Constraining Fundamental Physics with Planck

Constraints on Variations in Fundamental Constants

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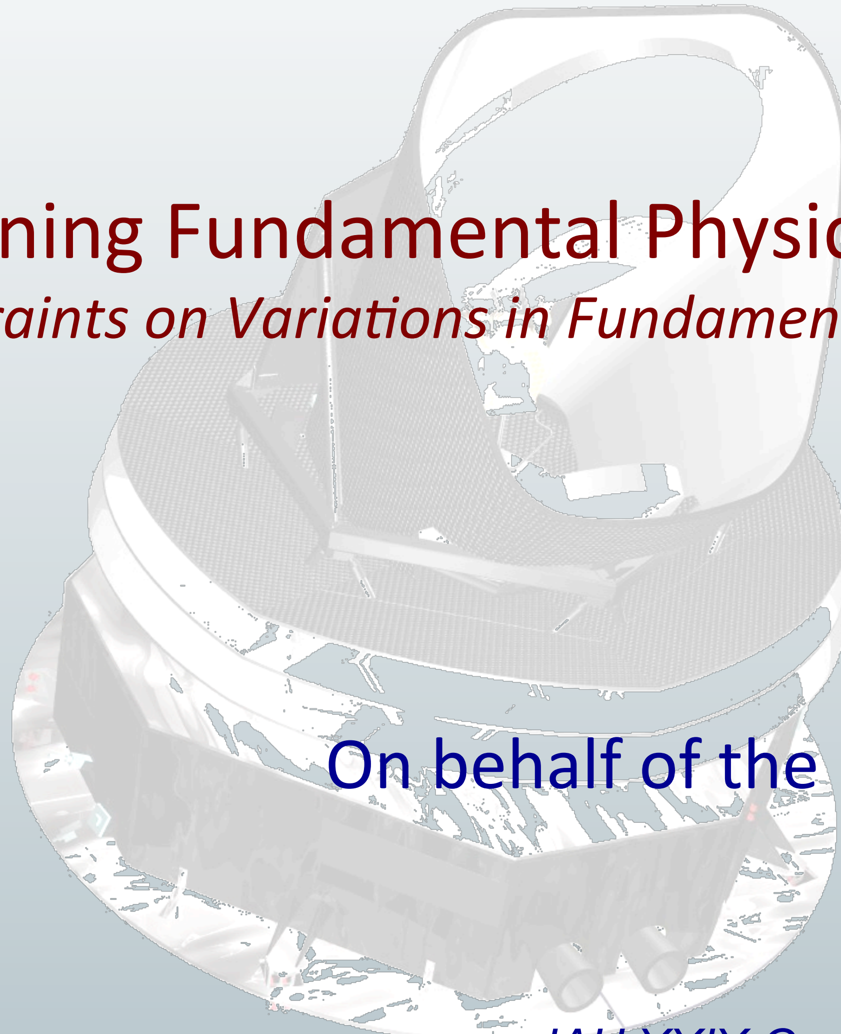
On behalf of the Planck collaboration



IAU XXIX General Assembly Symposia:
The Legacy of Planck, August 2015

Varying Fundamental Constants
Motivation

- 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*

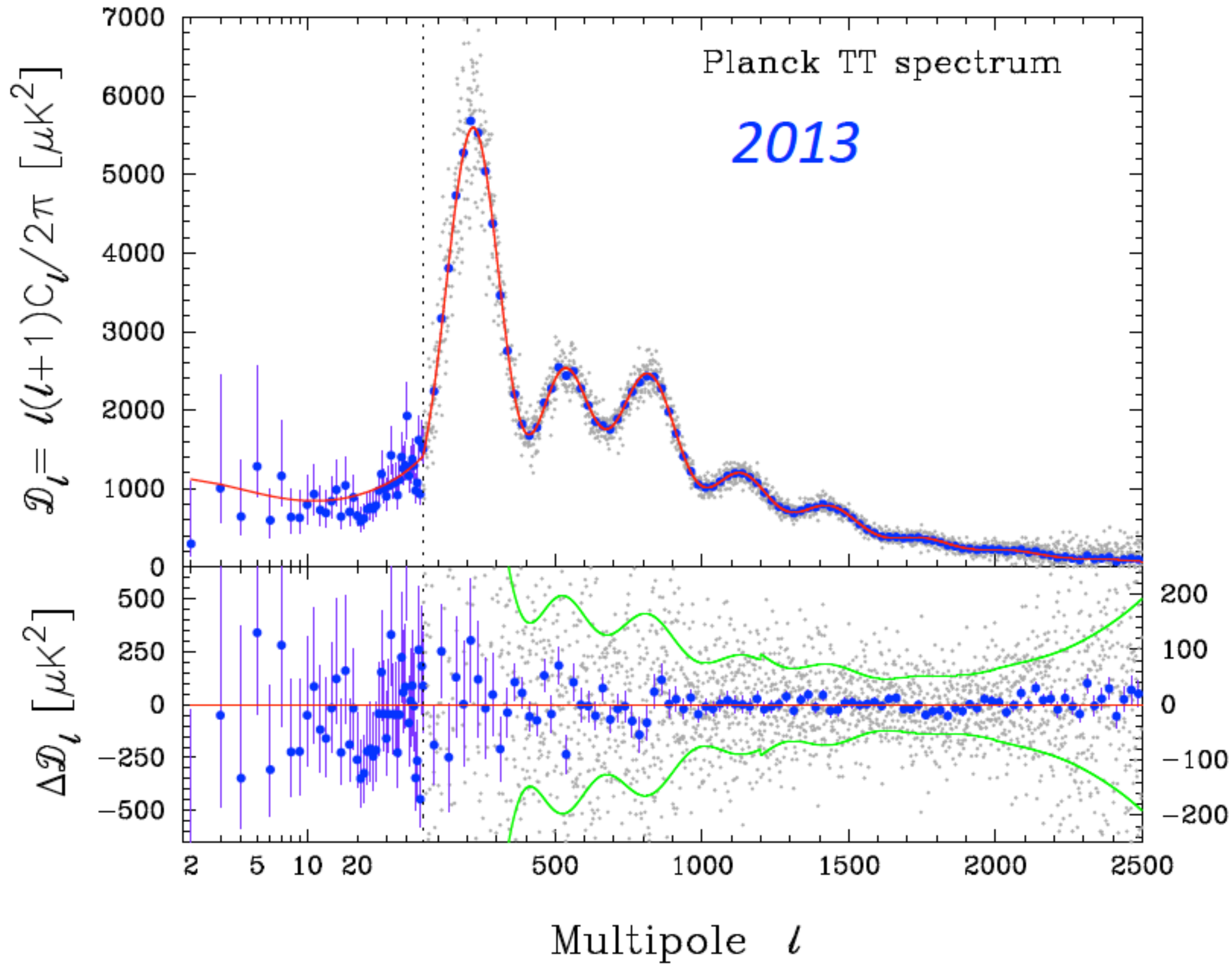
- The ΛCDM model assumes the validity of General Relativity on cosmological scales, as well as the physics of the standard model of particle physics

- 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.

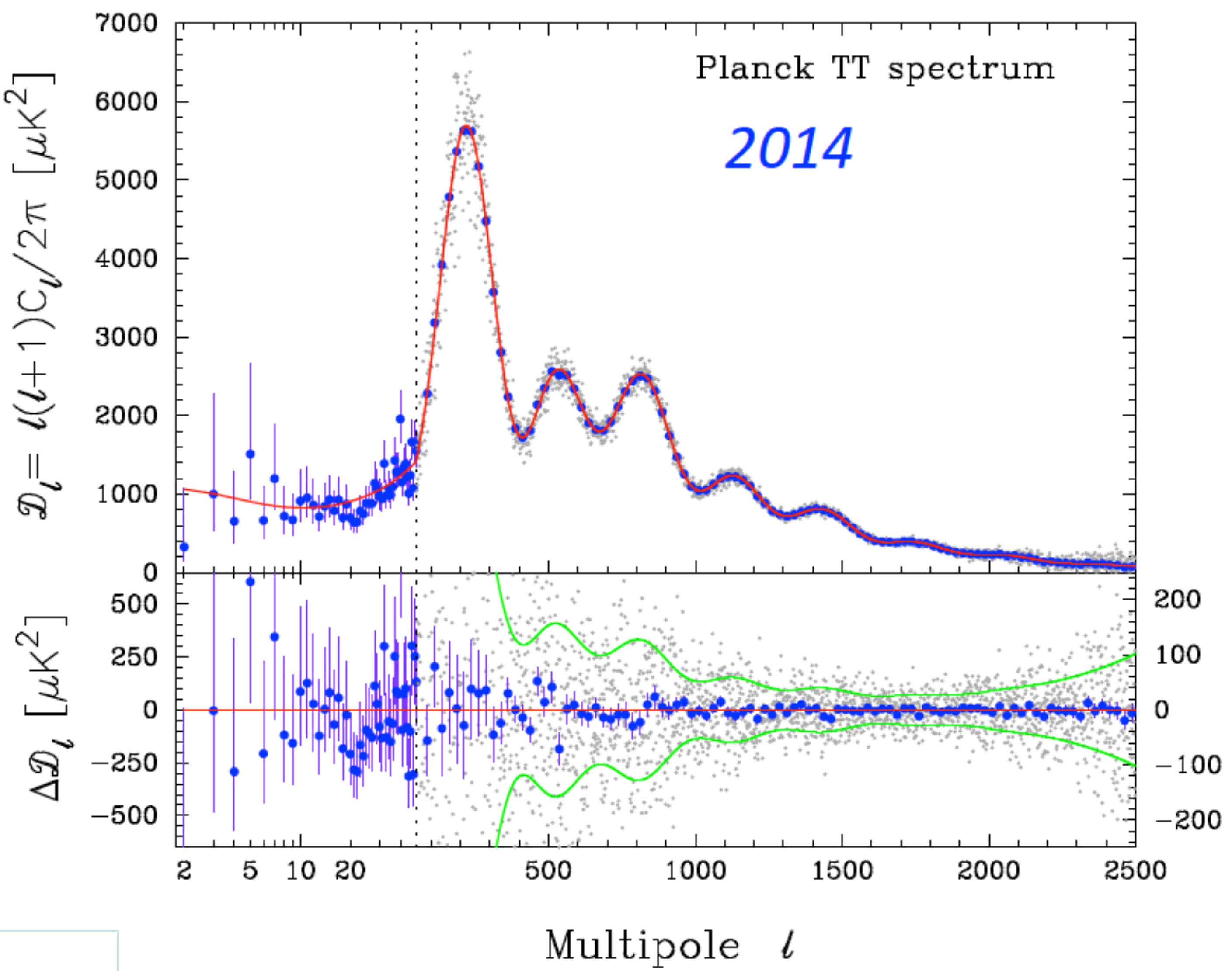
Observational ways to constrain VFC

- *Comparison of atomic clocks in the laboratory a z=0,*
  (Rosenband et al. 2008; Cing oz 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; Stefanecsu 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 $z\sim10^8$ (Bergstrom et al. 1999; Muller et al 2004; Coc et al. 2007, 2012)*

