Do CMB & LSS data require dark energy?

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“Outstanding questions for the standard cosmological model”, London, 26 March 2007
The standard cosmological model

... maximally symmetric, simply connected space-time containing ideal fluids (dust, radiation ...)

\[ ds^2 = a^2(\eta) \left[ d\eta^2 - d\mathbf{x}^2 \right] \]

\[ a^2(\eta) \equiv dt^2 \]

Space-time metric: Robertson-Walker

Dynamics: Einstein

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu} \]

\Rightarrow H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \]

\equiv H_0^2 \left[ \Omega_m (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_\Lambda \right]
The 3-yr WMAP data is said to confirm the ‘power-law ΛCDM model’

Best-fit: $\Omega_m h^2 = 0.13 \pm 0.01$, $\Omega_b h^2 = 0.022 \pm 0.001$, $h = 0.73 \pm 0.05$, $n = 0.95 \pm 0.02$

But the $\chi^2$/dof = 1049/982 $\Rightarrow$ probability of only $\sim$7% that this model is correct!
Observations of large-scale structure too are consistent with the ΛCDM model if the primordial fluctuations are adiabatic and ~scale-invariant (as is apparently “expected in the simplest models of inflation”)

![Graph showing power spectrum](image)

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest
Our present description of matter is an *effective* field theory … valid up to some cutoff energy $\Lambda$

Consider the Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model Lagrangian

$$\mathcal{L}_{\text{eff}} = (\Lambda^4 + \Lambda^2 \Phi^2)$$

Higgs mass correction

$$+ (D\Phi)^2 + \overline{\Psi} \partial \Psi + F^2 + \overline{\Psi} \Psi \Phi + \Phi^4$$

$\overline{\Psi} \Psi \Phi \Phi$ + $\overline{\Psi} \Psi \overline{\Psi} \overline{\Psi}$

$\Lambda$ + $\Lambda^2$ + …

The effects of new physics beyond the SM (neutrino masses, nucleon decay, FCNC …) are suppressed by powers of the cutoff so ‘decouple’ as $\Lambda \to M_P$

But as $\Lambda$ increases, the effects of the $d < 4$ operators are exacerbated!

Solution for 2nd term $\to$ softly broken’ supersymmetry at $\Lambda \sim 1$ TeV ($\Rightarrow \sim 100$ new parameters)

The 1st term couples *only* to gravity – must be cancelled order by order to reduce it from its *minimum* value of $\sim 1$ TeV$^4$ down to cosmologically indicated value - **fine tuning by $\sim 10^{60}$**
The formation of large-scale structure is akin to a scattering experiment

The **Beam**: inflationary density perturbations

No ‘standard model’ – usually *assumed* to be adiabatic and ~scale-invariant

The **Target**: dark matter (+ baryonic matter)

Identity unknown - usually taken to be cold (sub-dominant ‘hot’ component?)

The **Detector**: the universe

Modelled by a ‘simple’ FRW cosmology with parameters $h$, $\Omega_{\text{CDM}}$, $\Omega_b$, $\Omega_\Lambda$, $\Omega_k$ ...

The **Signal**: CMB anisotropy, galaxy clustering ...

measured over scales ranging from ~ 1 – 10000 Mpc ($\Rightarrow$ ~8 e-folds of inflation)

We cannot simultaneously determine the properties of *both* the beam *and* the target with an unknown detector

… hence need to adopt suitable ‘priors’ on $h$, $\Omega_{\text{CDM}}$, etc

in order to break inevitable parameter degeneracies
Astronomers have traditionally assumed a Harrison-Zeldovich spectrum:

\[ P(k) \propto k^n, \quad n = 1 \]

But models of inflation generally predict departures from scale-invariance

In single-field slow-roll models: \( n = 1 + 2V''/V - 3 (V'/V)^2 \)

Since the potential \( V(\Phi) \) steepens towards the end of inflation, there will be a scale-dependent spectral tilt on cosmologically observable scales:

e.g. in model with cubic leading term: \( V(\Phi) \approx V_o - \beta^3 + \ldots \Rightarrow n \approx 1 - 4/N_* \approx 0.94 \)

where \( N_* \approx 50 + \ln \left( k^{-1}/3000h^{-1}\text{Mpc} \right) \) is the # of e-folds from the end of inflation

This agrees with the best-fit value power-law index inferred from the WMAP data

In hybrid models, inflation is ended by the ‘waterfall’ field, not due to the steepening of \( V(\Phi) \), so spectrum is generally closer to scale-invariant …

In general there would be many other fields present, whose own dynamics may interrupt the inflaton’s slow-roll evolution (rather than terminate it altogether)

