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Particle physics implications of Wilkinson microwave anisotropy project measurements

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Abstract. We present an overview of the implications of the WMAP data for particle physics. The standard parameter set ϵ, η and ξ characterising the inflaton potential can be related to the power-law indices characterising deviation of the CMB spectrum from the scale invariant form. Different classes of inflation potentials are in turn naturally associated with different unified schemes. At present WMAP does not exclude any but a few simple unified models. In particular, hybrid models favoured by supersymmetric unification continue to be viable. However future improvement in data leading to better determination of the 'running' of power-law indices should help to narrow the possibilities for unified models. The main conclusion is that WMAP is consistent with the paradigm of GUT scale (10^{16} GeV) inflation.

Keywords. Cosmic microwave background radiation; inflation; Wilkinson microwave anisotropy project.

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1. Introduction

This review [1] is divided into three sections. In §2 we summarise the nature of experiments that have produced the rich data and the resulting new cosmography. In §3 we review the popular scenarios of inflation and requirements on them [2–4]. We then discuss the parameters characterising inflation and how they can be extracted from the fluctuation data. Section 4 contains a selective review of particle physics implications, mainly the admissible field theoretic models and a study on neutrinos. Section 5 contains conclusions.

2. Cosmos: The main features

Over the past decade several new classes of experiments have together contributed to our knowledge about the universe at the largest observable scale. These consist of the highly automated and extensive surveys of galaxies and their red-shifts, viz., the two-degree-field surveys, the study of large-scale radio sources (the so-called

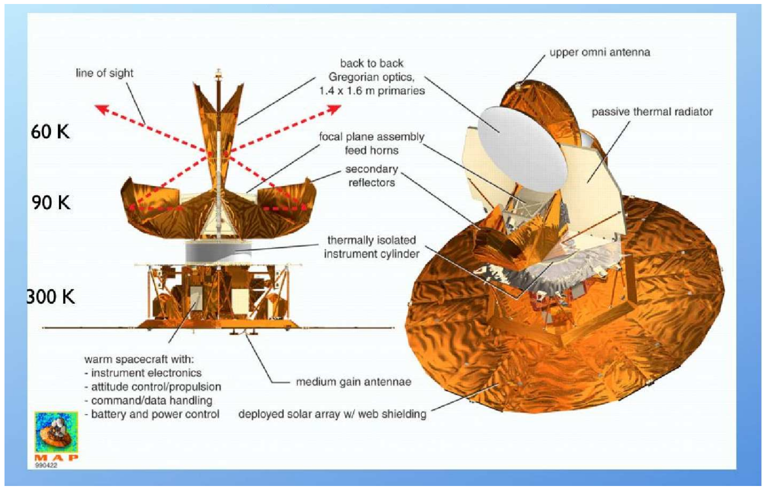

Figure 1. WMAP spacecraft and instrument. Note the chambers at widely different temperatures.

Lyman-α forests), the Hubble key project aimed at calibrating the distance scale, and the many careful observations of the cosmic microwave background (CMB). To these we add the serendipitous discovery of ancient type Ia supernovae from the Hubble data. Here is a rudimentary and very selective list of some of these experiments:

2.1 *Sources of data*

- CMB data
  - WMAP full sky survey
  - Finer scale CMB surveys ACBAR and CBI of restricted regions in the sky
- Fluctuations in matter distribution from large scale structure data (LSS)
  - 2dF galaxy red-shift survey – visible range
  - Lyman-α forest – distribution of intergalactic neutral hydrogen, mostly radio
- Hubble space telescope
  - Hubble key project determination of the Hubble constant
  - Hubble data on Type Ia supernovae (SN Ia)

Figure 1 shows a picture of the WMAP spacecraft and apparatus.

2.1.1 *Homogeneous features*: The few parameters characterising the universe at the largest scale have now been determined to be [5,6]:

Age $= 13.7 \pm 0.2$G yr,

Hubble constant from all CMB data:
$H = 0.71^{+004}_{-0.03} \times 100$ km/s/Mpc

Independently from Hubble key project:
$H_0 = 72 \pm 3$ (stat) ± 7(systematic) km/s/Mpc.
$T_{\rm CMB} = 2.725 \times 10^6\ \mu$K

2.1.2 *CMB inhomogeneity*: Departure from perfect homogeneity gave rise to the formation of galaxies. These fluctuations are also imprinted on the CMB.