Planck Temperature power spectrum: 2013



Planck Temperature power spectrum: 2014



CMB APS and VFC

- *CMB APS depends on the time and width of the LSS, ie 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*

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

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

Thomson scattering cross section

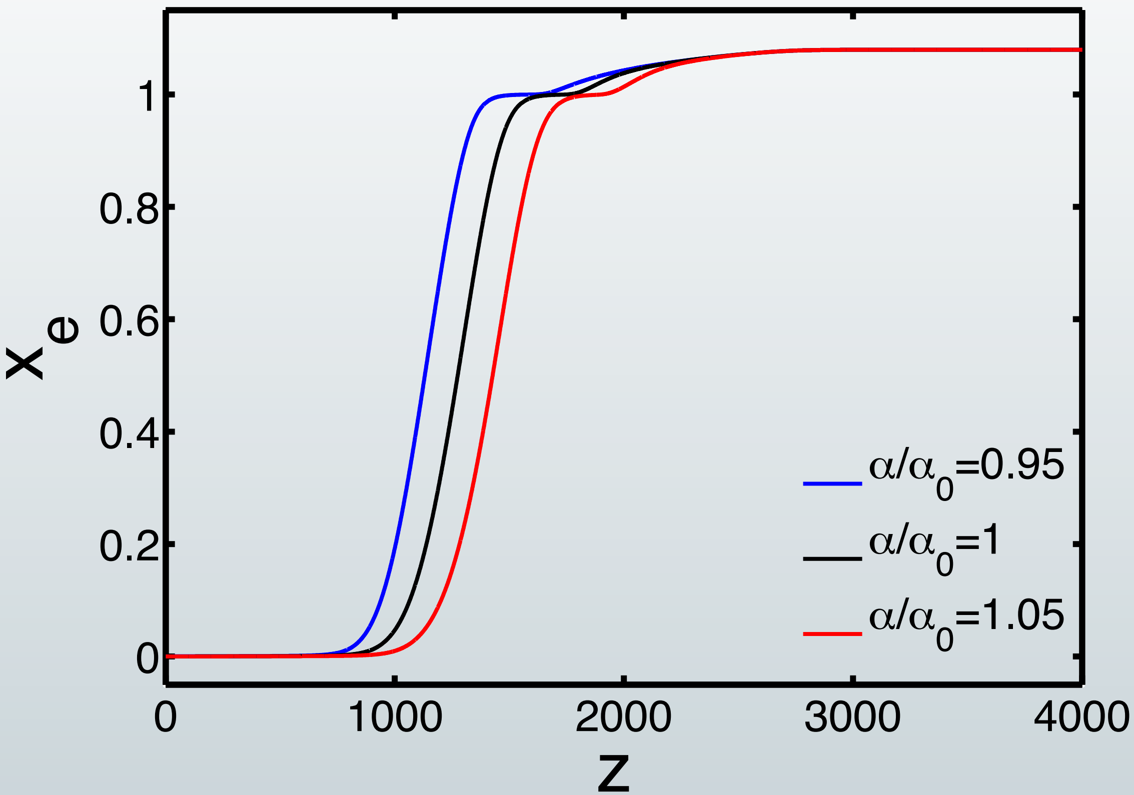
$$x_e = \frac{n_e}{n_e + n_H}$$

Free electron fraction

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

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

Evolution of x_e with time



A variation of α 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

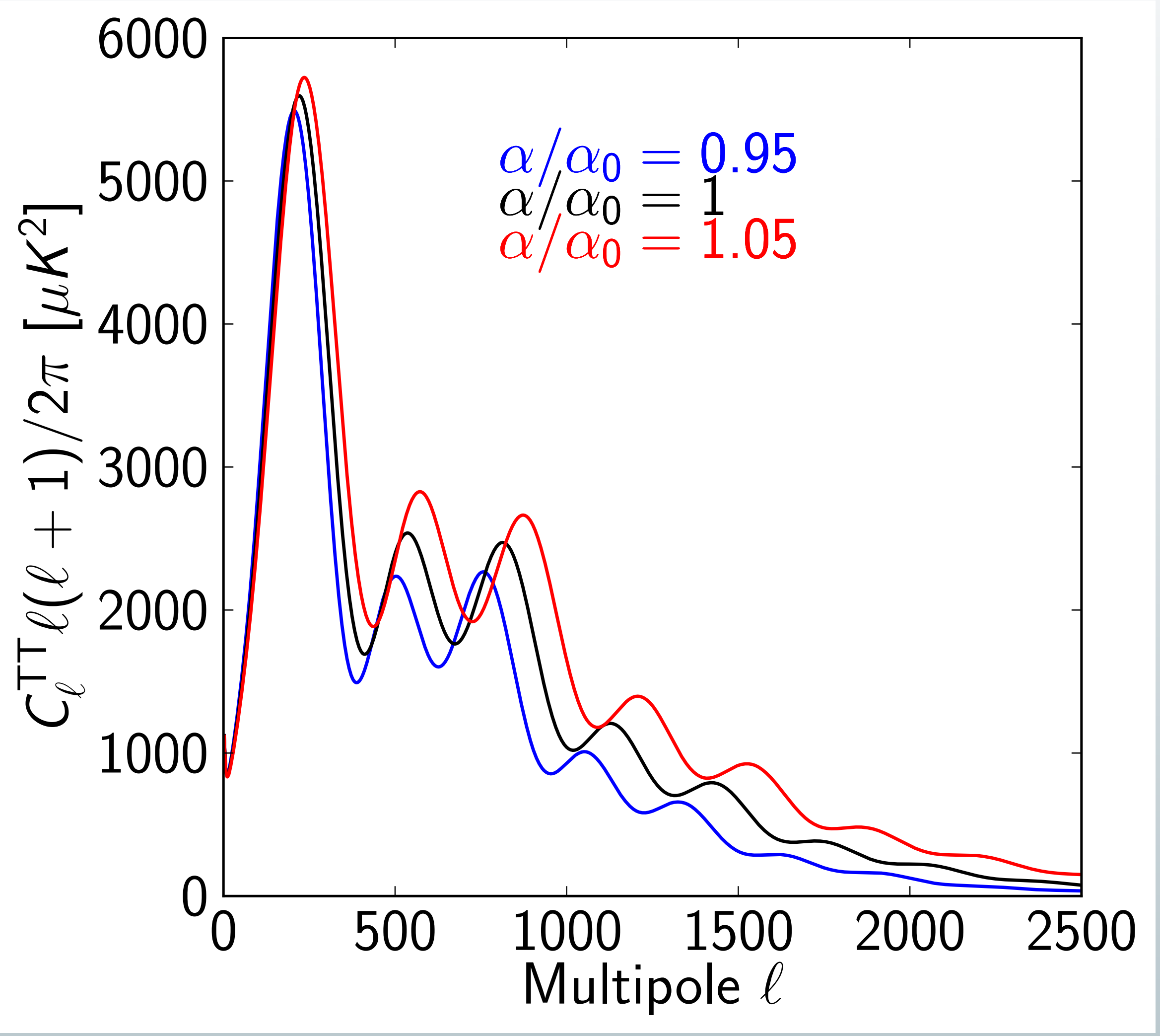
For a larger α recombination takes place at larger redshift ie at earlier times

These modifications are implemented in RECFAST

Avelino, Martins, Rocha, Viana., Phys. Rev. D64:103505, 2001

Varying α 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 α and the CMB APS

