Cosmological constraints on variations of fundamental constants from CMB data

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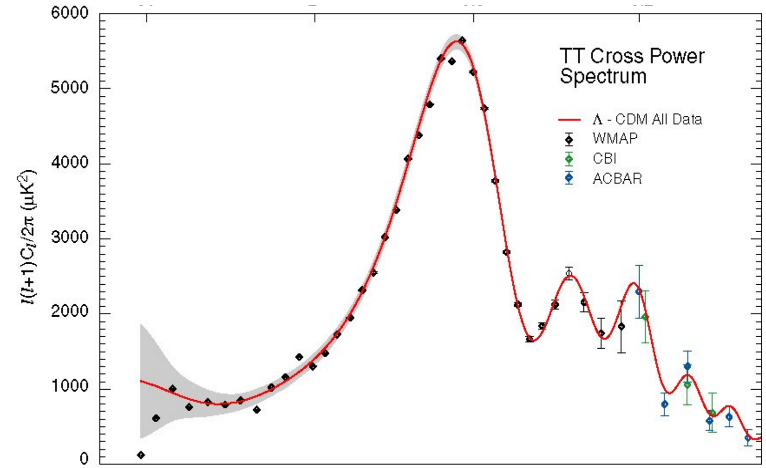
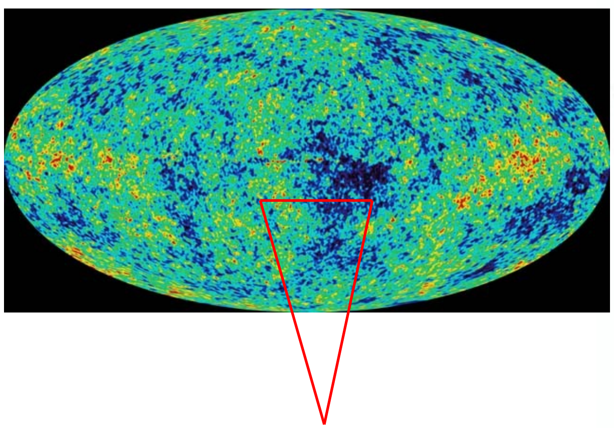
Outline

- The CMB anisotropies (Epoch of Recombination).
- Constraints on the fine structure constant.
- Relation between the fine structure constant and the equation of state parameter w.
- Constraints on the fine structure constant motivated by the presence of an early dark energy component driven by a scalar field at the Recombination.
- Conclusions .