WMAP data can be used to determine correlations between CMB temperatures observed from different directions of viewing, say, $\hat{\mathbf{n}}_\mathbf{1}$ and $\hat{\mathbf{n}}_\mathbf{2}$, which are then averaged over all $\hat{\mathbf{n}}_\mathbf{1}$ and $\hat{\mathbf{n}}_\mathbf{2}$.

Figure 2 shows the plot of temperature correlations, a function of $\theta = \arccos \hat{\mathbf{n}}_\mathbf{1} \cdot \hat{\mathbf{n}}_\mathbf{2}$ resolved into spherical harmonics $P_l(\cos\theta)$ as a function of l. Larger l values mean smaller angular scale. The occurrence of the first peak at $l \approx 230$ means that at the time of decoupling from the neutral hydrogen (called the recombination epoch), the photons were correlated over distance scales which now fit within about 1° in the sky. The peak corresponds to the fundamental mode of acoustic oscillations, a length scale comparable to the horizon at that epoch. The other peaks are higher harmonics. Their magnitudes yield additional information about damping processes. Overall amplitude of fluctuations is determined as $(\delta\rho/\rho)^2 \simeq 2.1 \times 10^{-9}$ from $A(k_0)$ for scalar perturbations as defined in [5].

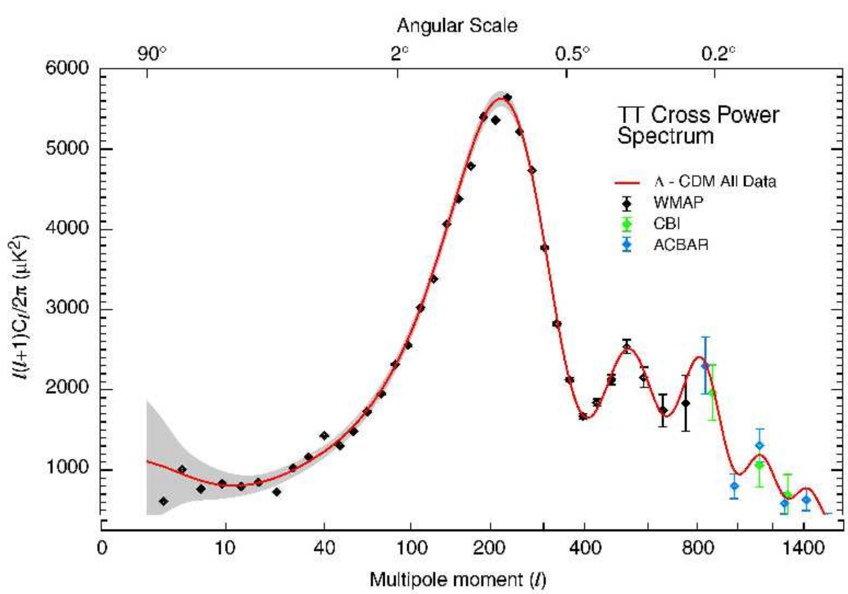

Figure 2. CMB temperature fluctuation spectrum data along with a best-fit Λ-CDM curve.

Detailed knowledge of CMB fluctuations permits determination of the constituents of the primordial energy. When these are combined with SN Ia data, existence of a large contribution from vacuum energy or dark energy is indicated.

Parameterising the energy momentum relation of the dark energy component as $p = w\rho$, the best fit to the CMB + SN Ia data gives the following for the break-up of the total energy density content. Here Ω is $\rho_{\rm total}/(8\pi G/3)$, and other Ωs are appropriately defined [6] as

$$\Omega = 1.02 \pm 0.02,$$
$$\Omega_{\rm matter} = 0.27 \pm 0.04,$$
$$\Omega_{\rm baryon} = 0.044 \pm 0.004,$$
$$\Omega_{\rm DE} = 0.69 \pm 0.06,$$
$$w < -0.78.$$

This leads to two broad paradigms.

1. Λ-CDM (cosmological constant + cold dark matter): Here we assume that the dark energy is simply what Einstein hesitated to add to general relativity, namely a cosmological constant, though with the opposite sign. The cold dark matter accounts for most of the matter content.

2. Quintessence + CDM: Here it is assumed that the dark energy is not a constant contribution but possesses non-trivial dynamics. This is generically referred to as quintessence.