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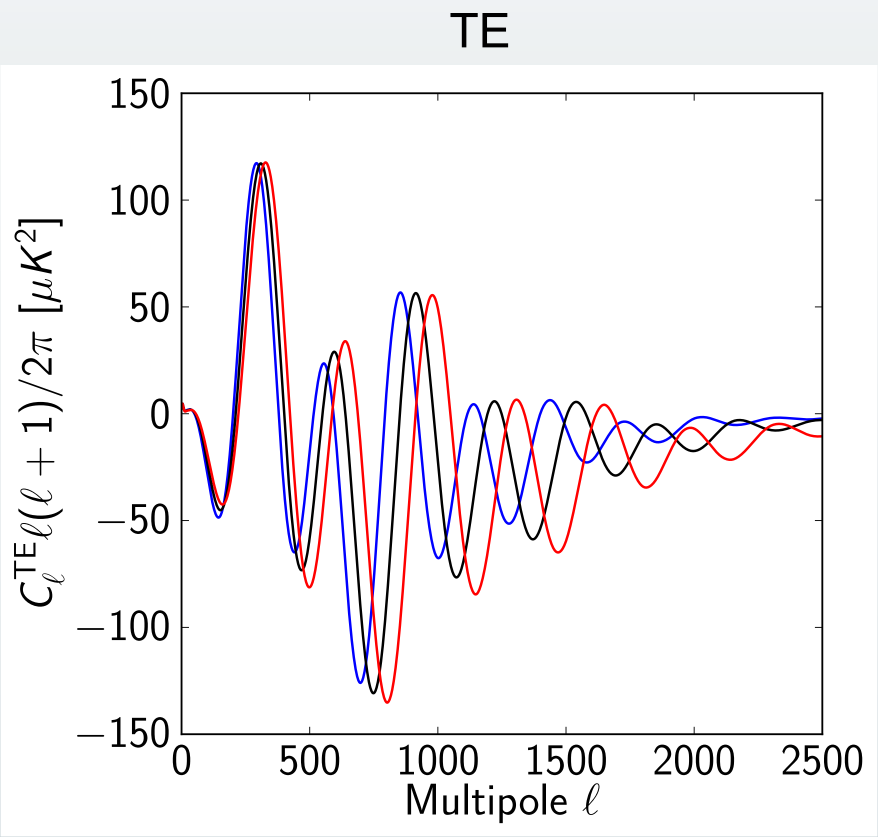
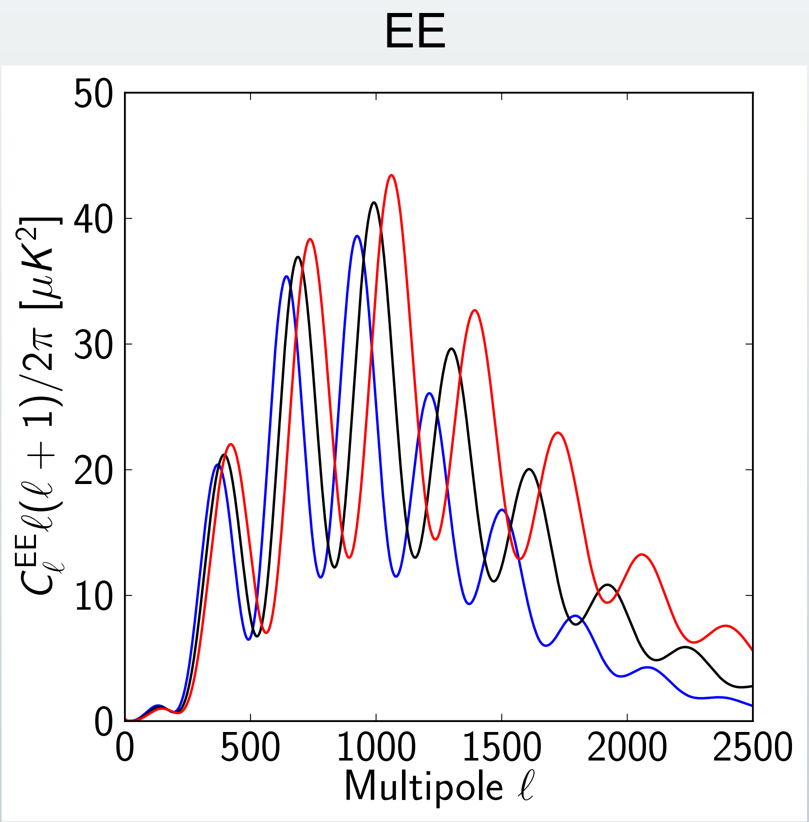
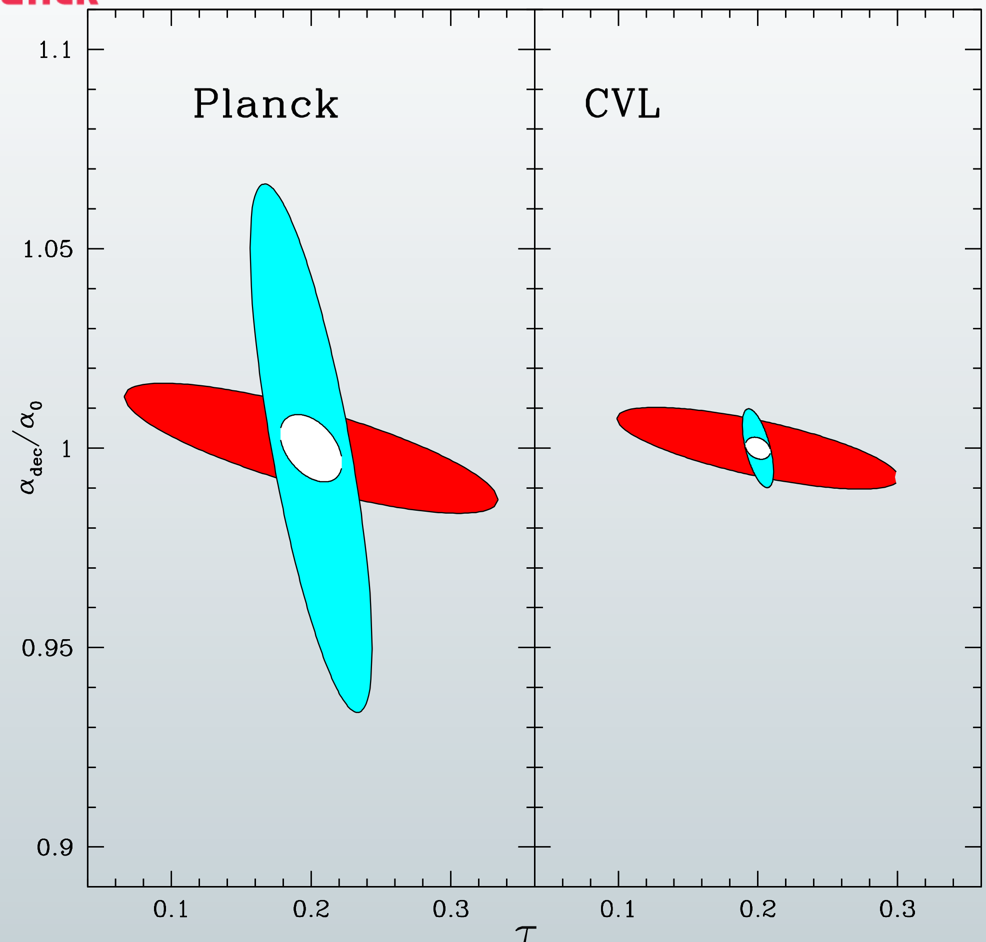




Forecasting constraints with Planck Temperature and Polarization



Conclusion → *Planck will be able to constrain variations of α at the epoch of decoupling within 0.34% (1σ, all other parameters marginalized), approx. a factor 5 improvement on the current upper bound.*

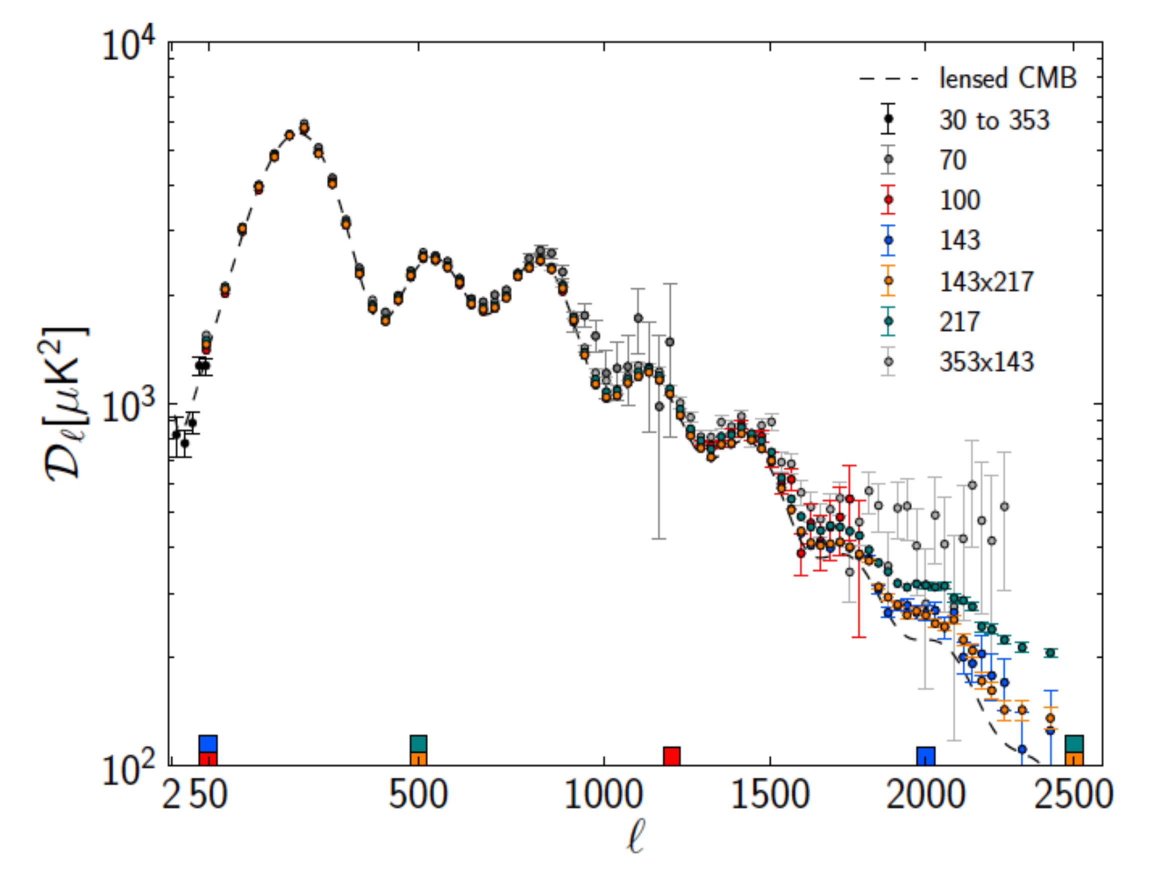
Compare to the actual constraints we get from Planck in the next few slides

Rocha et al., 2004, MNRAS 352, astro-ph0309211, 0309205

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

But variations in α should be larger at higher redshifts.