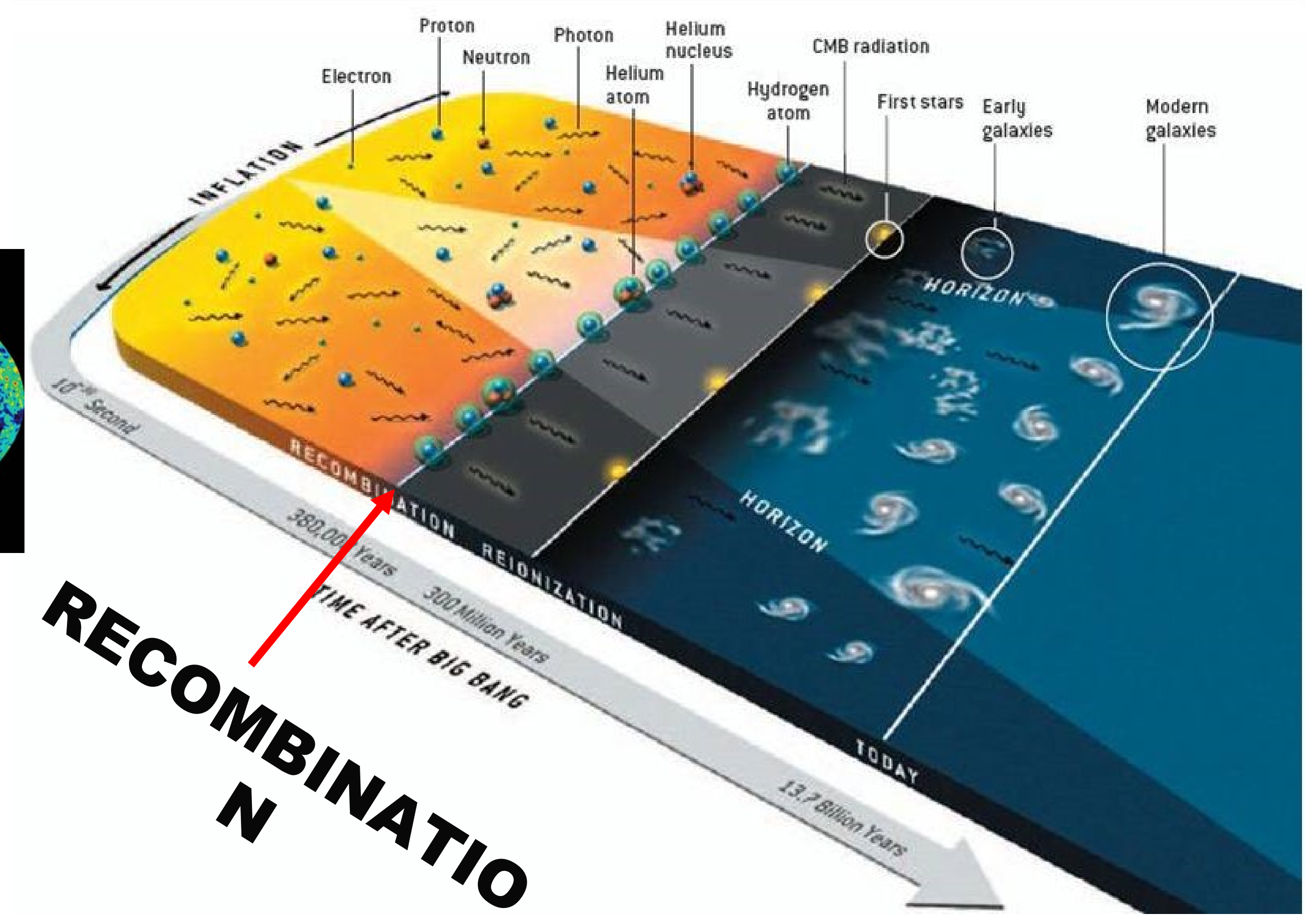
CMB anisotropies

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$





$\vartheta \approx 1/l$



RECOMBINATIO
N

Physical Processes that Induce CMB Fluctuations

The primary anisotropies of CMB are induced by three principal mechanisms:

- Gravity (Sachs-Wolfe effect, regions with high density produce big gravitational redshift)
- Adiabatic density perturbations (regions with more photons are hotter)
- Doppler Effect (peculiar velocity of electrons on last scattering surface)

The anisotropies in temperature are modulated by the **visibility function** which is define
the probability density that a photon is last scattered at redshift z:

$$\frac{\Delta T}{T}(\vec{n}) \doteq \int_0^\infty \left[g(z) \left(\Psi + \Theta_0 + \vec{n} \cdot \vec{v}_b \right) \right] dz$$