Figure 2 shows the best-fit power law Λ-CDM according to WMAP shown above. It assumes $n_{\rm s} = 0.99 \pm 0.04$, a parameter to be defined below. It also assumed tensor component of the perturbations to be zero, which seems to be borne out by the goodness of the fit.

3. Theories of inflation

3.1 *The need for inflation*

Flatness problem: The intrinsic time-scale of the expansion determined purely from gravity should simply be Planck time-scale, $t_{\rm Pl} \approx 10^{-44}$ s. An explanation for why the universe goes on to live for 1.4×10^{10} yr $\approx 10^{60} t_{\rm Pl}$ could be a fine-tuning of the energy density $\rho(t_{\rm Pl})$ to the expansion rate $(\dot{S}/S)^2(t_{\rm Pl})$. However, the fine-tuning required would be one part in 10^{60}.

Another way of thinking of the problem is that if the universe had finite history our past lightcone should include a small number, $O(1)$, of uncorrelated horizons created close to the Planck time. But there are of the order of ≈ 15000 horizons of even the much later recombination era ($t \approx 10^5$ yr$\gg t_{\rm Pl}$), included in our present horizon. This suggests that the universe has had a *very* long life.

Horizon problem: The ≈ 15000 horizons of the recombination era could not have been in causal communication with each other. However, when observed by us today they all have the same CMB temperature to within a part per million.

There are several other issues that are related to the early history of the universe. One is how did such a homogeneous Universe come to possess the density fluctuations which have now resulted in the formation of galaxies. Another is that typical grand unified theories (GUTs) predict various topological objects such as monopoles and domain walls, whose presence is inconsistent with observed cosmology. One may hope that a fundamental new paradigm addressing the flatness and horizon problems would also provide natural explanation for the fluctuations and for the non-occurrence of harmful relics.

3.2 *The inflation paradigm*

In 1981, Guth proposed a field theoretic solution to the above-mentioned problems and Linde and independently Albrecht and Steinhardt also suggested in 1982 a solution to the problem of fluctuations for galaxy formation in this framework, see [2–4]. The preceding problems can be solved if one assumes that there was an era in the universe when its expansion was unusually rapid. In the simplest model an exponential expansion phase lasting long enough so that the Friedmann–Robertson–Walker scale factor stretched by

$$R(t) = R_0 \mathrm{e}^{H_0(t-t_0)} \approx R_0 \mathrm{e}^{55}. \tag{1}$$

The proposed number of e-foldings would cure the horizon and flatness problems, and inflate away unwanted relics. Further, the quantum dynamics of inflation can ensure residual density perturbations needed for galaxy formation.

Such exponential expansion would be easily possible if the energy density of a field trapped in a false vacuum (i.e. a local minimum) comes to dominate the universe. Further, we shall see below that density perturbations generically arise in such scenarios from vacuum fluctuations of the inflaton field.

3.2.1 *Reheating*: It is required of the inflationary phase to end giving way to a hot universe, at least one that permits Big Bang nucleosynthesis which is very well established. More conservatively, we also expect the universe to heat up to a temperature T_{reheat} sufficient to permit some particle physics mechanism for baryogenesis to operate. i.e., baryon or lepton number violation out of equilibrium must be possible at or below T_{reheat}. This so-called ‘reheat’ temperature depends on the detail of the model and is an observable of the model.

3.3 *Inflation*: *Broad categories*

3.3.1 *The GUT scale or low-field scenario*: This is in the spirit of the ‘new inflation’ where the initial value for the field is at GUT scale, substantially smaller than M_{Pl}, and its potential is in principle known from particle physics. The expectation value is typically small to begin with and grows in the course of inflation.

The potential for such a field is given by

$$V = \Lambda^4 \left(1 - \left(\frac{\phi}{\mu}\right)^p\right) \tag{2}$$

as drawn in figure 3. In a renormalisable theory the power p should be 4.

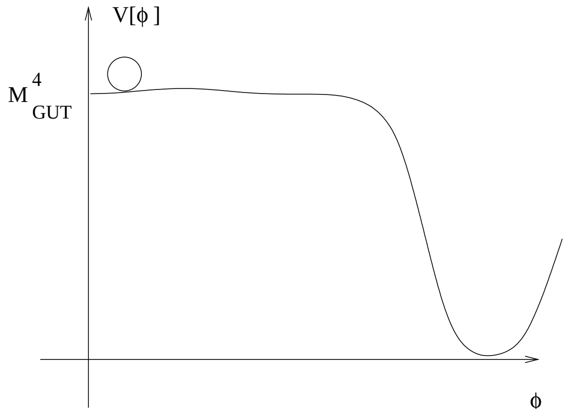

Figure 3. In the low-field scenario the expectation value of the inflaton is small to begin with. The ball shows a possible starting point for the scalar.