CMB angular power spectrum from Planck measurement vs models



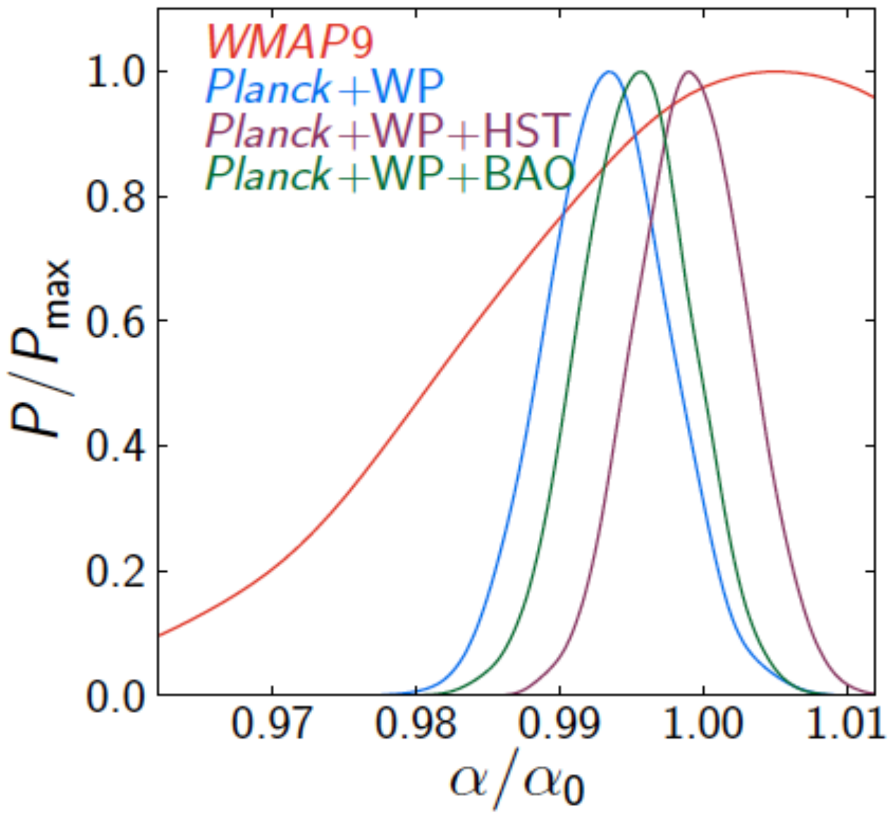
Extending the standard cosmological model to include α, fine structure constant

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

$$\omega_b, \omega_c, H_0, \tau, n_s, A_s, \alpha$$

Planck 2013 results XVI. Cosmological Parameters, A&A 571, A16, 2014

Constraints



$$\alpha/\alpha_0 = 0.9934 \pm 0.0042$$

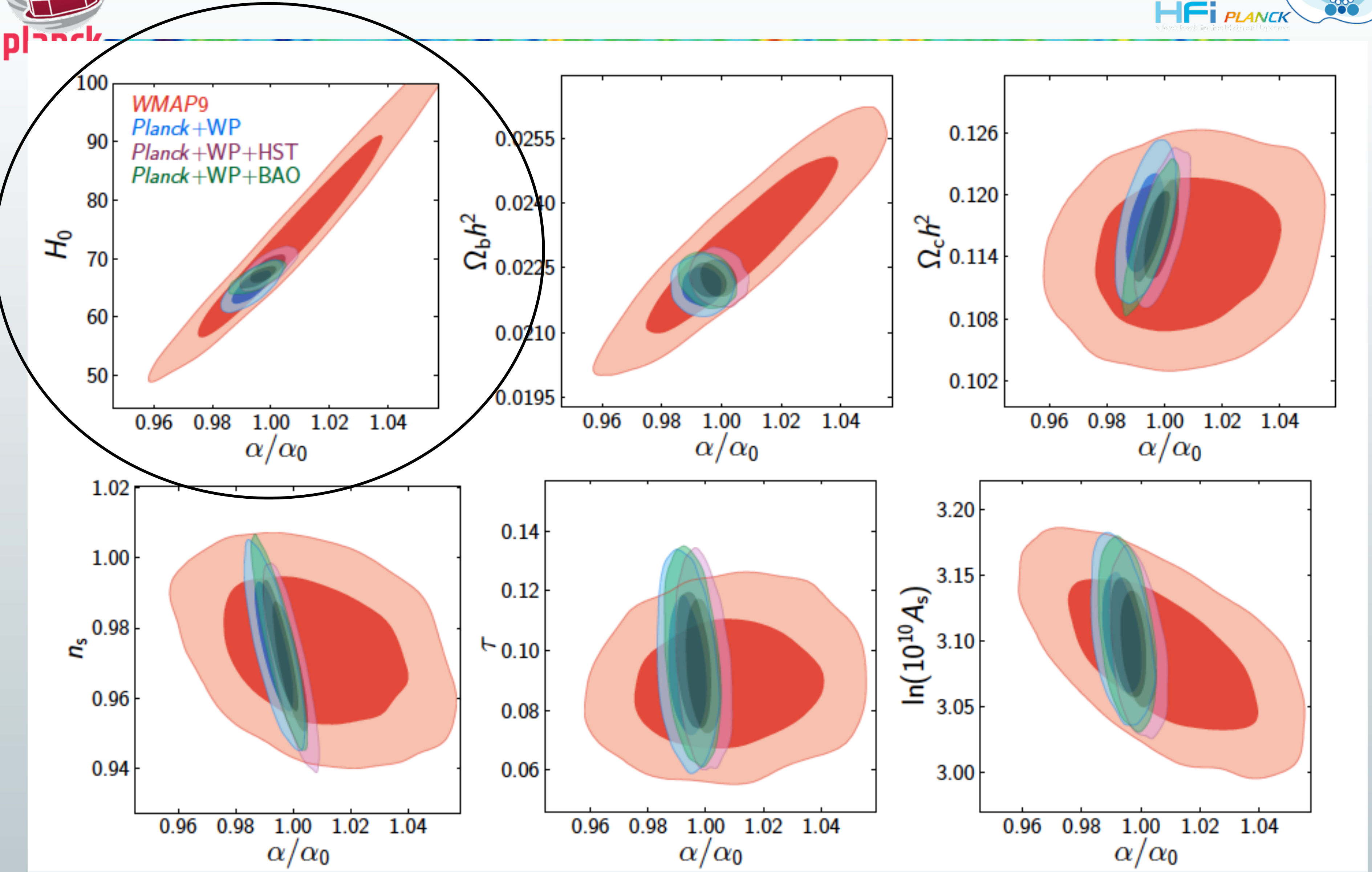
Planck gives 0.4% constraint

WMAP gives ~2% constraint on α/α_0

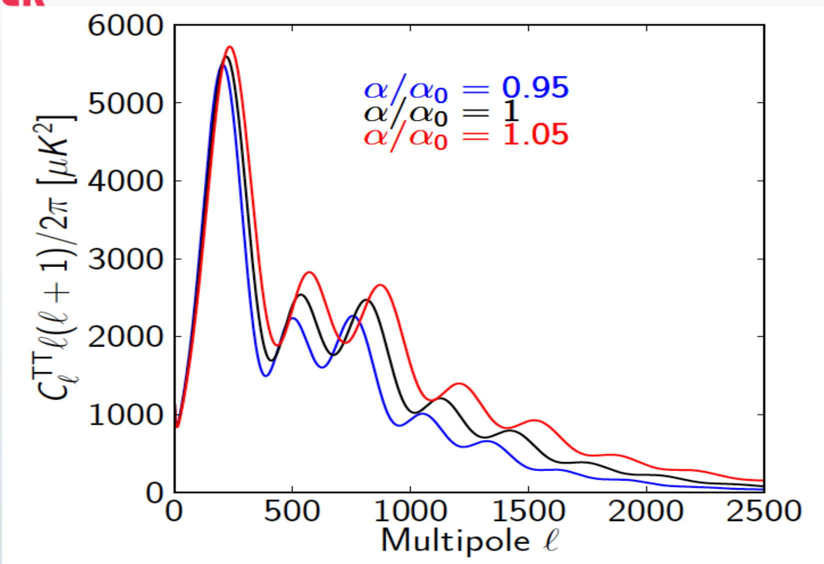
Adding other datasets do not improve the constraint substantially. In particular, adding HST does not shrink the error bars significantly.

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?