α

Gravity

Adiabatic

Doppler

Visibility function and fine structure constant

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

Rate of Scattering

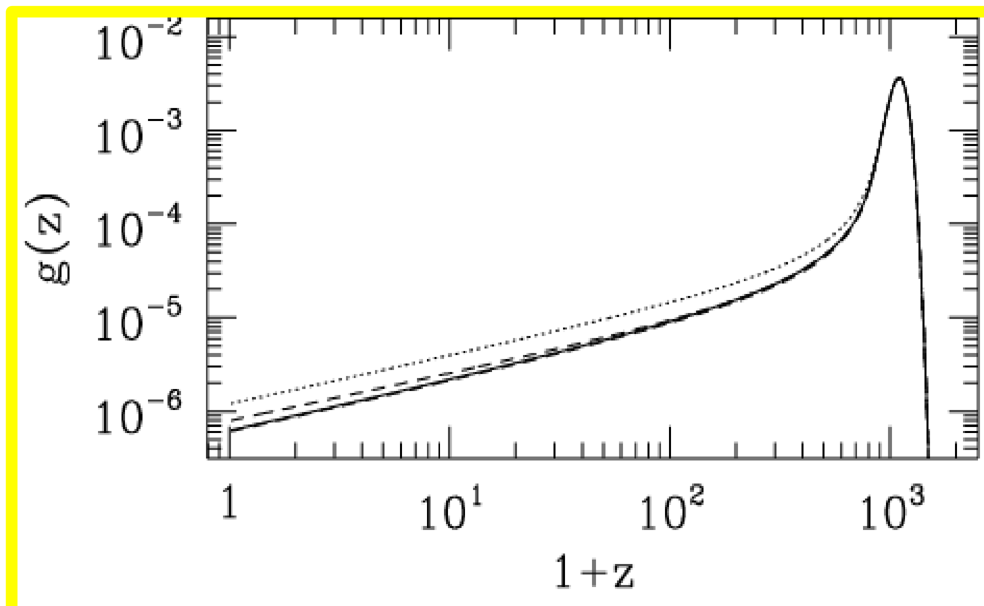
$$\dot{\tau}(\eta) = n_e\, x_e\, a\sigma_T$$

Optical depth

$$\tau(\eta) = \int_{\eta}^{\eta_0} d\eta'\, n_e\, x_e\, a\sigma_T$$

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

We can see that the visibility function is peaked at the Epoch of Recombination.



Thomson scattering cross section

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

Recombination: standard Model

Direct Recombination

NO net recombination

$$H_{1s} + \gamma \leftrightarrow H^{+} + e^{-}$$

Decay to 2 photons from 2s levels metastable

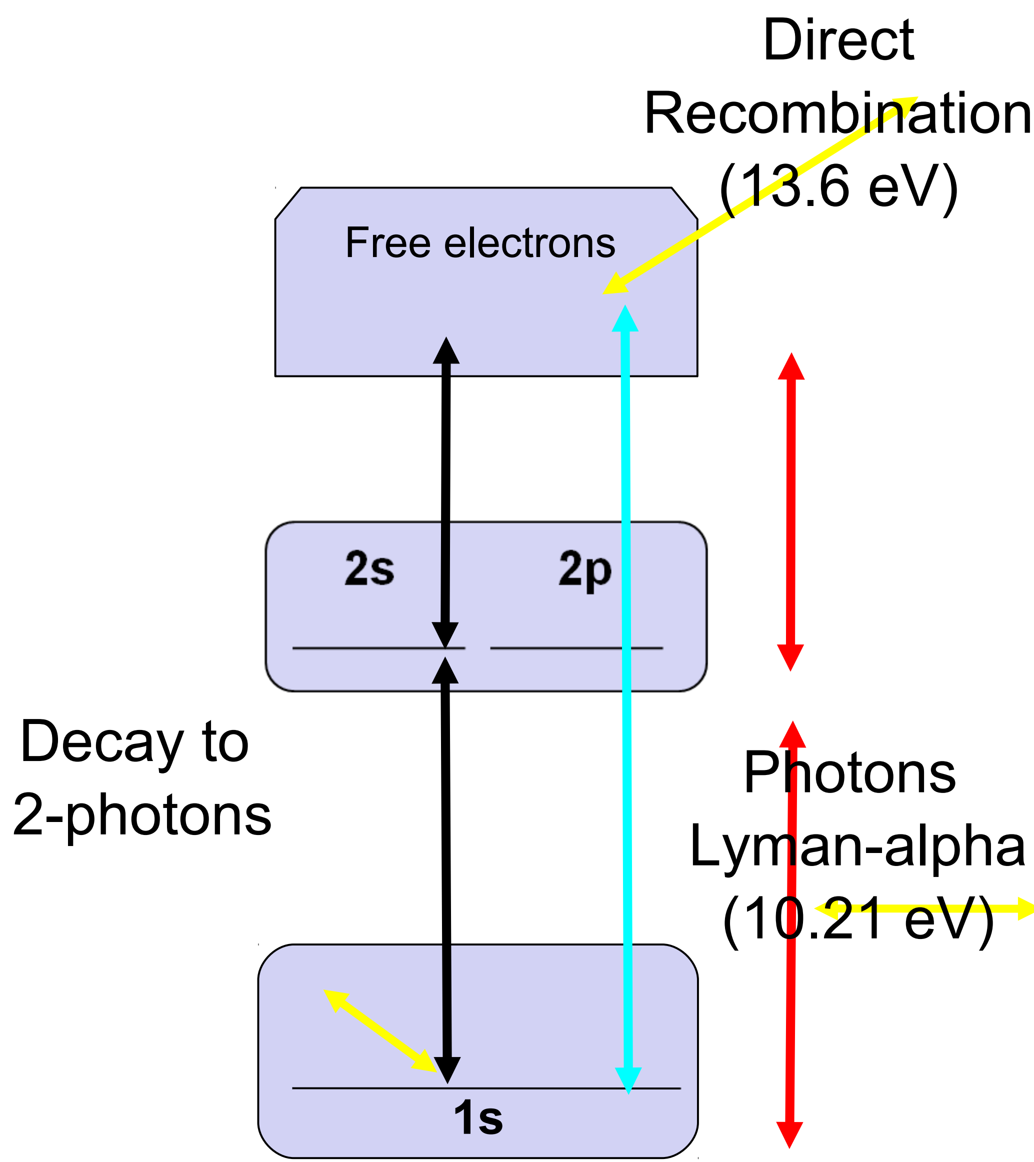
$$H^{+} + e^{-} \leftrightarrow H_{2s} + \gamma$$