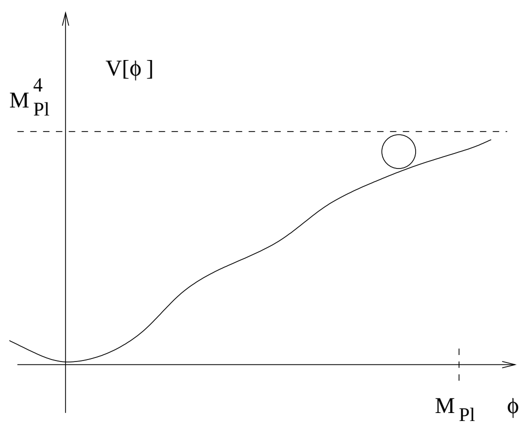

Figure 4. In the high field or chaotic scenario the expectation value of the scalar can be as high as $M_{\rm Pl}$. The ball shows a possible starting point for the scalar.

3.3.2 *Chaotic or 'high field'*: This is a less constrained variant of the 'new inflation', wherein the scalar field is not restricted to be small. It can possess large, random expectation value. Initial fine-tuning is therefore avoided but considerable predictive power is lost since the scalar is not necessarily connected to any known fields.

The form of the potential is assumed to be

$$V = \Lambda^4 \left(\frac{\phi}{\mu} \right)^p \tag{3}$$

and is shown in figure 4.

3.3.3 *The hybrid scenario*: In this case one utilises two fields, ϕ and χ. ϕ possesses a flat potential which is substantially modified when another field χ causes

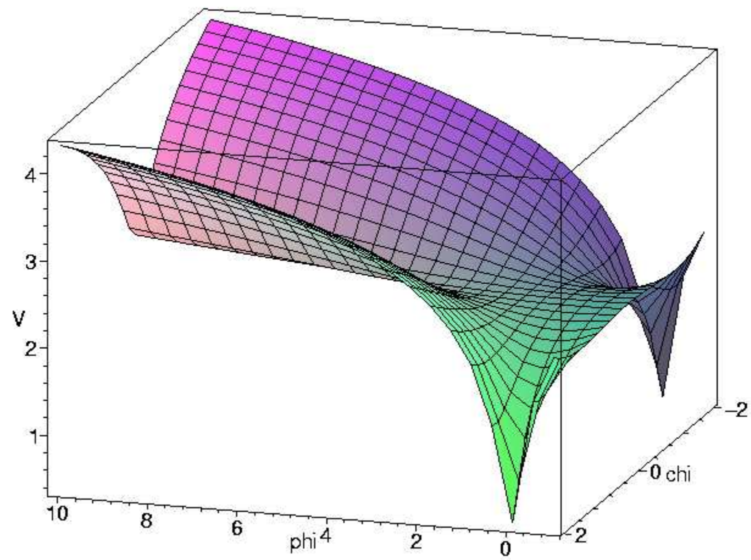

Figure 5. The hybrid scenario with a flat direction of a field ϕ ending abruptly as a function of another field χ (figure courtesy: C Burgess, private communication).

a phase transition. This ensures both, a slow roll through high vacuum energy region and also a predictable exit. This is depicted in figure 5. Such potentials are generic in SUSY theories:

$$V(\chi, \phi) = \kappa^2 \left(M^2 - \frac{\chi^2}{4} \right)^2 + \frac{\lambda^2 \chi^2 \phi^2}{4} + \frac{m^2 \phi^2}{2}. \tag{4}$$

3.4 *Nailing down inflation*

There are generic parameters one can define for any inflationary scenario relying on scalar field vacuum energy. These are known as slow roll parameters. Consider the equation of motion of the condensate of the scalar field in the early universe

$$\ddot{\phi} \ + \ 3H\dot{\phi} \ + \ V'(\phi) \ = \ 0. \tag{5}$$

Neglecting $\ddot{\phi}$ compared to $H\dot{\phi}$ and differentiating again,

$$\frac{\dot{H}}{H^2} \ + \ \frac{\ddot{\phi}}{H\dot{\phi}} \ = \ -\frac{V''}{3H^2}.$$

Define

$$-\epsilon \ - \xi \ = \ -\eta.$$

One requires $\epsilon \ll 1$ to ensure de Sitter-like phase (constant H). $\epsilon = 1$ is taken as the signal for end of inflation. Smallness of δ ensures slow roll, i.e. a substantial duration to the inflationary process. Finally, η the curvature of the potential has to be small so that the acceleration during the rolling motion can be neglected.

