Constraining Fundamental Physics with Planck

Constraints on Variations in Fundamental Constants

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On behalf of the Planck collaboration

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Current unification theories predict the existence of additional space-time dimensions, which have observable consequences, including:

- *modifications in the gravitational laws on very large (or very small) scales and space-time*
- *variations of the fundamental constants of nature*

The \( \Lambda \)CDM model assumes the validity of General Relativity on cosmological scales, as well as the physics of the standard model of particle physics.

Besides the claim that the fine structure constant may have been smaller in the past (Webb et al 2001, Murphy et al 2003) drawn from the observations of quasar absorption spectra by the Keck telescope,

all the systems, including the VLT observations of quasar absorption spectra (Srianand et al. 2004, 2007) and observations of molecular absorption lines (Kanekar, Carilli, Langston, Rocha et al 2005), are compatible with no variation.
Observational ways to constrain VFC

- **Comparison of atomic clocks in the laboratory at z=0,** (Rosenband et al. 2008; Cingoz et al. 2008; Peik et al. 2008; Bize et al. 2003)
- **the Oklo phenomenon at a redshift of z~0.14** (Kuroda 1956; Shlyakhter 1976; Damour & Dyson 1996; Fujii et al. 2000a; Gould et al. 2006)
- **Meteorite dating** (Wilkinson 1958; Dyson 1972; Fujii et al. 2000b; Olive et al. 2002),
- **Quasar absorption spectra observation** (Savedo 1956; Webb et al. 2001; Srianand et al. 2004, 2007)
- **Molecular absorption lines** (Carilli et al. 2001; Kanekar,..,Rocha et al. 2005)
- **Clusters of galaxies** (Galli 2013); population III stars, (Livio et al. 1989; Ekstrom et al. 2010, Coc et al 2009)
- **Cosmic microwave background (CMB) anisotropies at z~1000** (Rocha et al. 2004; Martins et al. 2004; Ichikawa et al. 2006; Stefanescu 2007; Scoccola et al. 2008; Nakashima et al. 2008; Menegoni et al. 2009; Menegoni 2010)- these studies typically indicate that, on cosmological scales both fine structure constant and \( m_e \) are constants to percent level
- **Big bang nucleosynthesis at z~10^8** (Bergstrom et al. 1999; Muller et al 2004; Coc et al. 2007, 2012)
Planck Temperature power spectrum: 2013

$D_l = \ell(\ell+1)C_l/2\pi \ [\mu K^2]$  

$\Delta D_l \ [\mu K^2]$  

Multipole $\ell$

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CMB APS and VFC

- CMB APS depends on the time and width of the LSS, i.e. on when and how the photon-electron decoupling happened - this information is encoded in the visibility function - quantifies the probability density that a photon is last scattered at redshift $z$

$$g(\eta) = \tau \exp^{-\tau}$$

$$\sigma_T = \frac{8\pi}{3} \frac{\hbar^2}{m_e^2 c^2} \alpha^2$$

$$x_e = \frac{n_e}{n_e + n_H}$$

Thomson scattering cross section  

Free electron fraction

$$\frac{dx_e}{dt} = C_H \left[ \beta_H (1 - x_e) e^{\frac{B_1 - B_2}{K_B T}} - R_H n_p x_e^2 \right]$$

$$\alpha_0 = \frac{e^2}{\hbar c} \approx \frac{1}{137.035999}$$

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Evolution of $x_e$ with time

A variation of $\alpha$ induces:

- Modification of the recombination rates
- Changes in the way light and atoms interact by changing the energy levels and the binding energy of Hydrogen and Helium
- The Thomson Scattering cross section

For a larger $\alpha$ recombination takes place at larger redshift i.e. at earlier times

These modifications are implemented in RECFAST


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Varying $\alpha$ and the CMB APS

The lines refer to variations of -5% (blue) and +5% (red), while the standard case is shown in black.