$$H_{2s} \leftrightarrow H_{1s} + 2\gamma$$

Cosmological redshift of **Lyman alpha's photons**

$$H^{+} + e^{-} \leftrightarrow H_{2p} + \gamma$$

$$H_{2p} \leftrightarrow H_{1s} + \gamma$$



olution of the free electron fraction with ti

ionization coefficient

$$\beta_H \equiv R_H \left(\frac{2\pi m_e K_B T}{h^2} \right) e^{-B_2 / K_B T}$$

recombination coefficient

$$R_H \approx \sigma_{nl} f(B_n, T)$$

cross section of ionization

$$\sigma_{nl} \propto \alpha^{-1} m_e^{-2} f(h\nu / B_1)$$

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

$$C_H = \frac{1 + K\Lambda_{2s}(1 - x_e)}{1 + K(\beta_H + \Lambda_{2s})(1 - x_e)}$$

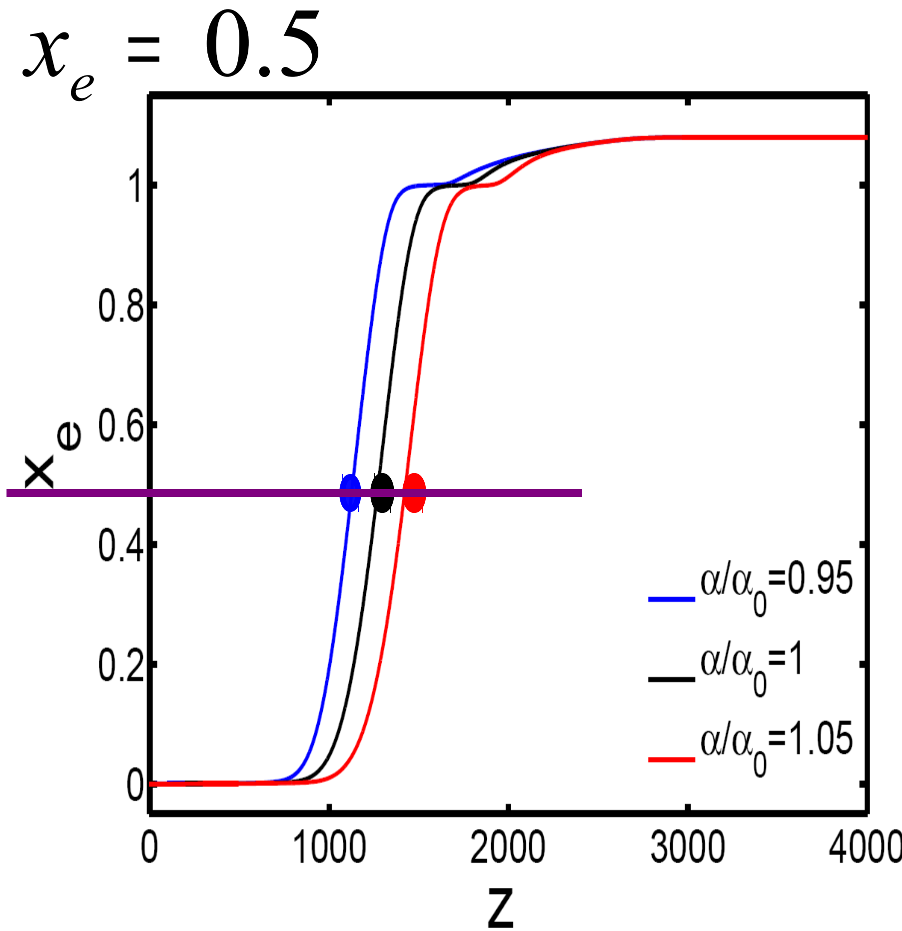
Rate of decay 2s a 1s $\Lambda_{2s} \propto m_e \alpha^8$