→ can generate features in the spectrum (‘steps’, ‘oscillations’, ‘bumps’ …)
Consider inflation in context of *effective* field theory: $N=1$ SUGRA
(successful description of gauge coupling unification, EW symmetry breaking, ⋅⋅⋅)

The visible sector could be important during inflation if gauge symmetry breaking occurs

Supersymmetric theories contain ‘flat directions’ in field space where the potential vanishes in the limit of unbroken SUSY

This is due to various symmetries and non-renormalisation theorems

Flat directions are lifted by

- SUSY
- Higher dimensional operators $\rho^n/M_P^{n-4}$ which appear after integrating out heavy degrees of freedom

These fields undergo phase transitions *during* inflation, causing the inflaton mass to change

(Adams, Ross & Sarkar 1997)
If this happens as cosmologically interesting scales ‘exit the horizon’ (likely if last phase of inflation did not last much longer than 50 e-folds) then ‘step’ like features with ‘ringing’ can be imprinted on the spectrum.
This is just what is seen by reconstructing the primordial spectrum (using non-parametric methods) assuming $\Lambda$CDM (Shafieloo & Souradeep 2004)

Tochhini-Valentini, Hoffman & Silk (2005)
Fits are all acceptable … but fit parameters change little except for large-scale amplitude.

Measurable in galaxy surveys?

*WMAP* does not require the primordial density perturbation to be scale-free

Hunt & Sarkar (2007)
MCMC likelihood distributions for $\Lambda$CDM (‘step’ spectrum) … not too different from ‘power law $\Lambda$CDM’

Hunt & Sarkar (2007)
Since there are many flat direction fields, two phase transitions may occur in quick succession, creating a ‘bump’ in the primordial spectrum on cosmologically relevant scales.

The *WMAP* data can then be fitted just as well with *no dark energy* ($\Omega_m = 1$, $\Omega_\Lambda = 0$, $h = 0.46$)
$h = 0.46$ is inconsistent with Hubble Key Project value ($h = 0.72 \pm 0.08$) but is in fact indicated by direct (and much deeper) determinations 

*e.g. gravitational lens time delays ($h = 0.48 \pm 0.03$)*

Best fit E-deS

$\Lambda$CDM model

Low $h$ E-deS

Are we in a void that is expanding $\sim 30\%$ faster than the global rate?
The Lemaitré-Tolman-Bondi model may even explain the SNIa Hubble diagram without acceleration!

$\Lambda \text{CDM}$

Gold dataset

L TB

$\sqrt{\langle \delta^2 \rangle} = 0.34$

Biswas, Mansouri & Notari (2006)
The small-scale power would be excessive unless damped by free-streaming

But adding 3 vs of mass 0.8 eV (⇒Ων≈0.14) gives good match to large-scale structure

(note that Σmν≈2.4 eV – well above ‘WMAP bound’)

Fit gives Ωbh² ≈ 0.021 → BBN √ ⇒ baryon fraction in clusters predicted to be ~11% √
Parameter degeneracies - CHDM universe ('bump' spectrum)

Hunt & Sarkar (2007)
This is $\sim$50\% higher than the ‘WMAP value’ used widely for CDM abundance. To fit the large-scale structure data requires $\sim$eV mass neutrinos. Consistent with data on clusters and weak lensing. Consistent age for the universe.

Hunt & Sarkar (2007)
However in the E-deS model, the ‘baryon acoustic peak’, although at the same *physical* scale, is displaced in observed (redshift) space ...

We *can* match the angular size of the 1st acoustic peak at $z \sim 1100$ by taking $h \sim 0.5$, but we *cannot* then also match the angular size of the baryonic feature at $z \sim 0.35$.

**But for inhomogeneous LTB model** ($h \sim 0.7$ for $z < 0.08$, then $h \rightarrow 0.5$) angular diameter distance @ $z = 0.35$ is similar to $\Lambda$CDM

Biswas, Mansouri, Notari (2006)
Conclusions

*WMAP* data have supposedly confirmed the need for a dominant component of dark energy from precision observations of the CMB.

- But we cannot simultaneously determine *both* the primordial spectrum and the cosmological parameters from just CMB (and LSS) data.

We do not know the physics behind inflation hence cannot just assume that the generated scalar density perturbation is scale-free … and then conclude that the data confirm the power-law ΛCDM model.

The data provides intriguing hints for features in the primordial spectrum … this has crucial implications for parameter extraction e.g. a ‘bump’ in the spectrum allows the data to be well-fitted *without* dark energy!

- Given the unacceptable degree of fine-tuning required to accommodate dark energy, we should explore if the SNIa Hubble diagram, BAO etc can be equally well accounted for in inhomogeneous cosmological models.

*The FRW model may be an oversimplified description of the universe.*