For $\alpha/\alpha_0 > 1$

- sound horizon at recombination is smaller, and the angular diameter distance to the LSS is larger -> peaks shifts to larger multipoles (smaller angular scales)
  
  (degeneracy with $H_0$)

- larger redshift at LS increases the amplitude of the peaks at small scales due to a decrease of the Silk damping

- Larger early ISW effect -> larger amplitude of the first peak

...
Varying $\alpha$ and the CMB APS

The lines refer to variations of -5% (blue) and +5% (red), while the standard case is shown in black.
Conclusion → Planck will be able to constrain variations of $\alpha$ at the epoch of decoupling within 0.34% (1$\sigma$, all other parameters marginalized), approx. a factor 5 improvement on the current upper bound.

Compare to the actual constraints we get from Planck in the next few slides


CMB alone can only constrain variations of $\alpha$ up to $O(10^{-3})$ at $z \sim 1100$ while in quasar absorption systems (Webb et al. 2001), $\delta \alpha/\alpha_0 = O(10^{-5})$ at $z \sim 2$.

But variations in $\alpha$ should be larger at higher redshifts.
Extending the standard cosmological model to include $\alpha$, fine structure constant.

We sample 7 LCDM cosmological parameters + 14 nuisance parameters for foreground/instrument parameters to fit the data.
Constraints

\[ \frac{\alpha}{\alpha_0} = 0.9934 \pm 0.0042 \]

Planck gives 0.4% constraint

WMAP gives \( \sim2\% \) constraint on \( \alpha/\alpha_0 \)

Adding other datasets do not improve the constraint substantially. In particular, adding HST does not shrink the error bars significantly.

Why is the constraint so good?
Why is the mean value slightly different from 1?
Why does including HST the value of alpha shifts to larger values?
Degeneracies with other parameters
The observation of the damping tail breaks the degeneracy between $H_0$ and the fine structure constant.
A low fine structure constant?

Is deviation due to the apparent tension between low/high multipoles in Planck data?

Value of $\alpha$ is more consistent with unity when the multipoles at $l<49$ are not used.

The value of $\alpha$ goes from $\alpha/\alpha_0=0.9934\pm0.0042$ to $\alpha/\alpha_0=0.9970\pm0.0054$. 
Extending the constraints from Planck 2013

\( N_{\text{eff}}, Y_p \)

Uncertainty goes up by a factor of 2

\( N_{\text{eff}} \) agrees with standard value

Stronger degeneracy

Constrain of \( \alpha \) at 1% level worse by a factor of 4

\[ \begin{array}{c}
\text{WMAP9} \\
\text{Planck+WP} \\
\text{Planck+WP+highL}
\end{array} \]

\[ \begin{array}{c}
\text{0.950} \\
\text{0.975} \\
\text{1.000} \\
\text{1.025} \\
\text{1.050}
\end{array} \]

\[ \begin{array}{c}
\alpha/\alpha_0
\end{array} \]

\[ \begin{array}{c}
\text{0.32} \\
\text{0.24} \\
\text{0.16}
\end{array} \]

\[ \begin{array}{c}
\text{0.40} \\
\text{0.48}
\end{array} \]

\[ \begin{array}{c}
\text{0.950} \\
\text{0.975} \\
\text{1.000} \\
\text{1.025} \\
\text{1.050}
\end{array} \]

\[ \begin{array}{c}
\alpha/\alpha_0
\end{array} \]

\[ \begin{array}{c}
\end{array} \]
Electron mass, $m_e$

The lines refer to variations of -5% (blue) and +5% (red), while the standard case is shown in black.

$m_e/m_{e0} = 0.95$

$m_e/m_{e0} = 1$

$m_e/m_{e0} = 1.05$
Varying $m_e$ and the CMB APS

The lines refer to variations of -5% (blue) and +5% (red), while the standard case is shown in black.