3.5 *Inflation*: *Theory*

3.5.1 *Fluctuation*: What does inflation say about fluctuations? Classically there would not be any signature of inflation left; this was the required goal of the paradigm! However quantum mechanically,

$$\delta\phi \equiv \sqrt{\langle(\delta\phi)^2\rangle} = T_{\mathrm{Hawking}} \equiv \frac{H}{2\pi} \tag{6}$$

from which $\delta\rho = V'(\phi)\delta\phi$ can be calculated. The magnitude of perturbation in a given mode is to be evaluated when it leaves the horizon. This magnitude remains constant till the mode reenters.

$$\left(\frac{\delta\rho}{\rho}\right) = \frac{16\sqrt{6\pi}}{5}\ \frac{V^{\frac{3}{2}}}{M_P^3 V'}. \tag{7}$$

The spectrum of perturbations can be calculated by evaluating the above as a function of the scale, with V and V' evaluated for ϕ at corresponding scale.

For models $V(\phi) = \lambda\phi^\nu$, as a function of length scale ℓ,

$$\left(\frac{\delta\rho}{\rho}\right)_\ell = \left(\frac{\delta\rho}{\rho}\right)_0 \left(\frac{N_\ell}{N_0}\right)^{\frac{\nu+2}{4}}, \tag{8}$$

where N_ℓ is the number of e-foldings during which the scale ℓ remained outside the horizon. Using the present horizon $\sim 10^4$ Mpc,

$$\left(\frac{\delta\rho}{\rho}\right)_\ell \approx \left(\frac{\delta\rho}{\rho}\right)_0 \left(\frac{\ell}{2H_0^{-1}}\right)^{\alpha_{\mathrm{s}}} \tag{9}$$

with $\alpha_{\mathrm{s}} = (\nu+2)/4N_0$. Thus with $\nu = 4$, $\alpha_{\mathrm{s}} \approx 0.03$, essentially scale invariant spectrum ($\alpha_{\mathrm{s}} = 1 - n_{\mathrm{s}}$, the index defined earlier in k space).

3.5.2 *Reheating*: As inflaton rolls down to the true minimum vacuum energy is converted to normal particles. Introducing decay constant Γ_ϕ,

$$\dot{\rho} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) = -(3H + \Gamma_\phi)\dot{\phi}^2. \tag{10}$$

This leads to reheat temperature

$$T_{\mathrm{r}} = \left(\frac{45}{16\pi^3 g_*}\right)^{\frac{1}{4}} (\Gamma_\phi M_P)^{\frac{1}{2}}. \tag{11}$$

Thus given the potential function the duration of inflation, slow roll parameters as well the fluctuation observables can be calculated and tested against the data.

3.5.3 *Number of e-foldings*: Finally, inflaton dynamics must ensure correct value (∼55) for

$$N(\phi_i \to \phi_f) \;=\; -\int_{\phi_i}^{\phi_f} \frac{3H^2(\phi)\mathrm{d}\phi}{V'(\phi)}. \tag{12}$$

3.5.4 *Adiabatic vs. isocurvature fluctuations*: Universal formula for fluctuations in a quantity X in an expanding gravity background is $\delta X = \dot{X}\delta t$ where t is the co-moving time. All quantities with such perturbations are called adiabatic; specifically they preserve the relation $p = w\rho$.

Isocurvature perturbations violate this universality condition. They can be characterised by projecting the component that is not of the universal form.

3.5.5 *Curvaton hypothesis*: Dynamics of a single field may be insufficient to produce (1) inflation, (2) correct density perturbations. Thus a 'curvaton' field σ is introduced, characterised by (1) $\rho_\sigma \ll \rho_\gamma$ i.e., insignificant contribution to the curvature itself and (2) $\mathcal{R}_{\mathrm{s}} \approx \delta\rho_\sigma/\rho_\sigma \approx \delta\rho_\gamma/\rho_\gamma$ i.e., significant contribution to fluctuations.