Constant K $K = n_e \lambda^3 / (8\pi H) \propto m_e^{-3} \alpha^{-6}$

Lyman-alpha $\lambda_\alpha = 16\pi \bullet/(3 m_e c \alpha^2)$

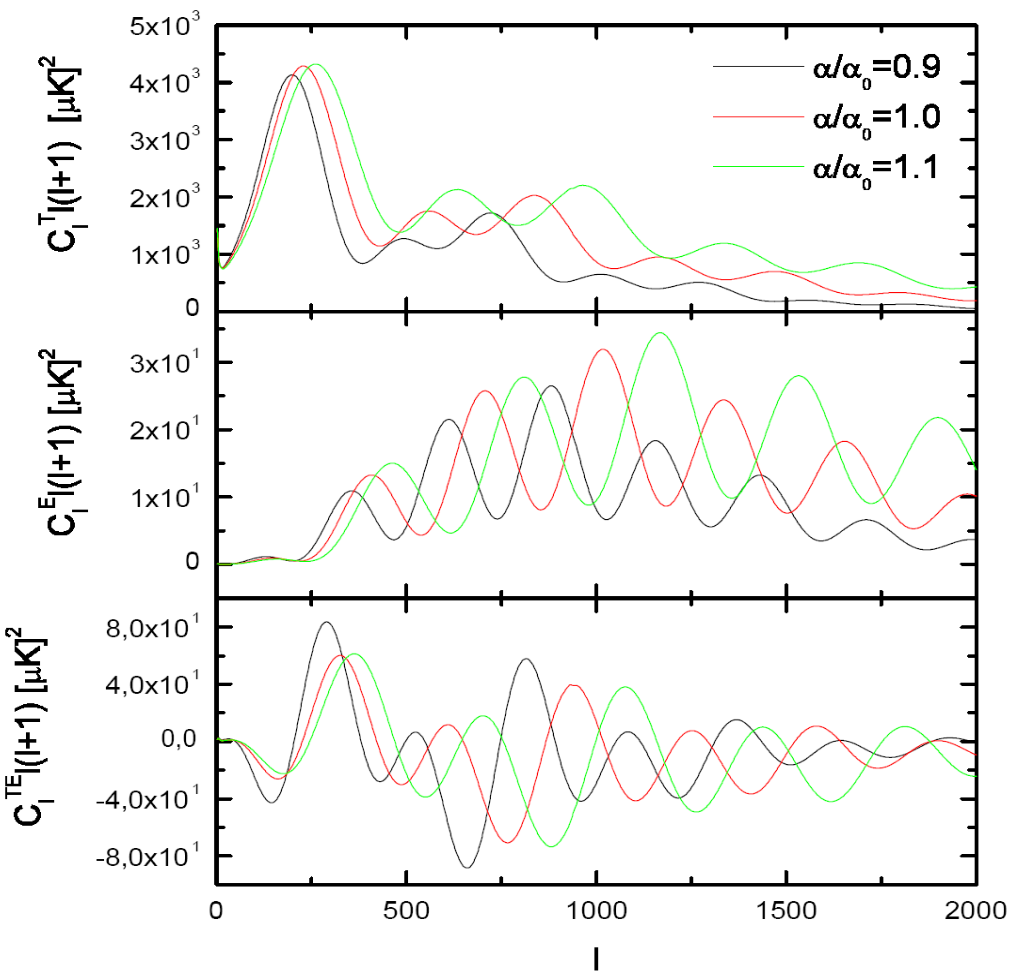
Variation of free electron fraction

If we plot the free electron fraction versus the redshift, we can notice a different epoch of Recombination for different values of alpha. In particular if the fine structure constant α is smaller than the present value, then the Recombination takes place at smaller z.