An increase of $m_e$

- decreases the Thomson scattering cross-section, thus partially compensating for the decrease of the Silk damping length $\lambda_D$ due to the earlier recombination.

For this reason $\alpha$ has a larger impact on the damping tail than $m_e$.

The overall amplitude of the peaks is less affected by a change in $m_e$ than by a change in $\alpha$, due to the different effect on the damping tail.
Varying $m_e$ and the CMB APS

The lines refer to variations of -5% (blue) and +5% (red), while the standard case is shown in black.

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\[ \frac{m_e}{m_{e0}} = 0.977^{+0.055}_{-0.070} \]

No much improvement with respect to WMAP-9 constraints
Including BAO decreases the error by a factor ~ 5
Degeneracies with other parameters

- $H_0$
- $\Omega_b h^2$
- $\Omega_c h^2$
- $n_s$
- $\ln(10^{10} A_s)$
- $\tau$

**Data Sets**
- WMAP9
- Planck+WP+HST
- Planck+WP
- Planck+WP+BAO

**Parameters**
- $m_e/m_{e0}$
- $m_e/m_{e0}$
- $m_e/m_{e0}$
- $m_e/m_{e0}$
- $m_e/m_{e0}$
Spatial variations of $\alpha$

Recent analysis of quasar data have supported the claim that there may exist a dipole in the fine structure constant \textit{(Webb et al. 2011; Berengut et al. 2011; King et al. 2012)}.

Dipolar modulation of $\alpha$ implies mode couplings between the $a_{lm}$

$$c_a(n, z) = c_0 a(z) + \sum_{t=-1}^{1} \delta c_a^{(t)}(z) Y_{11}(n).$$

$$\Theta(n) = \Theta[n, c_a(n)]$$

$$= \Theta \left[ n, c_0 a + \sum_{t=-1}^{1} \delta c_a^{(t)}(z) Y_{11}(n) \right]$$

$$\simeq \Theta[n] + \sum_{a} \sum_{t=-1}^{+1} \frac{\partial \Theta[n]}{\partial c_a} \delta c_a^{(t)}(z) Y_{11}(n)$$

$$\delta c_a^{(t)}$$

three parameters which characterize the amplitude and direction of the modulation develop $l(l+1)$ correlations

$$D^{(i)}_{\ell m} \equiv \langle a_{\ell m} a^{*}_{\ell+1 m+i} \rangle$$

for $i=0,1$

Estimators: heuristic - \textit{Prunet et al (2005)}, optimal - \textit{Hanson & Lewis (2009)}
Spatial variations of $\alpha$

Estimators: heuristic - Prunet et al (2005), optimal - Hanson & Lewis (2009)

\[ a_{\ell m} \sim \bar{a}_{\ell m} \]

\[ + \sum_a \sum_{LM} \sum_i \frac{\partial \bar{a}_{LM}}{\partial c_a} \delta c_a^{(i)} \int d^2 n Y_{\ell m}^*(n) Y_{LM}(n) Y_{11}(n) \]

\[ C_{\ell_1 \ell_1 \ell_2 \ell_2} = \delta_{\ell_1 \ell_2} \delta_{m_1 m_2} C_{\ell_1} + \frac{1}{2} \sum_a \sum_i \delta c_a^{(i)} \left[ \frac{\partial C_{\ell_1}}{\partial c_a} + \frac{\partial C_{\ell_2}}{\partial c_a} \right] \]

\[ \times \int d^2 n Y_{11}(n) Y_{\ell_1 m_1}(n) Y_{\ell_2 m_2}(n). \]

Unnormalised QML takes the form

\[ \tilde{\alpha}_{\ell m}^{(i)} = \sum_a \int d^2 n Y_{11}^*(n) \left[ \sum_{\ell_1 m_1} \Theta_{\ell_1 m_1} Y_{\ell_1 m_1}(n) \right] \times \left[ \sum_{\ell_2 m_2} \frac{1}{2} \frac{\partial C_{\ell_2}}{\partial c_a} \Theta_{\ell_2 m_2} Y_{\ell_2 m_2}(n) \right] \]