With more than one fields participating in inflation isocurvature perturbations are generic.

3.6 *Inflation confronts WMAP and friends*

3.6.1 *Spectral indices*: Recall again that successful inflation leaves behind no signature ... *by hypothesis*!!

However to next order, it does leave imprints on the density perturbations. These effects can be parameterised in terms of the slow roll parameters and provide information about the potential. The observables, studied as functions of the wavenumber **k** are: (a) scalar perturbations

$$\Delta^2_{\mathcal{R}}(k) \equiv k^3/(2\pi^2)\langle|\mathcal{R}_{\mathbf{k}}|^2\rangle \propto k^{n_{\mathrm{s}}-1}, \tag{13}$$

and (b) tensor perturbations

$$\Delta^2_h(k) \equiv 2k^3/(2\pi^2)\langle|h_{+\mathbf{k}}|^2 + |h_{\times\mathbf{k}}|^2\rangle \propto k^{n_{\mathrm{t}}}. \tag{14}$$

Here $\mathcal{R}$ is the magnitude of curvature perturbation and h_+ and $h_\times$ are the magnitudes of the two polarisations of the tensor perturbations. The values $n_{\mathrm{s}} = 1$ and $n_{\mathrm{t}} = 0$ would signify scale invariance as per Harrison–Zel'dovich conjecture [2–4].

3.6.2 *'Running' indices*: Small deviations from presumed power laws are accommodated by mildly k dependent n_{s} and n_{t}.

$$n_{\mathrm{s}}(k) - 1 \equiv \frac{\mathrm{d}\ln\Delta^2_{\mathcal{R}}}{\mathrm{d}\ln k} = n_{\mathrm{s}}(k_0) - 1 + \frac{\mathrm{d}n_{\mathrm{s}}}{\mathrm{d}\ln k}\ln\left(\frac{k}{k_0}\right), \tag{15}$$

$$n_{\mathrm{t}}(k) \equiv \frac{\mathrm{d}\ln\Delta^2_h}{\mathrm{d}\ln k} = n_{\mathrm{t}}(k_0) + \frac{\mathrm{d}n_{\mathrm{t}}}{\mathrm{d}\ln k}\ln\left(\frac{k}{k_0}\right). \tag{16}$$

Magnitude of the scalar perturbations are parameterised by A at some convenient scale k_0,

$$\Delta^2_{\mathcal{R}}(k_0) = 800\pi^2 \left(\frac{5}{3}\right)^2 \frac{1}{T^2_{\rm CMB}} A(k_0), \tag{17}$$

$$\simeq 2.95 \times 10^{-9} A(k_0). \tag{18}$$

Tensor perturbations are expressed as ratio to scalar ones by

$$r \equiv \frac{\Delta^2_h(k_0)}{\Delta^2_{\mathcal{R}}(k_0)}. \tag{19}$$

Thus there are six observables A, r, $n_{\rm s}$, $n_{\rm t}$, ${\rm d}n_{\rm s}/{\rm d}\ln k$, ${\rm d}n_{\rm t}/{\rm d}\ln k$.

3.6.3 *Relation to inflaton potential*: Using $3H\dot{\phi} + V' = 0$ and $H^2 = M^2_{\rm Pl} V/3$. (here V is the nearly constant value of potential during inflation; $M_{\rm Pl}$ here absorbs 8π factor) the slow roll parameters are expressed as

$$\epsilon \equiv \frac{M^2_{\rm Pl}}{2}\left(\frac{V'}{V}\right)^2, \tag{20}$$

$$\eta \equiv M^2_{\rm Pl}\left(\frac{V''}{V}\right), \tag{21}$$

$$\xi \equiv M^4_{\rm Pl}\left(\frac{V'V'''}{V^2}\right), \tag{22}$$

showing the relation of the parameters to derivatives of the potential. It can then be shown that [7]

$$\Delta^2_{\mathcal{R}} = \frac{V/M^4_{\rm Pl}}{24\pi^2\epsilon}, \tag{23}$$

$$r = 16\epsilon, \tag{24}$$

$$n_{\rm s} - 1 = -6\epsilon + 2\eta = -\frac{3r}{8} + 2\eta, \tag{25}$$

$$n_{\rm t} = -2\epsilon = -\frac{r}{8}, \tag{26}$$

$$\frac{{\rm d}n_{\rm s}}{{\rm d}\ln k} = 16\epsilon\eta - 24\epsilon^2 - 2\xi = r\eta - \frac{3}{32}r^2 - 2\xi \tag{27}$$

$$= -\frac{2}{3}\left[(n_{\rm s}-1)^2 - 4\eta^2\right] - 2\xi, \tag{28}$$

$$\frac{{\rm d}n_{\rm t}}{{\rm d}\ln k} = 4\epsilon\eta - 8\epsilon^2 = \frac{r}{8}\left[(n_{\rm s}-1) + \frac{r}{8}\right]. \tag{29}$$

Given the $V[\phi]$ for any model these can be computed.