(see e.g. Avelino et al., Phys.Rev.D64:103505,2001)

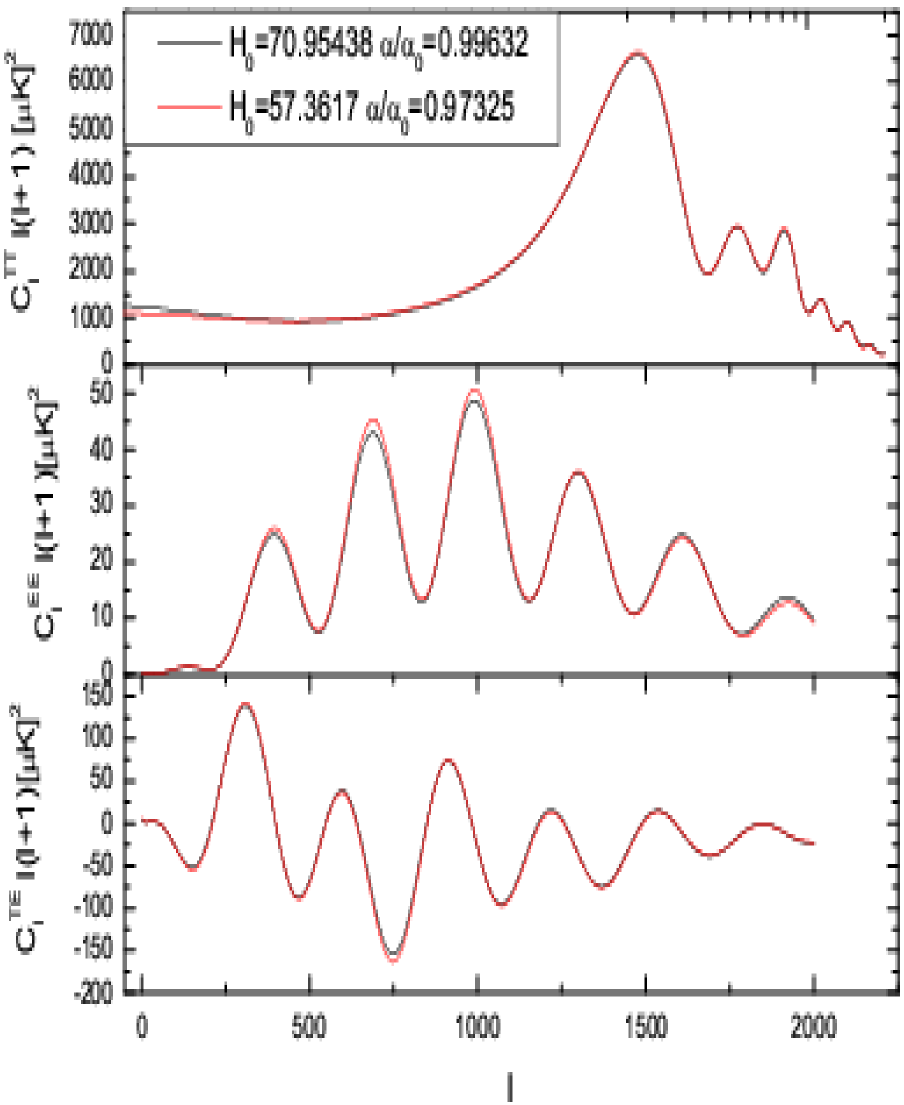
Modifications caused by variations of the fine structure constant



If the fine structure constant is $\alpha/\alpha_0 < 1$ recombination is delayed, the size of the horizon at recombination is larger and as a consequence the peaks of the CMB angular spectrum are shifted at lower l (larger angular scales).