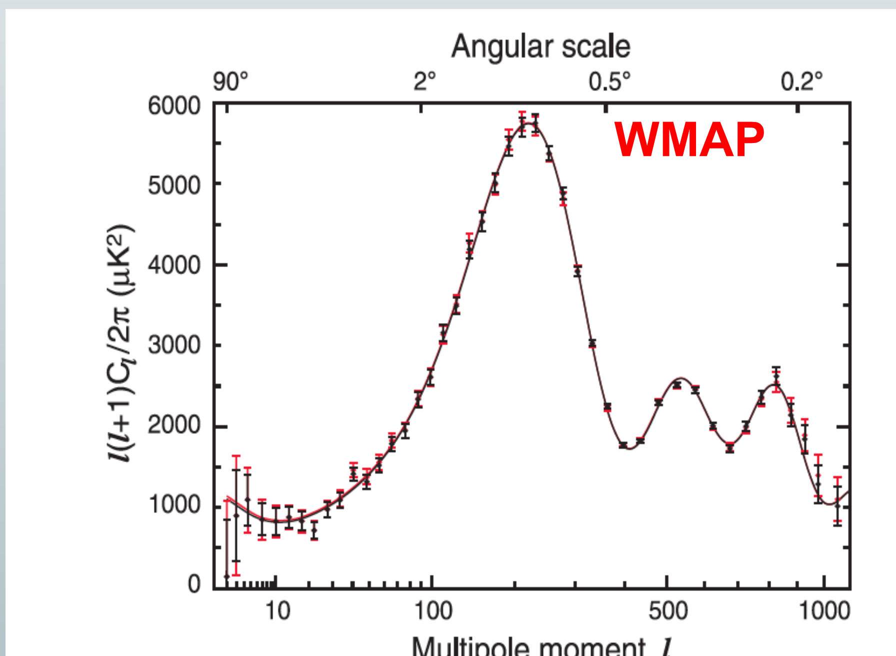
Degeneracies with other parameters

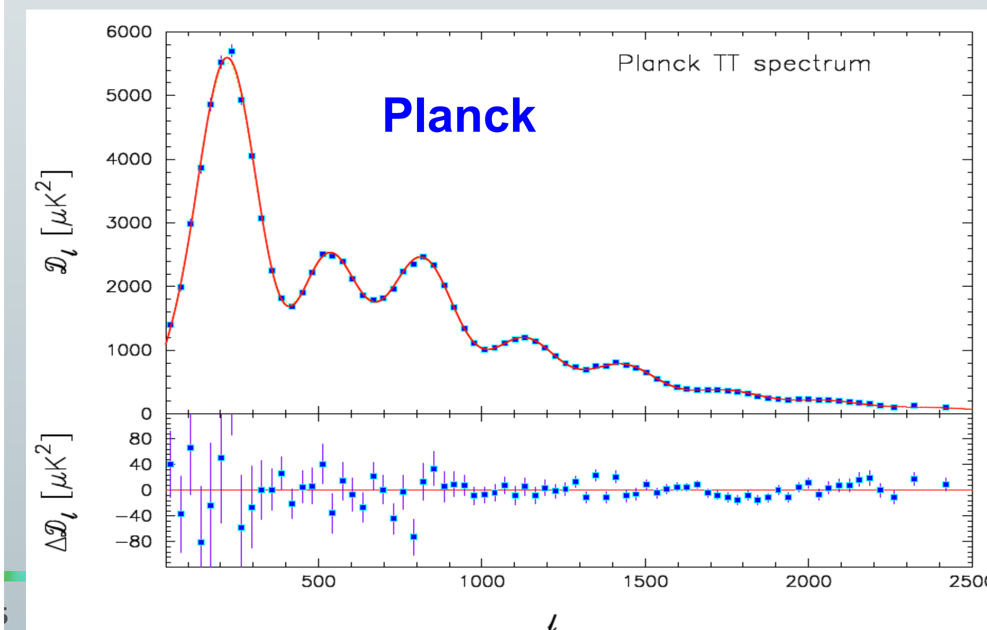


Damping tail



The observation of the damping tail breaks the degeneracy between H_0 and the fine structure constant.



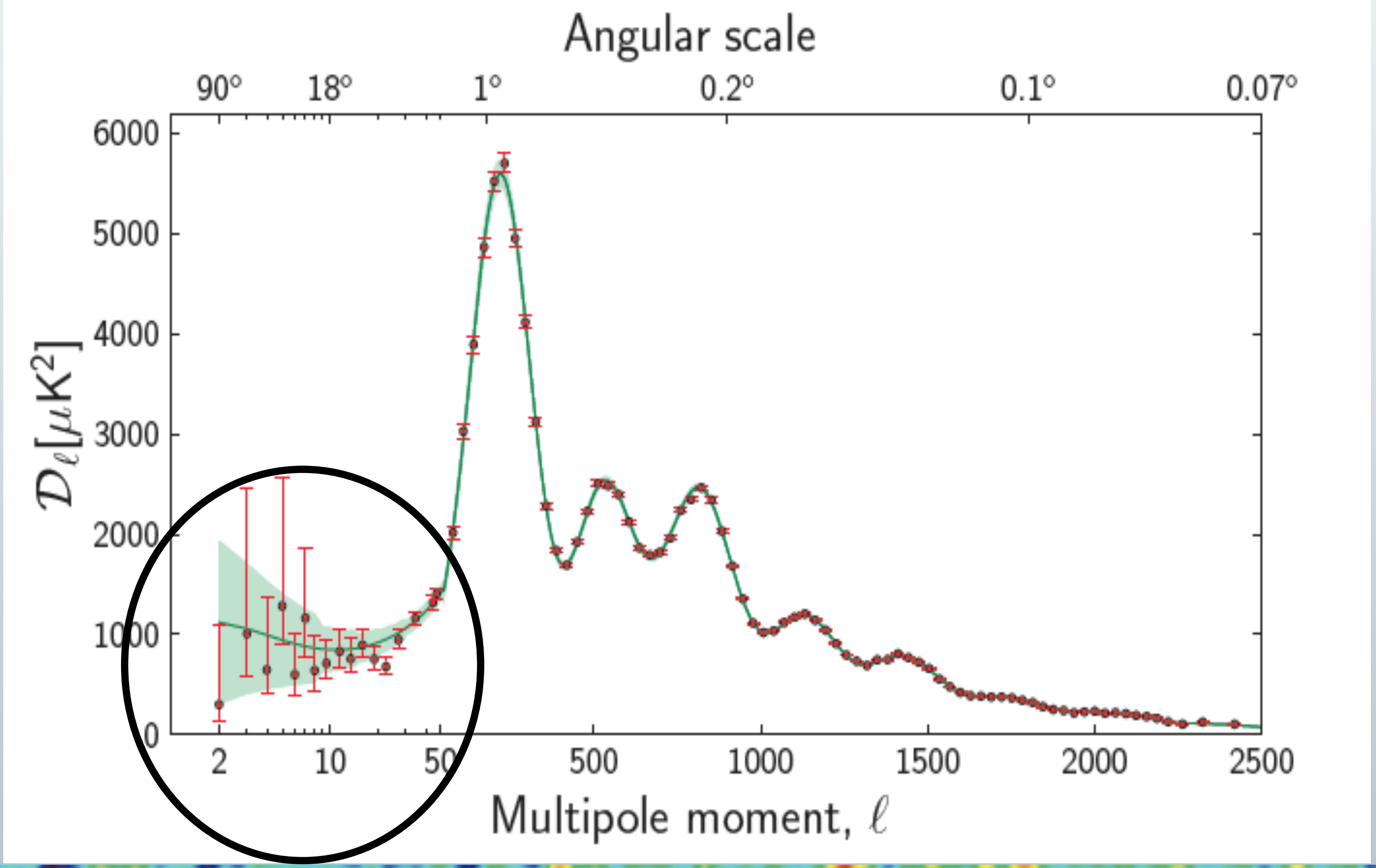


A low fine structure constant?

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

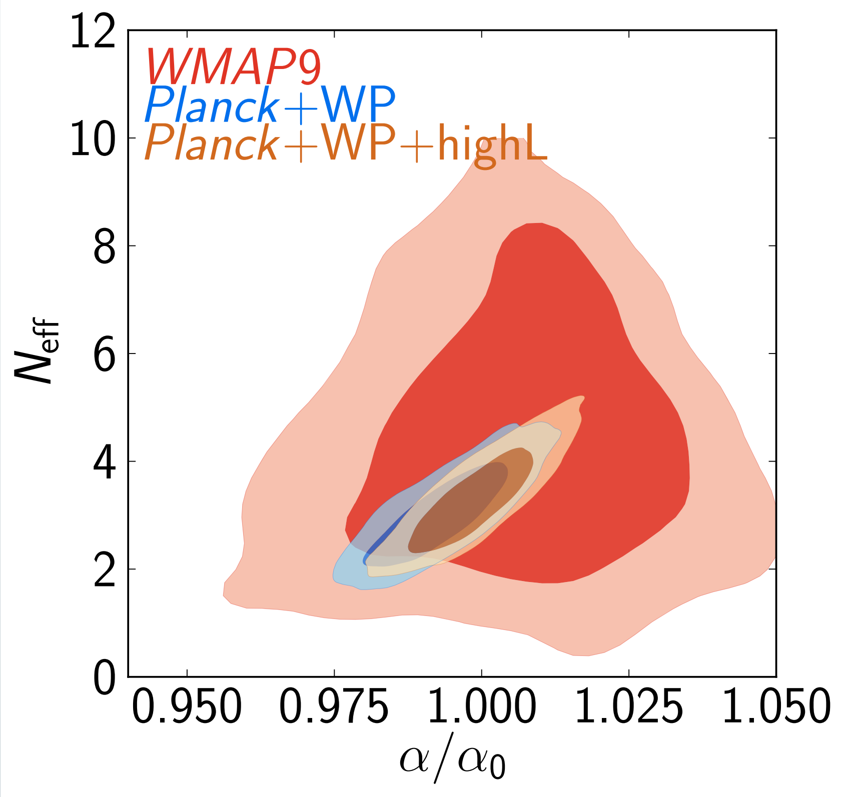
Value of α is more consistent with unity when the multipoles at l<49 are not used

