The Politically Incorrect Report on Planck 1st Data Release, March 2013

* cost 5 ~~cent~~/European/year
* Data release: 2 scans out of 5 high freq. and 8 low freq. scans.

  Only TT spectra. No polarization (use WMAP pol.)

  [Show map & TT spectra]

Rest of the talk:

① Perliminaries
② Minimal 6 parameters model
③ ~~The~~ Planck Results
④ Interesting Anomalies
⑤ Inflation.
⑥ Place your bets.

Based on:

① Planck 2013 results XVI, XXII: 1303.5076
1303.5082

② Presentations by Julien Lesgourges & Jo Dunkley

③ Personal bias

Heidelberg KITP

PLANCK DATA

Perliminaries:

① Cosmological Measuremets require a model to compare data to theory

② Even within a model, there are several choices for parameters and parameterization.

③ Once deciding what is the parameterization to be used, one usually still needs to set some a-priori limits on the parameter values for a successful determination.
Also apply several statistical notions:
Priors, marginalization, estimators etc.
Bayesian Analysis vs. Frequentist approach.

④ Combining several probes is rather crucial.

prior - If we allow params. to vary arbitrarily, we cannot ~~get to~~ derive conclusions
⇒ Limit the allowed range a-priori like $0.9 < n_s < 1.1$
danger: The prior might affect the result. We have to make sure it's big enough and reasonable (log prior vs. flat)

<u>Marginalization</u>: The data give a multi-dim. volume. How do we deduce the actual values?

We <u>marginalize</u> over params. i.e. integrate over the probability distribution of $n-1$ (or $n-2$) params. to get the 1-d (2-d) distribution of the desired other params.

After the analysis one gets ML ≡ most likelihood value. Usually this is a marginalized result, but sometimes, params. are fixed by brute force ⇒ Greatly affects the outcome.

<u>Additional params.</u>:

Obviously I can add params. and they will give me a better fit to the data.

Are they true?

⇒ One pays a "penalty" for adding the parameters. To "accept" an additional one the improvement has to be significant enough $\Delta\chi$ test.

<u>Discovery / Ruling out</u>: Let's agree on 3σ ≈ 99.5 %.

The "actual" measurement - Figure 1

One example of a Temp. CMB map.

Minimal 6 parameters cosmological model

Theoretical Background

General Relativity, simple QED

FLRW metric

energy components: photons, electrons, baryons, neutrinos, cold DM, Λ

Table 1

θ_{MC}, Ω_b, Ω_c, n_s, A_s, τ

Derived params. H_0, $\Omega_\Lambda \equiv 1-\Omega_m$, σ_8, ...

Additional Extensions: $\frac{dn_s}{d\ln k}$, $\frac{d^2 n_s}{d\ln k^2}$, r, Ω_K, Σm_ν, Y_P, N_{eff}, $m_{\nu,\,sterile}^{eff}$, w_0, w_a, ...

Simplified Friedmann eq:

$$\frac{H^2(z)}{H_0^2} = \Omega_{m0}(1+z)^3 + \Omega_{R0}(1+z)^4 + \Omega_{K0}(1+z)^2 + \Omega_\Lambda$$

Primordial Power spectrum:

$$P_R(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\frac{dn_s}{d\ln k}\ln\frac{k}{k_0} + \frac{1}{6}\frac{d^2 n_s}{d\ln k^2}\left(\ln\left(\frac{k}{k_0}\right)\right)^2 + \dots}$$

$$P_T = A_t \left(\frac{k}{k_0}\right)^{n_t + \frac{1}{2}\frac{dn_t}{d\ln k}\ln\left(\frac{k}{k_0}\right) + \dots}$$

$$r \equiv \frac{P_T(k_0)}{P_S(k_0)} \simeq 16\epsilon \quad ; \text{where} \quad \epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$

$$H_0 = h \times 100 \frac{km}{sec \cdot Mpc}$$

Results

The basic 6 param. model is rather insensitive to foreground modeling & supplementary data sets.

$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2}$

$\theta_* = \frac{r_s(z_*)}{D_A(z_*)} = \frac{\text{sound horizon @ last scattering}}{\text{angular diameter distance}}$

$\Rightarrow$ We actually constrain $\Omega_m h^{3.2} (\Omega_b h^2)^{-0.54} = 0.695 \pm 0.002$

Figure 2: Value of params. & likelihood.

Figure 3: $\Omega_m - H_0 - n_s$

* Deviations from the basic 6 param. model

Several Anomalies:

① Absence of enough power at $20 \leq \ell \leq 40$ $\sim 2-3\sigma$

② Direct H_0 measurement tension.