Therefore, we can constrain variations in the fine structure constant at recombination by measuring CMB anisotropies !

Caveat: is not possible to place strong constraints on the fine structure constant by using cmb data alone !



A "cosmic" degeneracy is cleary visible in CMB power spectrum in temperature and polarization between the fine structure constant and the Hubble constant.

The angle that subtends the horizon at recombination is indeed given by:

$$\theta_H \approx c_s H^{-1}(z_r) / d_A(z_r)$$

The horizon size increases by decreasing the fine structure constant but we can compensate this by lowering the Hubble parameter and increasing the angular distance.

New constraints on the variation of the fine structure constant

Menegoni, Galli, Bartlett, Martins, Melchiorri, arXiv:0909.3584v1

Physical Review D *80 08/302 (2009)*

We sample the following set of cosmological parameters from WMAP-5 years observations:

- Baryonic density $\Omega_b h^2$
- Cold dark matter density $\Omega_c h^2$
- Hubble parameter H_0
- Scalar spectrum index n_S
- Optical depth τ
- Overall normalization of the spectrum A_s
- Variations on the fine structure constant α / α_0

We also permit variations of the parameter of state w .

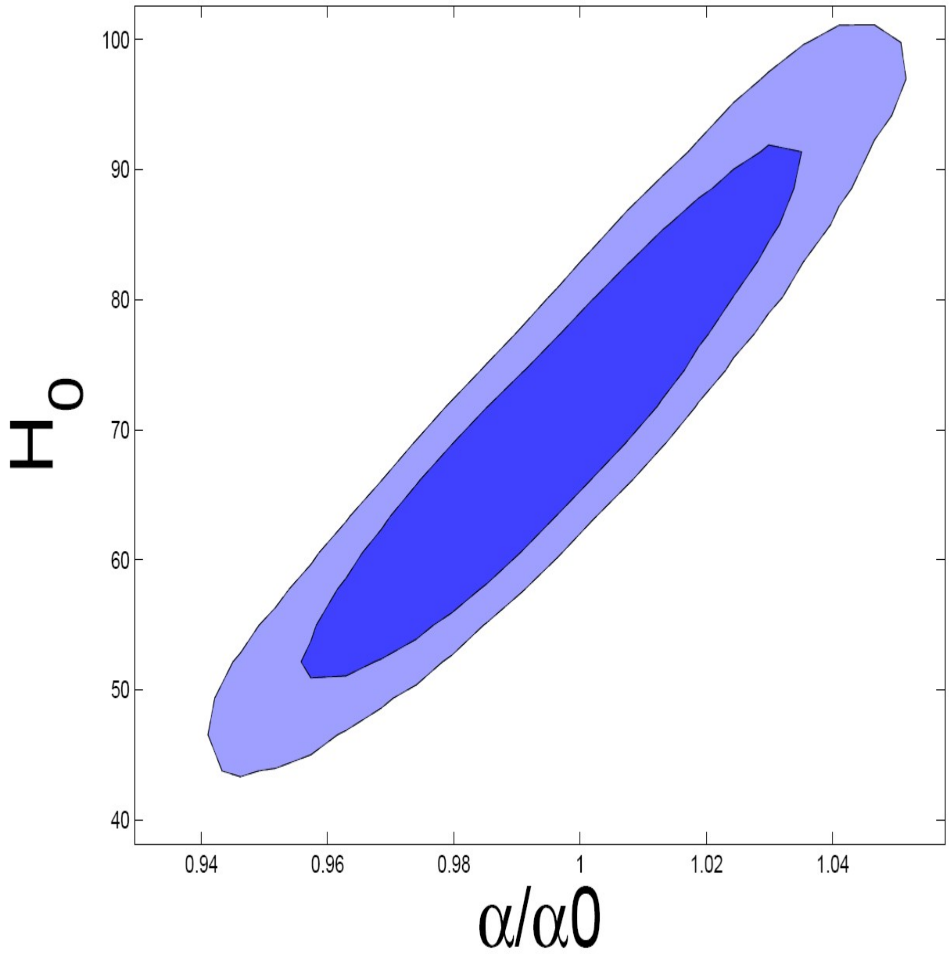
We use a method based on Monte Carlo Markov Chain (the algorithm of Metropolis-Hastings).