The value of α goes from α/α_0=0.9934±0.0042 to α/α_0=0.9970±0.0054

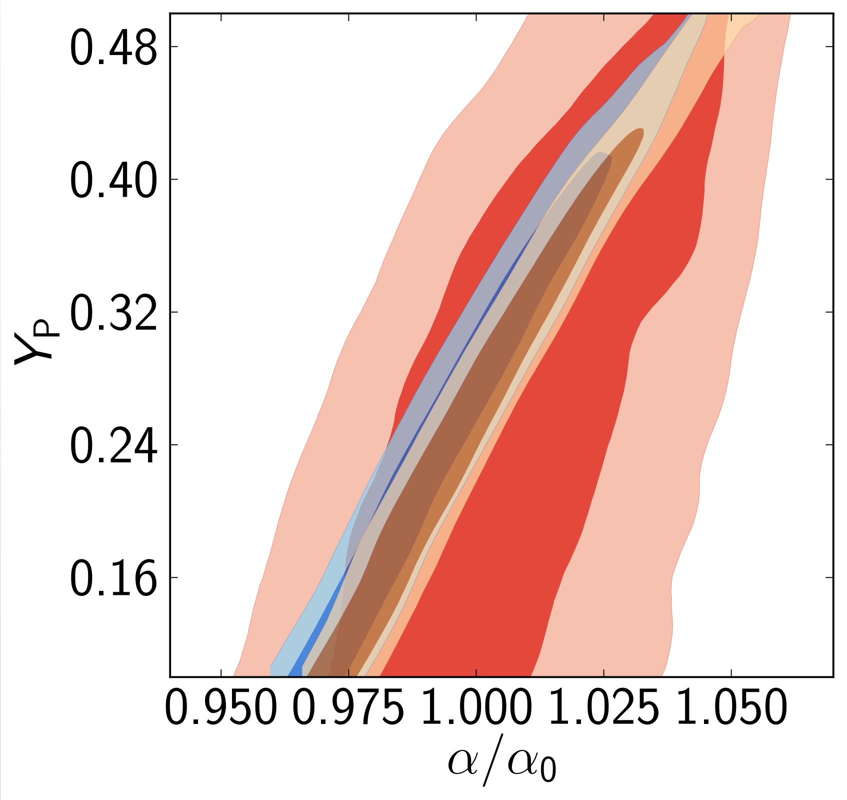


Extending the constraints from Planck 2013
N_{eff} , Y_p

Uncertainty goes up by a factor of 2
N_{eff} agrees with standard value



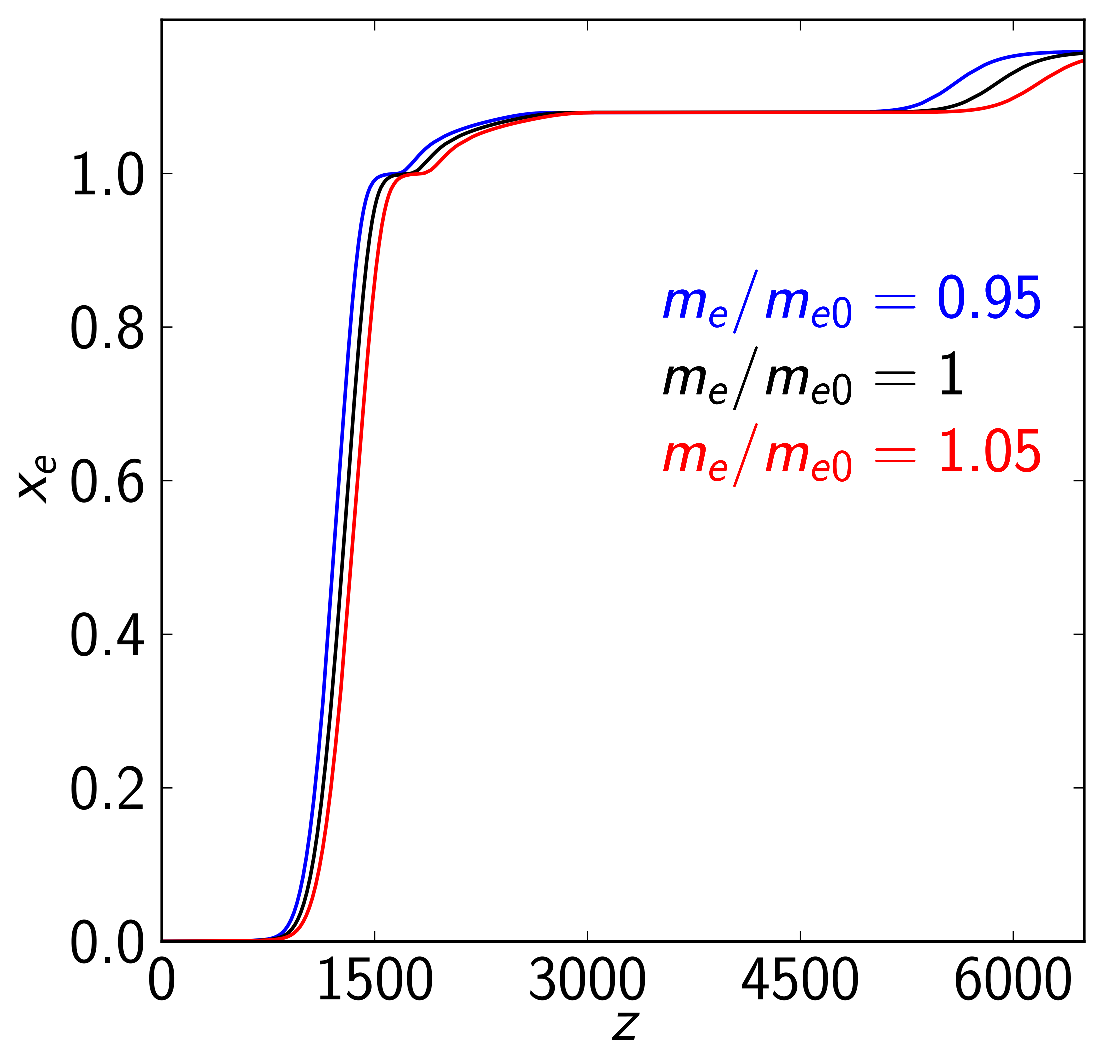
Stronger degeneracy
Constrain of α at 1% level worse by a factor of 4



PIP XXIV A&A, 580, A22, 2015 (arXiv:1407.7482)

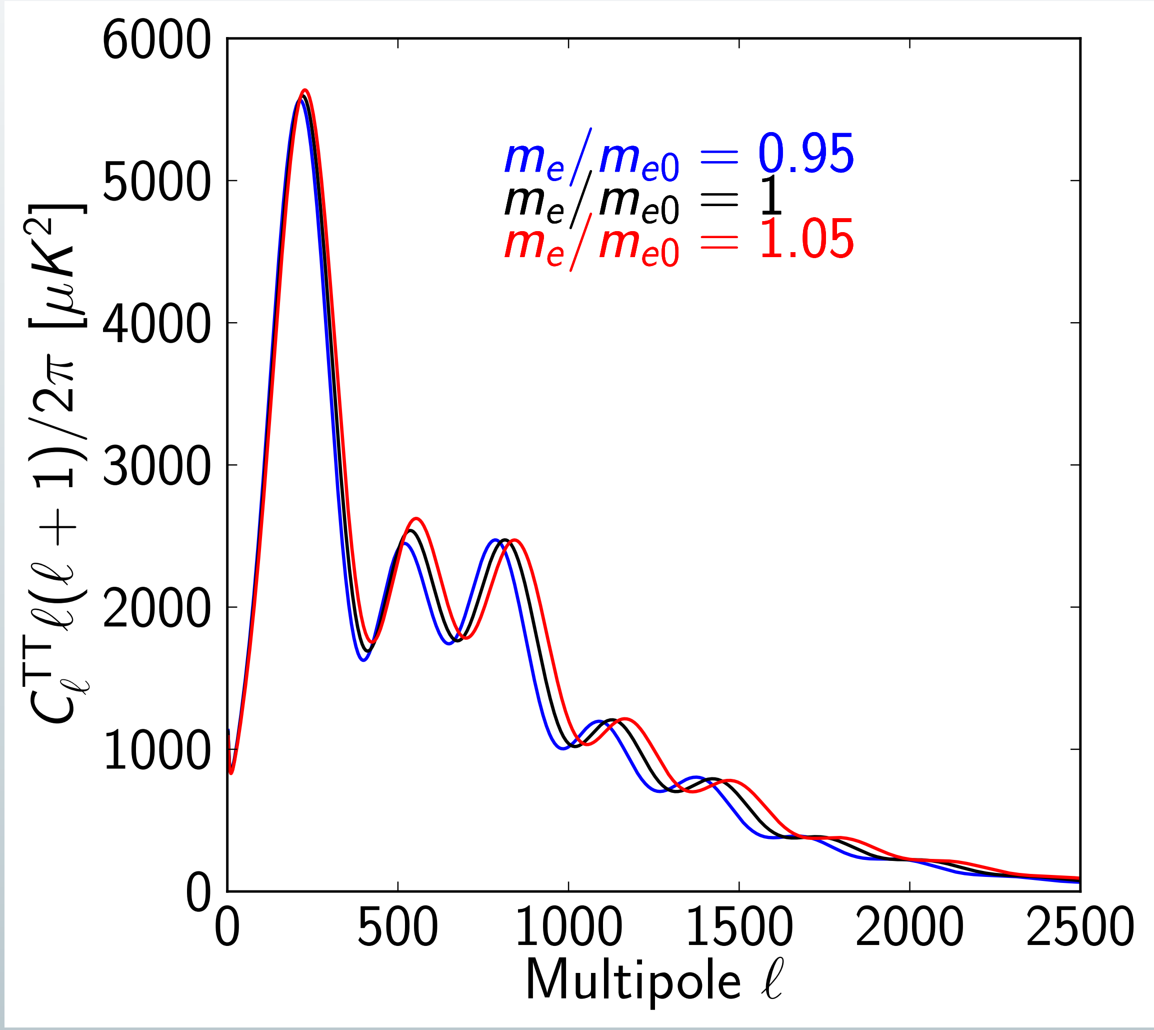
Electron mass, m_e

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



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 λ_D due to the earlier recombination.

