Dark Radiation and Inflationary Freedom

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in collaboration with **E. Di Valentino, M. Gerbino, E. Giusarma**

Abstract

A non-standard primordial power spectrum (PPS) of scalar fluctuations is motivated by the existence of deviations, observed in the CMB spectrum at low multipoles, from the simple power-law PPS. We show that a non-standard PPS can partially compensate the effects of non-standard properties of dark radiation. We study the possible degeneracies of a non-standard PPS with the neutrino masses and the effective number of relativistic species. If we include only the observed temperature auto-correlation spectrum, the limits on the additional parameters are less constraining when a free PPS is adopted. The inclusion of the polarization spectra measured by Planck helps to reduce noticeably the degeneracies and the obtained results typically show no deviations from the ΛCDM model with a standard power-law PPS.

Based on [Di Valentino et al., 2015].

Introduction

One of the main assumptions about the early Universe in the cosmological analysis is the power-law form of the Primordial Power Spectrum (PPS), that is predicted by the simplest models of inflation. Deviations from the simplest inflationary model can in principle lead to different shapes of the PPS with respect to the power-law form. Any cosmological analysis performed assuming a power-law PPS can in principle result in biased constraints.

We study how the freedom in the PPS form can affect the limits on the cosmological parameters, with particular interest on the bounds on the presence in the early Universe of additional dark radiation, such as axions [not treated here, see Di Valentino et al., 2015] or neutrinos.

Experimental data

We consider the following experimental data:

- CMB, from Planck 2015: temperature data plus polarization at low-ℓ (***Planck TT+lowP***) or full temperature and polarization data (***Planck TT,TE,EE+lowP***);
- Large Scale Structures: the matter power spectrum (***MPkW***) at different redshifts from the WiggleZ Dark Energy Survey.

PPS Parameterization

In this work we follow [Gariazzo et al., 2015a] and we parametrize the free PPS of scalar perturbations with a “piecewise cubic Hermite interpolating polynomial” or `PCHIP` [Fritsch and Carlson, 1980], in order to avoid some unwanted oscillating behaviour related to the commonly adopted natural cubic spline function.

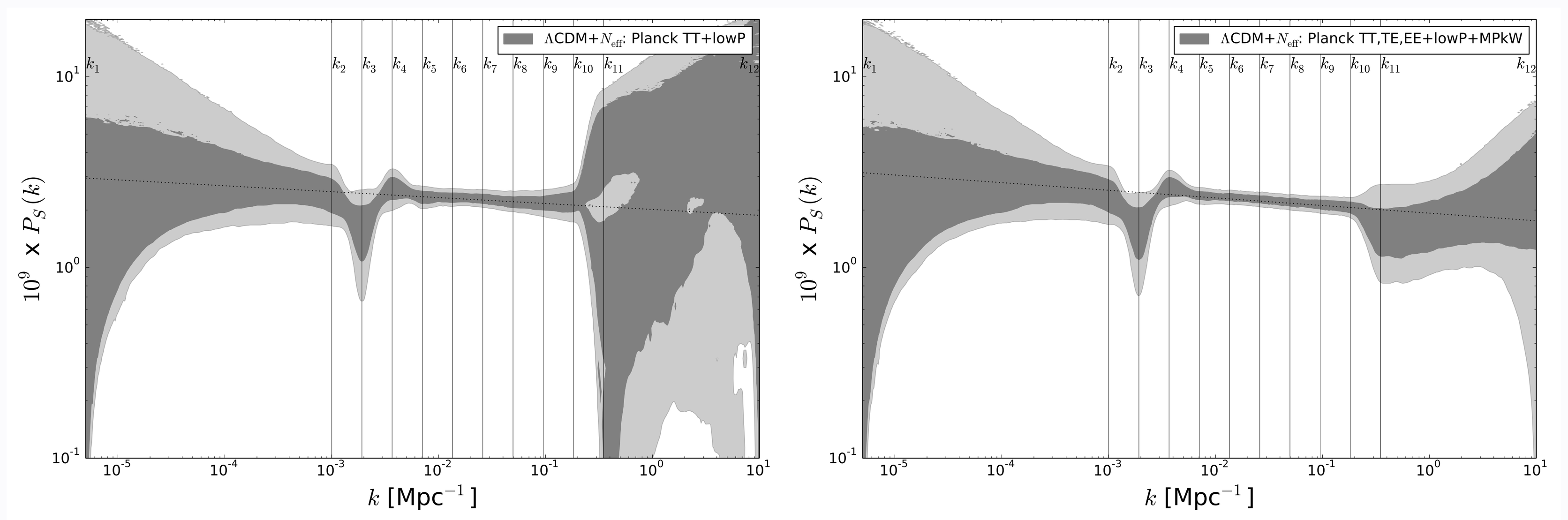
The PPS of scalar perturbations is described in this way:

- When we consider the ***power-law (PL)*** PPS, it is described by the usual parameters n_s and $\ln(10^{10}A_s)$, respectively the spectral index and the amplitude.
- To parametrize a ***free*** PPS, we use $N = 12$ nodes to describe the ***`PCHIP`*** function:
  - ten equally spaced nodes in the range ($k_2 = 0.001\,\mathrm{Mpc}^{-1}$, $k_{11} = 0.35\,\mathrm{Mpc}^{-1}$), better constrained from the data;
  - two nodes $k_1 = 5\cdot 10^{-6}\,\mathrm{Mpc}^{-1}$ and $k_{12} = 10\,\mathrm{Mpc}^{-1}$, to parametrize a non-constant behaviour at the outermost wavemodes.

  The spectrum is described by $P_s(k) = P_0 \times \mathtt{PCHIP}(k, P_{s,j})$, where:
  - $P_{s,j} = P_s(k_j)/P_0$
  - $0.01 \leq P_{s,j} \leq 10$,
  - $P_0 = 2.2\cdot 10^{-9}$ (arbitrary).

Results on the PPS

An helpful way to visualize how the `PCHIP` form of the PPS is constrained by data in our model is to plot the marginalized constraints on the PPS shape. These are obtained marginalizing over the obtained PPS for each different value of k independently.



1, 2σ bounds on the constrained PPS compared with the best-fit PL PPS.

The reconstructed PPS can be described in this way:

- the ***least constrained*** nodes are in $k = 5\cdot 10^{-6}\,\mathrm{Mpc}^{-1}$ and $k = 10\,\mathrm{Mpc}^{-1}$;
- nodes from $k \simeq 0.007\,\mathrm{Mpc}^{-1}$ to $k \simeq 0.2\,\mathrm{Mpc}^{-1}$ are the ***best constrained***;
- the `PCHIP` PPS is in ***perfect agreement*** with the PL PPS for $0.007\,\mathrm{Mpc}^{-1} \leq k \leq 0.2\,\mathrm{Mpc}^{-1}$;
- there is a ***small dip*** ($\simeq 2\sigma$) at $k \simeq 0.002\,\mathrm{Mpc}^{-1}$;
- there is a ***small bump*** ($\simeq 1\sigma$) at $k \simeq 0.0035\,\mathrm{Mpc}^{-1}$;
- the addition of Planck high-ℓ polarization and MPkW data tightens significantly the constraints on the PPS at $k > 0.2\,\mathrm{Mpc}^{-1}$.

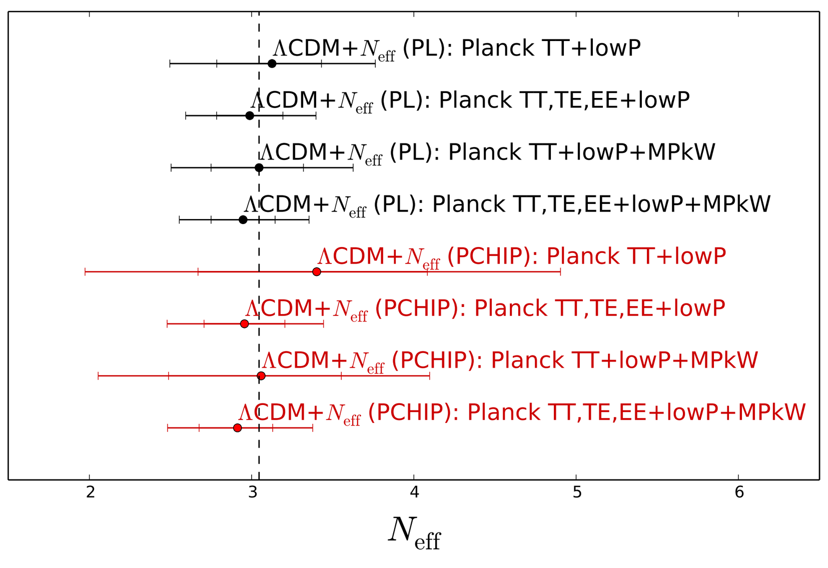
Parametrization

We base our analysis on a flat ΛCDM model, described by:

- $\omega_{\rm cdm} \equiv \Omega_{\rm cdm}h^2$ and $\omega_{\rm b} \equiv \Omega_{\rm b}h^2$, the present-day physical CDM and baryon densities,
- $\theta_{\rm s}$, the angular sound horizon,
- τ, the optical depth to reionization,

To accomodate the presence of dark radiation, we extend this model varying the effective number of relativistic degrees of freedom $N_{\rm eff}$ and the sum of the neutrino masses $\sum m_\nu$.

Results on $N_{\rm eff}$

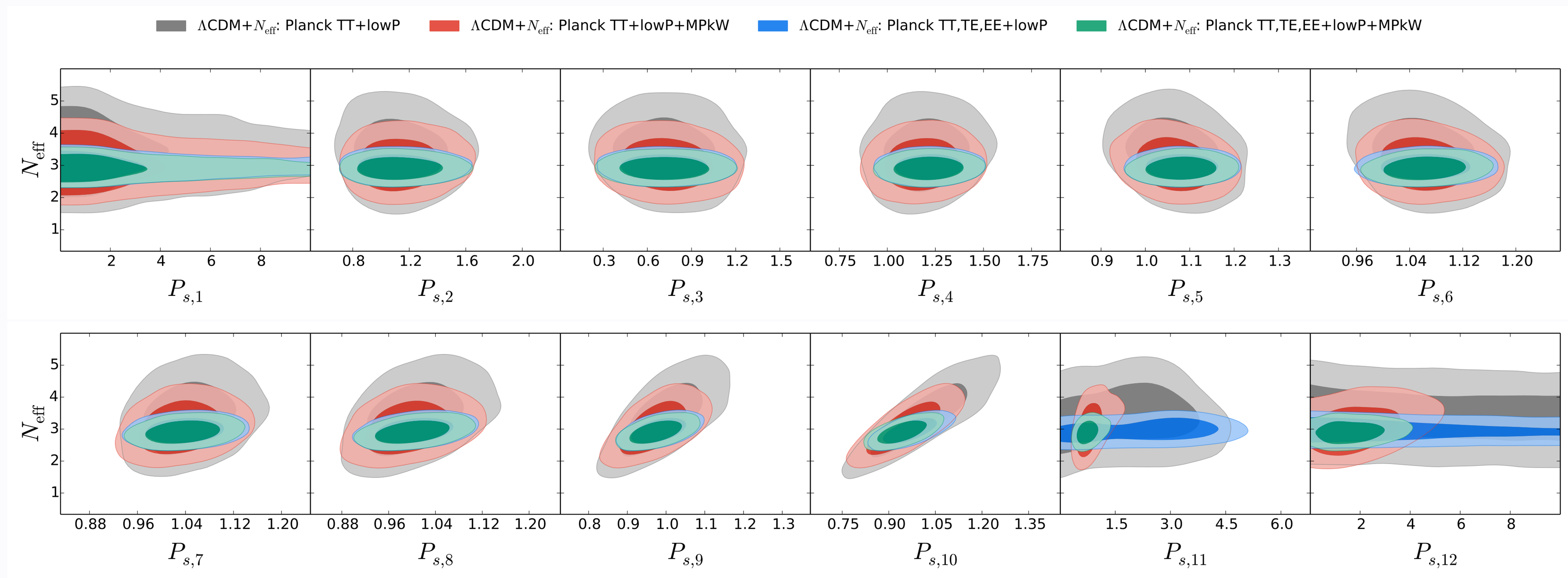


1, 2σ limits for $N_{\rm eff}$.

The strongest degeneracies among the `PCHIP` nodes and a cosmological parameters appear for $N_{\rm eff}$.