3.6.4 *Experimental fits*:

Parameter	Combined WMAP, other CMB +2dFGRS+Lyman-α
n_s ($k_0 = 0.002$ Mpc^{-1})	1.13 ± 0.08
r ($k_0 = 0.002$ Mpc^{-1})	< 0.9; < 0.29 if n_s is assumed < 1
$dn_s/d\ln k$	$-0.055^{+0.028}_{-0.029}$
A ($k_0 = 0.002$ Mpc^{-1})	$0.75^{+0.08}_{-0.09}$

- r is consistent with zero. Hence n_t and its running are ignored.
- The assumption $n_s < 1$ ('red' index; more power at lower k) is favoured by non-hybrid inflation models.
- Above results lead to further conclusion $V^{1/4} < 3.3 \times 10^{16}$ at 95% confidence level.

4. Testing particle physics

4.1 *Predictions from models*

Inflationary potentials of the three varieties discussed above have been explored for the values of the slow roll parameters they predict. They can be plotted on the n_s–r plane which conveniently divides into three regions as shown in figure 6 taken from ref. [9]. At present, reality seems to sit pretty at the juncture of the three classes of scenarios without disfavouring any of them. As pointed out earlier, this is firstly a confirmation of the efficacy of inflation which apparently has not left any easily discernible signature. However it does offer the hope that as the error bars are reduced, it may be possible to distinguish a preferred class of models.

4.2 *Reconstructing potentials*

One can also attempt to reconstruct the inflaton potential from the knowledge of its derivatives as available from the data. Such a study has been carried out in ref. [8]. The results are shown in figure 7.

4.3 $\eta_{\rm baryon}$, *nucleosynthesis (BBN) and WMAP*

CMB spectrum is sensitive to total number of relativistic degrees of freedom, g_*. Increase in g_* means faster expansion and quicker cooling. This means smaller sound horizon at the surface of last scattering, which means shift of the peaks towards larger l.

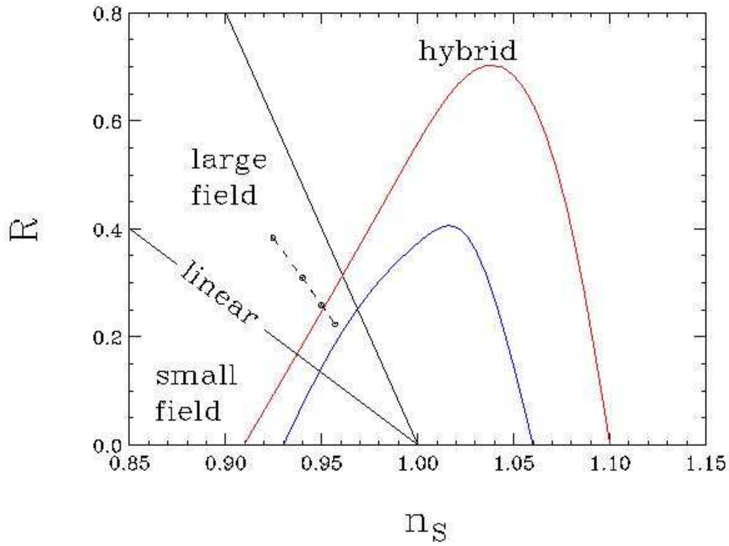

Figure 6. The regions in parameter space consistent with WMAP at 1σ and 3σ confidence levels. Classes of inflationary potential corresponding to different regions are indicated.

BBN process is sensitive to the total number of light degrees of freedom for similar reasons. In particular, the presence of chemical potential μ_e for the electron neutrino tends to deplete neutrons relative to protons, causing problems with formation of sufficient He via D.