Masking - bias the estimator further -> to constrain use 900 CMB MCs at ns=2048+noise+mask
Take into account the mean field in the case of no modulation; renormalize using the modulated MCs and estimate the variance of the estimator from the unmodulated MCs.
Spatial variations of $\alpha$

The field $\langle \delta \alpha \rangle$ and variance $\sigma_{\alpha}^2 = \langle \delta \alpha^2 \rangle - \langle \delta \alpha \rangle^2$ of the amplitude $\delta \alpha$ of the modulation for 900 Planck resolution $\ell_{\text{max}}$ = 600 and $\ell_{\text{max}}$ = 1500. Hanson-Lewis estimator

<table>
<thead>
<tr>
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<th>$\ell_{\text{max}}$ = 600</th>
<th>$\ell_{\text{max}}$ = 1500</th>
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</thead>
<tbody>
<tr>
<td>Variance $\sigma_{\delta \alpha}$</td>
<td>$1.17 \times 10^{-3}$</td>
<td>$2.71 \times 10^{-4}$</td>
</tr>
<tr>
<td>Mean fields $\langle \delta \alpha \rangle$</td>
<td>$2.72 \times 10^{-3}$</td>
<td>$6.29 \times 10^{-4}$</td>
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Summary of the results obtained for the amplitude of the spatial modulation of the fine structure constant $\alpha$ according to the Hanson & Lewis (2009) estimator applied to the Planck data for $\ell_{\text{max}}$ = 600 and $\ell_{\text{max}}$ = 1500. We show

<table>
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<tr>
<th>$\ell_{\text{max}}$ = 600</th>
<th>$\ell_{\text{max}}$ = 1500</th>
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<tbody>
<tr>
<td>$\bar{\alpha}$</td>
<td>$-5.56 \times 10^{-4} \pm 1.17 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{\alpha}^{(0)}$</td>
<td>$4.09 \times 10^{-3} \pm 2.95 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\text{Re}(\bar{\alpha}^{(1)})$</td>
<td>$8.57 \times 10^{-4} \pm 2.70 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\text{Im}(\bar{\alpha}^{(1)})$</td>
<td>$-8.66 \times 10^{-4} \pm 2.61 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$\delta \alpha / \alpha_0 = \left( -2.4 \pm 3.7 \right) \times 10^{-2}$ (68%, $\ell_{\text{max}}$ = 1500)

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Conclusions

- Planck places a constraint on $\alpha$ at the $\sim0.4\%$ level, improving WMAP constraints by a factor 5 as predicted by our Fisher analysis
  - *Improvement comes mainly from observation of the damping tail, which breaks the degeneracy with $H_0$.*
- 1.6 $\sigma$ deviation of $\alpha/\alpha_0$ from unity when considering the Planck+WP case is reduced when the low-l data is removed
  - *this mild deviation is probably coming from the low versus high-l tension*
- Constraint on $\alpha$ weakens by about a factor of 1.5 when $N_{\text{eff}}$ is allowed to float, while it weakens by up to a factor of 4 when the helium abundance, $Y_p$ is allowed to vary,
- Constraint from Planck on $m_e$ is comparable to WMAP-9 data constraint
  - *Planck data combined with BAO provide a constraint on $m_e$ at the 1% level.*
- Dipolar modulation of $\alpha$:
  $$ \frac{\delta \alpha}{\alpha_0} = (-2.4 \pm 3.7) \times 10^{-2} \quad (68\%, l_{\text{max}}=1500) $$
- Expected further improvement from Planck polarization data and from other CMB experiments
- Euclid will improve the Planck constraints on $\alpha/\alpha_0$ by a factor of 2
- CMB alone can only constrain variations of $\alpha$ up to 0.1% at $z\sim1100$
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada. Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.