- The consequence of increasing $N_{\rm eff}$ with fixed matter-radiation equality and coincidence redshift is an enhancement of the ***diffusion damping*** at small scales [see e.g. Gariazzo et al., 2015b];
- If one modifies the scalar PPS and increases it only at the scales interested by the enhanced diffusion damping and not at the other scales, the effect of the large $N_{\rm eff}$ can be cancelled.

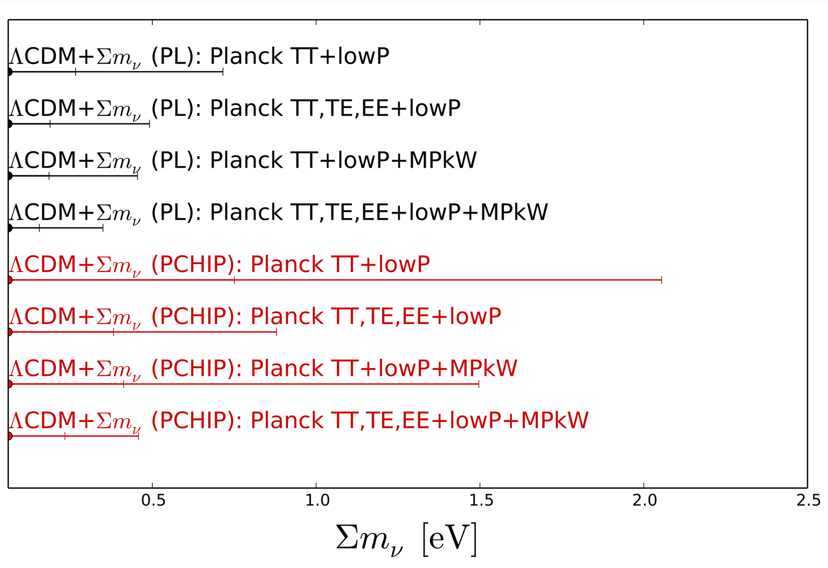
- This is the reason for which the model with the `PCHIP` PPS parameterization, considering Planck TT+lowTEB data only, allows high values of $N_{\rm eff}$:
  - → the PPS freedom allows to modify the small scales without altering the large scales;
  - → a large $N_{\rm eff}$ can be accomodated.
- As we expect, the ***degeneracies*** between $N_{\rm eff}$ and the nodes $P_{s,j}$ are stronger for the nodes at high wavemodes ($P_{s,7}$ to $P_{s,10}$):



Correlations between $N_{\rm eff}$ and the nodes $P_{s,j}$.

The inclusion of the high-ℓ polarization of the CMB prevents this compensation and forces $N_{\rm eff}$ to be very close to the standard value $N_{\rm eff} = 3.046$ also with the free PPS.

Results on $\sum m_\nu$



1, 2σ limits for $\sum m_\nu$.

Cosmology can constrain the absolute scale of neutrino masses:

- the main effect of increasing the neutrino masses is to obtain a change in the ***early and late ISW effects*** [see e.g. Lesgourgues et al., 2013];
  - → only if the other cosmological parameters are changed to fix the angular position of the CMB peaks.
- the freedom in the PPS can compensate the changes in the early and late ISW effects without altering the other scales
  - → marginalized constraints weakened.

- Also in this case the addition of the high-ℓ polarization data takes back the cosmological bounds on $\sum m_\nu$ to values similar to those obtained with the standard PPS.

Conclusions

- Features in the PPS!
- ***Warning***: possible degeneracies between PPS and dark radiation parameters.
- ***Hint***: The CMB polarization helps to break the degeneracies between the parameters
  - → including those related to the PPS.

Forthcoming Research

The natural prosecution of this work would be the analysis of the effects arising from a free parametrization for the PPS of tensor perturbations. We expect that the tensor PPS is weakly constrained by the available data, being the B-mode polarization measured only by BICEP/Keck experiments, with a significant contamination from dust emission.

The determination of the tensor PPS is more important than the determination of the scalar PPS, since it is directly related to the shape of the inflation potential and the energy scales of inflation [see e.g. Baumann and Peiris, 2009, and references therein]. The determination of primordial tensor modes could increase our understanding of the physics that occurs at energy scales we cannot access directly.

Short Bibliography

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