Currently, a discrepancy seems to exist between BBN calculations and observed relative abundances. This suggests that the effective number of light neutrinos N_ν was less than the expected 3 from LEP data. Figure 8 from [10] shows the parameter plane of $\Delta N_\nu \equiv N_\nu - 3$, and η_{10} the baryon to entropy ratio scaled by 10^{10}. The preferred region seems to deviate by more than 1σ from $\Delta N_\nu = 0$ but still within 3σ deviation.

This seems to be corroborated by WMAP, although the latter only places a lower bound on ΔN_ν. It is remarkable that two phenomena so widely separated in time and energy scales are in such close agreement.

5. Conclusion

- To the several outstanding puzzles gets added the puzzle of dark energy to be solved by particle physics. It is worth emphasising, a century after special relativity, that the dictionary meanings of the words Aether and quintessence are not very different.
- WMAP essentially confirms inflation, specifically the occurrence of (1) superhorizon fluctuations which are (2) Gaussian.

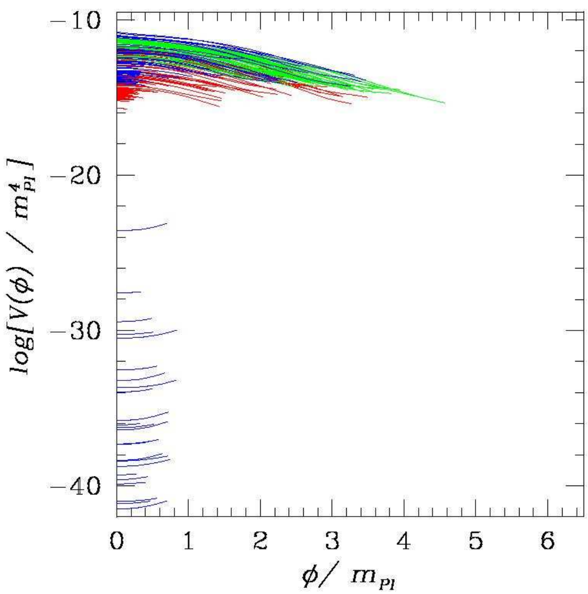

Figure 7. The figure shows many examples of potentials reconstructed from data which include WMAP as well as other CMB experiments. Colours signify class of inflationary models with red representing low field, green the high field and blue the hybrid models.

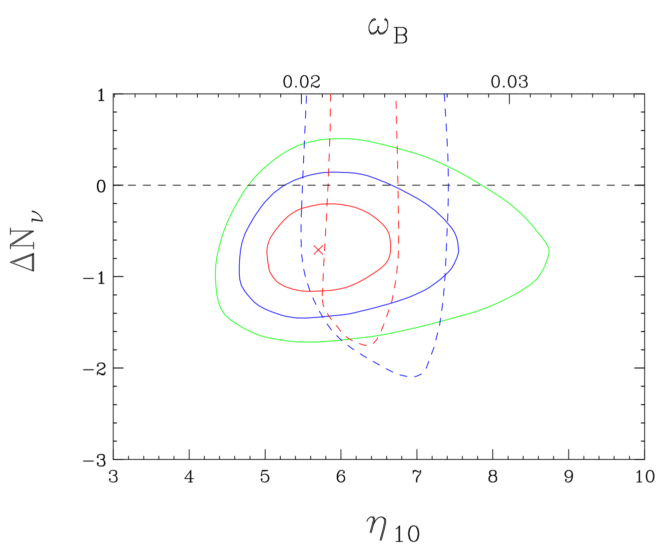

Figure 8. Discrepancy between the expectation (horizontal dashed line) and data for BBN shown as closed curves of 1σ, 2σ and 3σ deviation. WMAP results plotted as the open dashed curves seem to corroborate this deviation

- The models fitted by WMAP to the observed fluctuation spectrum rule out single field $\lambda\phi^4$ inflation at 95% confidence level.
- No isocurvature perturbations are needed to explain the data.
- A large class of inflation models consistent with WMAP observations are identified. At present it is not possible to single out any one among the broad classes of inflationary scenarios.
- However the hybrid scenario (read SUSY) does afford larger parameter space consistent with the 'red' running of the scalar fluctuations mildly suggested by the data index.

5.1 *Outlook*

Further data from WMAP should reduce error bars, while future experiment such as the Planck satellite should give very precise data on the very fine angular scale. Such observations will make more definite determination of fluctuation spectrum parameters such as the scalar and tensor indices and their running. This in turn can narrow down the possibilities for the inflaton potential.

Acknowledgement

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