From Planck + WP + highL $H_0 = 67.3 \pm 1.2 \ \frac{km}{sec\,Mpc}$

From local measurements (Cepheids + SNe or Carnegie)

$H_0 = 74.3 \pm 1.5 \pm 2.1 \ \frac{km}{sec\,Mpc}$

or $H_0 = 73.8 \pm 2.4 \ \frac{km}{sec\,Mpc}$

(3) Tension in the value of Ω_m from SNe vs. Planck.

SNLS ~~predict~~ $\Omega_m = 0.227$

Planck +WP $\Omega_m \simeq 0.315 \pm^{0.016}_{0.018}$

Inflation (Started it all)

Most important: No non-gaussianity has been detected!

$f_{NL}^{local} = 2.7 \pm 5.8$ $\qquad f_{NL}^{slow\text{-}roll} \lesssim 1$

Equilateral $= -42 \pm 75$

Orthogonal $= -25 \pm 39$

Simplest model: $n_s = \text{const}$, no running, no tensors. Strictly speaking, this cannot be. However, if $r \ll 10^{-2}$ and $\frac{dn_s}{d\ln k} \ll 10^{-2}$ then we can just consider A_s, n_s which is the basis of the minimal model.

Now considering the simple models $\frac{dn_s}{d\ln k} \sim (n_s - 1)^2$ so it is below Planck sensitivity while $r > 10^{-2}$ is not

$\Longrightarrow$ The famous $n_s - r$ plot

$\Longrightarrow$ Inflation is still consistent with simple single field models, but not with "vanilla" models such as $V \approx \phi^4$. Also all $V \sim \phi^n$ are getting ruled out gradually.

Running spectral index $\frac{dn_s}{d\ln k}$

In the usual slow-roll hierarchy

$n_s = 1 + 2\eta - 6\varepsilon$ where $\eta = M_p^2 \frac{V''}{V}$

$$\varepsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2$$

where $'$ denotes differentiation w.r.t. the inflaton.
There are generalizations to multifield models, non-canonical kinetic terms, SUGRA, $c_s^2 \neq 1$ etc.

The true quantity is $P(k)$.
Using $P(k) = A\left(\frac{k}{k_s}\right)^{n_s-1}$ is only a parameterization.
In practice, even in slow-roll, $P(k)$ has some additional k dependence. So we go to the next order $\frac{dn_s}{d\ln k}$ which in the slow-roll approx. corresponds to:

$$\frac{dn_s}{d\ln k} = -16\varepsilon\eta + 24\varepsilon^2 + 2\xi^2$$

where $\xi^2 \equiv M_p^4 \frac{V'V'''}{V^2}$ (ξ^2 is <u>not</u> positive definite)

similarly $$\frac{d n_s^2}{d\ln k^2} = -192\varepsilon^3 + 192\varepsilon^2\eta - 32\varepsilon\eta^2 - 24\varepsilon\xi^2 + 2\eta\xi^2 + 2\omega^3$$

$$\omega^3 \equiv M_p^6 \frac{V'^2 V''''}{V^3}$$

Throughout the years WMAP 1 - PLANCK
The data always favoured some non-zero negative running.

Is this statistically significant?
Until now, at most $\sim 2\sigma$ and with not enough Δx.

Planck considers "Running of running", $\frac{d^2 n_s}{d \ln k^2}$ for the first time – consistent with 0.

Important comments:

a. For the first time Planck really manages to take $n_s = 1$ out, even if one adds running, tensors, and general reionization.
Possible caveats: $N_{eff} = 4$ or $Y_{He} \approx 0.3$ bring it back.

b. Considering running, significantly affects the constraint on r.
If we will also allow "running of running" the bound on r will be even weaker.

c. No strong enough evidence for $n_s \neq \text{const}$

d. If running is $O(10^{-2}) \sim n_s - 1$, then the usual slow-roll expression $n_s - 1 = 2\eta - 6\epsilon$ needs to be modified. Similarly if $\frac{d^2 n_s}{d \ln k^2}$ is big enough.
See for example Lyth & Riotto from 1999.
Easther & Peiris 2006.
A better analysis will be to simply give the binned spectrum, and compare models directly.

~~d. If future experiments can measure NG to the level of [illegible], it will be a much more~~

e. Is there a future for NG? probably yes.
It depends on the sensitivity of future experiments and our theoretical ability to disentangle primordial NG from late-time effects.

f. The bound on $r<0.13$ is ~~simply~~ practically the WMAP bound which is the optimal one without polarization data. Expect an improvement of ~~[illegible] if the~~ a factor of ~ 2 if PLANCK lives up to its promises, and manages to measure the polarization according to specifications.

Place your bets:

Even in the final data release, I bet that

1. No NG
2. No r
3. Running, still not significant enough.
4. Still have an endless stream of papers concerning the above three bets.

Conclusions: 1. RTFM!!!

2. Planck has finally removed many degeneracies in cosmological parameters. The basic model is still a good fit, but there are interesting anomalies and important, well-motivated theoretical extensions which are worth pursuing.