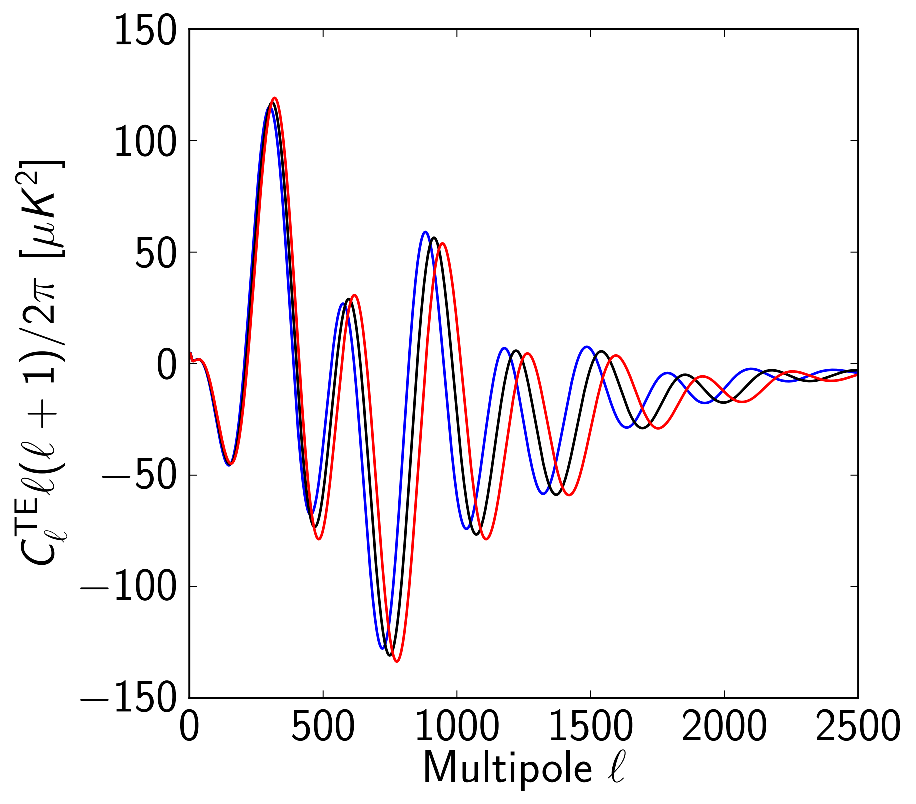
For this reason α has a larger impact on the damping tail than m_e

The overall amplitude of the peaks is less affected by a change in m_e than by a change in α, due to the different effect on the damping tail

