbam and L. Sriramkumar, In preparation.

5 Prospects

Proliferation of inflationary models[a]

- 5-dimensional assisted inflation
- anisotropic brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic hybrid inflation
- chaotic inflation
- chaotic new inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation
- F-term inflation
- F-term hybrid inflation
- false vacuum inflation
- false vacuum chaotic inflation
- fast-roll inflation
- first order inflation
- gauged inflation
- generalised inflation
- generalized assisted inflation
- generalized slow-roll inflation
- gravity driven inflation
- Hagedorn inflation
- higher-curvature inflation
- hybrid inflation
- hyperextended inflation
- induced gravity inflation
- induced gravity open inflation
- intermediate inflation
- inverted hybrid inflation
- isocurvature inflation
- K inflation
- kinetic inflation
- lambda inflation
- large field inflation
- late D-term inflation
- late-time mild inflation
- low-scale inflation
- low-scale supergravity inflation
- M-theory inflation
- mass inflation
- massive chaotic inflation
- moduli inflation
- multi-scalar inflation
- multiple inflation
- multiple-field slow-roll inflation
- multiple-stage inflation
- natural inflation
- natural Chaotic inflation
- natural double inflation
- natural supergravity inflation
- new inflation
- next-to-minimal supersymmetric hybrid inflation
- non-commutative inflation
- non-slow-roll inflation
- nonminimal chaotic inflation
- old inflation
- open hybrid inflation
- open inflation
- oscillating inflation
- polynomial chaotic inflation
- polynomial hybrid inflation
- power-law inflation
- pre-Big-Bang inflation
- primary inflation
- primordial inflation
- quasi-open inflation
- quintessential inflation
- R-invariant topological inflation
- rapid asymmetric inflation
- running inflation
- scalar-tensor gravity inflation
- scalar-tensor stochastic inflation
- Seiberg-Witten inflation
- single-bubble open inflation
- spinodal inflation
- stable starobinsky-type inflation
- steady-state eternal inflation
- steep inflation
- stochastic inflation
- string-forming open inflation
- successful D-term inflation
- supergravity inflation
- supernatural inflation
- superstring inflation
- supersymmetric hybrid inflation
- supersymmetric inflation
- supersymmetric topological inflation
- supersymmetric new inflation
- synergistic warm inflation
- TeV-scale hybrid inflation

A (partial?) list of ever-increasing number of inflationary models. Actually, it may not even be possible to rule out some of these models!

[a] From E. P. S. Shellard, *The future of cosmology: Observational and computational prospects*, in *The Future of Theoretical Physics and Cosmology*, Eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge University Press, Cambridge, England, 2003).

Features and non-Gaussianities

- Recent re-analysis of the three year WMAP data seems to indicate sufficiently large non-Gaussianities with $26.91 < f_{\rm NL} < 146.71$ at 95% confidence level with a central value of $f_{\rm NL} = 86.8$[a].

- If forthcoming missions such as PLANCK indeed confirm such a large level of non-Gaussianity, then it can result in a substantial tightening in the constraints on the various inflationary models. For example, canonical scalar field models that lead to a nearly scale invariant primordial spectrum contain only a small amount of non-Gaussianity and, hence, may cease to be viable[b].

- However, it is known that primordial spectra with features can lead to reasonably large non-Gaussianities[c]. Therefore, if non-Gaussianity indeed proves to be large, then either one has to reconcile with the fact that the primordial spectrum contains features or one has to take non-canonical scalar field models such as, say, D brane inflation models, seriously[d].

[a] A. P. S. Yadav and B. D. Wandelt, Phys. Rev. Letts. **100**, 181301 (2008).
[b] J. Maldacena, JHEP **05**, 013 (2003).
[c] See, for instance, X. Chen, R. Easther and E. A. Lim, JCAP **0706**, 023 (2007).
[d] See, for example, X. Chen, M.-x. Huang, S. Kachru and G. Shiu, JCAP **0701**, 002 (2007).

Post-inflationary dynamics

At present, the analysis of post-inflationary dynamics is highly model dependent. Needless to add, a model independent approach is called for.

The issues that need to be addressed in this context include:

- ✦ The extent to which the scalar amplitude can be enhanced after inflation
- ✦ The possibility of suppressing the tensor-to-scalar ratio post-inflation[a]
- ✦ Do post-inflationary dynamics introduce non-Gaussianities[b]?

[a] See, for instance, A. Linde, V. Mukhanov and M. Sasaki, JCAP **0510**, 002 (2005).

[b] See, for example, A. Silvestri and M. Trodden, arXiv:0811.2716.

Thank you for your attention