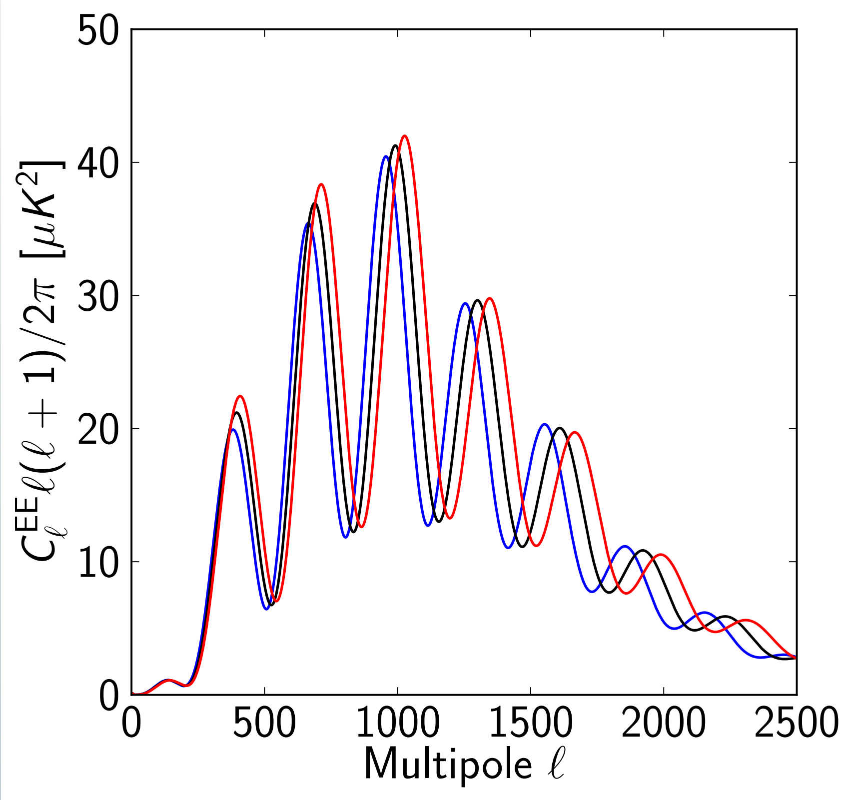
Varying m_e and the CMB APS

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

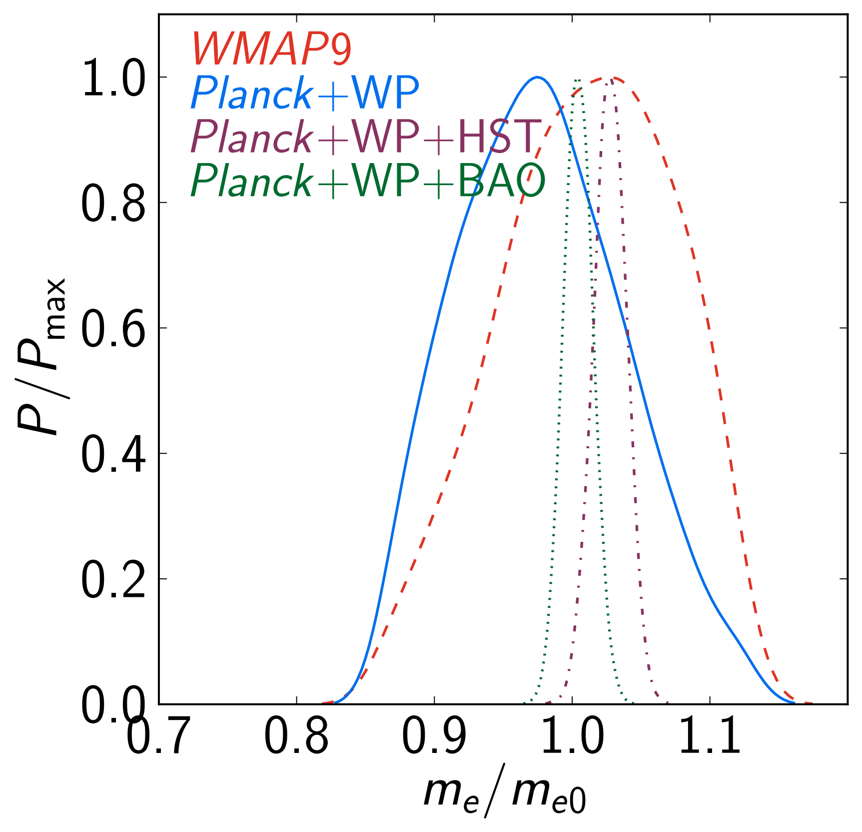
TE

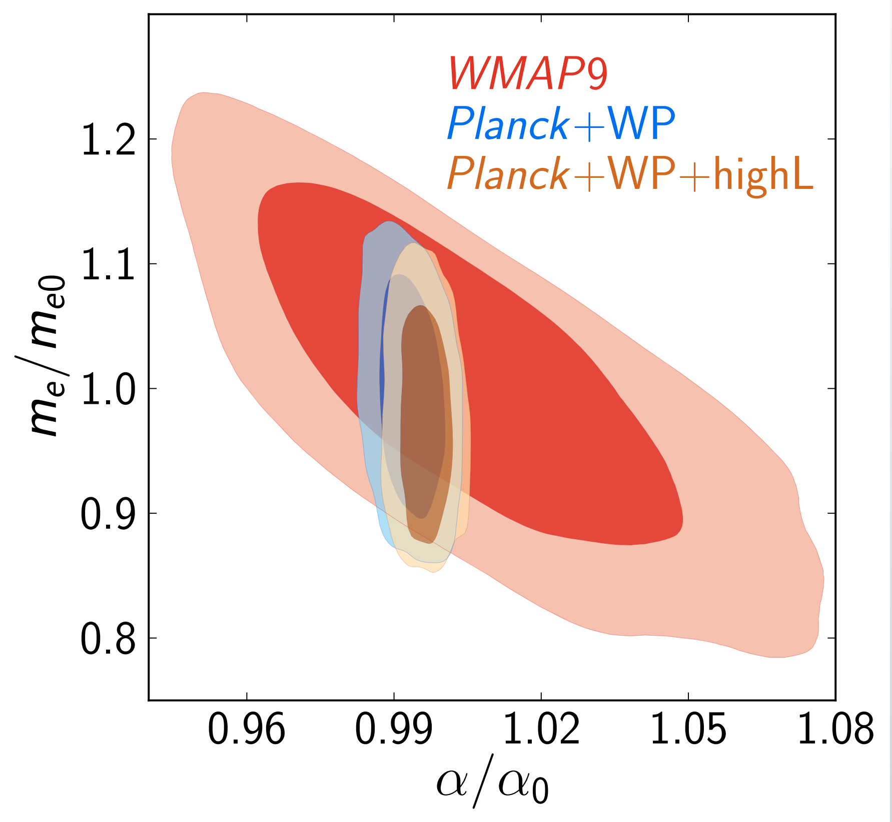


EE



Constraints





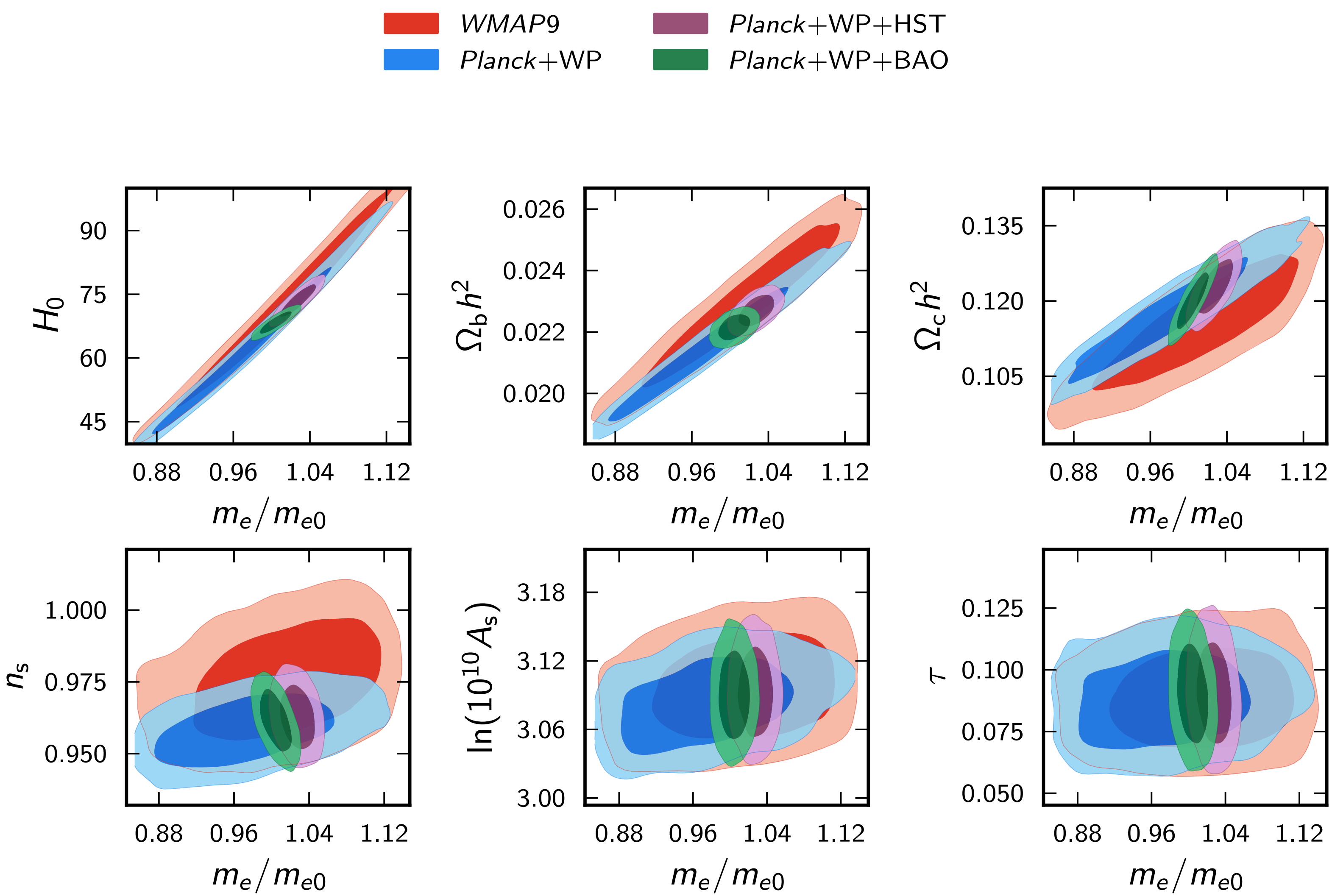
$$m_e / m_{e0} = 0.977^{+0.055}_{-0.070}$$

No much improvement with respect to WMAP-9 constraints

Including BAO decreases the error by a factor ~ 5

PIP XXIV A&A, 580, A22, 2015 (arXiv:1407.7482)

Degeneracies with other parameters



Spatial variations of α

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

$$c_a(\boldsymbol{n}, z) = c_{0a}(z) + \sum_{\imath=-1}^{1} \delta c_a^{(\imath)}(z) Y_{1\imath}(\boldsymbol{n}).$$

Dipolar modulation of α implies mode couplings between the a_{lm}

$$\begin{aligned}
\Theta(\boldsymbol{n}) &= \bar{\Theta}[\boldsymbol{n}, c_a(\boldsymbol{n})] \\
&= \bar{\Theta}\left[\boldsymbol{n}, c_{0a} + \sum_{\imath=-1}^{1} \delta c_a^{(\imath)}(z) Y_{1\imath}(\boldsymbol{n})\right] \\
&\simeq \bar{\Theta}[\boldsymbol{n}] + \sum_a \sum_{\imath=-1}^{+1} \frac{\partial \bar{\Theta}[\boldsymbol{n}]}{\partial c_a} \delta c_a^{(\imath)}(z) Y_{1\imath}(\boldsymbol{n})
\end{aligned}$$

$\delta c_a^{(\imath)}$ three parameters which characterize the amplitude and direction of the modulation

develop l(l+1) correlations $D_{\ell m}^{(i)} \equiv \left\langle a_{\ell m}\, a^*_{\ell+1\ m+i} \right\rangle$ for i=0,1

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

Spatial variations of α

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

$$a_{\ell m} \simeq \bar{a}_{\ell m} + \sum_a \sum_{LM} \sum_i \frac{\partial \bar{a}_{LM}}{\partial c_a} \delta c_a^{(i)} \int \mathrm{d}^2 \boldsymbol{n} Y^*_{\ell m}(\boldsymbol{n}) Y_{LM}(\boldsymbol{n}) Y_{1i}(\boldsymbol{n}) \tag{40}$$

$$C_{\ell_1 m_1 \ell_2 m_2} = \delta_{\ell_1 \ell_2} \delta_{m_1 m_2} C_{\ell_1} + \frac{1}{2} \sum_a \sum_i \delta c_a^{(i)} \left[\frac{\partial C_{\ell_1}}{\partial c_a} + \frac{\partial C_{\ell_2}}{\partial c_a} \right] \times \int \mathrm{d}^2 \boldsymbol{n} Y_{1i}(\boldsymbol{n}) Y^*_{\ell_1 m_1}(\boldsymbol{n}) Y_{\ell_2 m_2}(\boldsymbol{n}). \tag{41}$$

Unormalised QML takes the form

$$\widetilde{\delta\alpha}^{(i)} = \sum_a \int \mathrm{d}^2 \boldsymbol{n} Y^*_{1i}(\boldsymbol{n}) \left[\sum_{\ell_1 m_1} \underline{\Theta}_{\ell_1 m_1} Y_{\ell_1 m_1}(\boldsymbol{n}) \right] \times \left[\sum_{\ell_2 m_2} \frac{1}{2} \frac{\partial C_{\ell_2}}{\partial c_a} \underline{\Theta}_{\ell_2 m_2} Y_{\ell_2 m_2}(\boldsymbol{n}) \right]$$

$$\underline{\Theta}_{\ell m} = \sum_{\ell' m'} (C^{-1}_{\mathrm{obs}})_{\ell m \ell' m'} \Theta_{\ell' m'}$$

$$C^{-1}_{\mathrm{obs}} \simeq 1/(C_\ell b_\ell^2 + N_\ell)$$

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 α

field $\langle\widetilde{\delta\alpha}\rangle$ and variance $\sigma^2_{\alpha} = \langle\delta\alpha^2\rangle - \langle\delta\alpha\rangle^2$ of the amplitude $\delta\alpha$ of the modulation for 900 *Planck* re
vis (2009) estimator for the specific choices $\ell_{\max} = 600$ and $\ell_{\max} = 1500$.

Hanson-Lewis estimator	$\ell_{\max} = 600$	$\ell_{\max} = 1500$
Variances $\sigma_{\widetilde{\delta\alpha}}$	1.17×10^{-3}	2.71×10^{-4}
Mean fields $\langle\widetilde{\delta\alpha}\rangle$	2.72×10^{-3}	6.29×10^{-4}

nary of the results obtained for the amplitude of the spatial modulation of the fine structure constant
on & Lewis (2009) estimator applied to the *Planck* data for $\ell_{\max} = 600$ and $\ell_{\max} = 1500$. We show

Planck results	$\ell_{\max} = 600$	$\ell_{\max} = 1500$
$\widehat{\delta\alpha}$	$-5.56 \times 10^{-4} \pm 1.17 \times 10^{-3}$	$-1.73 \times 10^{-4} \pm 2.71 \times 10^{-4}$
$\widehat{\delta\alpha^{(0)}}$	$4.09 \times 10^{-3} \pm 2.95 \times 10^{-3}$	$5.20 \times 10^{-4} \pm 6.50 \times 10^{-4}$
$\mathrm{Re}(\widehat{\delta\alpha^{(1)}})$	$8.57 \times 10^{-4} \pm 2.70 \times 10^{-3}$	$-6.93 \times 10^{-5} \pm 6.45 \times 10^{-4}$
$\mathrm{Im}(\widehat{\delta\alpha^{(1)}})$	$-8.66 \times 10^{-4} \pm 2.61 \times 10^{-3}$	$-5.44 \times 10^{-4} \pm 5.97 \times 10^{-4}$

$$\delta\alpha / \alpha_0 = \left(-2.4 \pm 3.7\right) \times 10^{-2}$$

(68%, l_{max}=1500)

PIP XXIV A&A, 580, A22, 2015 (arXiv:1407.7482)

Conclusions

- Planck places a constraint on α at the ~0.4% 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 σ deviation of α/α_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 α weakens by about a factor of 1.5 when N_{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 me at the 1% level.*
- Dipolar modulation of α : $\delta\alpha/\alpha_0 = (-2.4 \pm 3.7)\times 10^{-2}$ (68%, l_{max}=1500)
- Expected further improvement from Planck polarization data and from other CMB experiments
- Euclid will improve the Planck constraints on α/α_0 by a factor of 2
- CMB alone can only constrain variations of α up to 0.1% at z~1100

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.