The results are given in the form of likelihood probability functions.

We are looking for possible degeneracies between the parameters.

We assume a flat universe.

Constraints from WMAP-5



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

! External prior on the Hubble parameter:

$$40\ km/s/Mpc < H_0 < 100\ km/s/Mpc$$

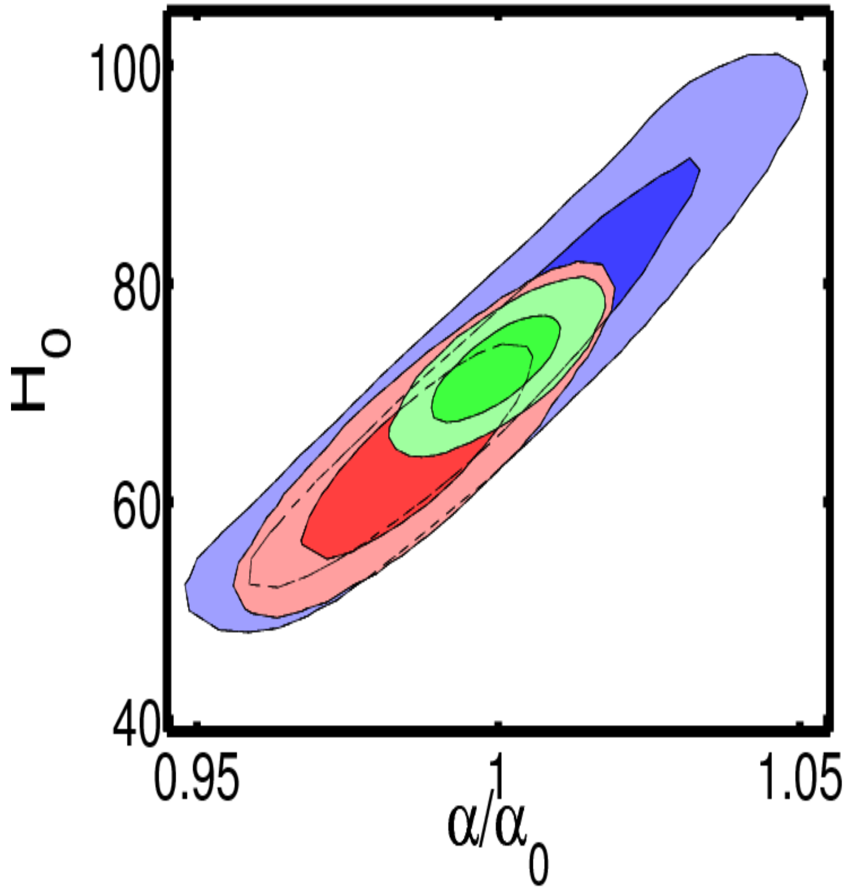
Constraints on the fine structure constant

In this figure we show the 68% and 95% c.l. constraints on the α/α_0 vs Hubble constant for different datasets .

Experiment	α/α_0	68% c.l.	95% c.l.
WMAP-5	0.998	±0.021	$^{+0.040}_{-0.041}$
All CMB	0.987	±0.012	±0.023
All CMB+ HST	1.001	±0.007	±0.014

TABLE I: Limits on α/α_0 from WMAP data only (first row), from a larger set of CMB experiments (second row), and from CMB plus the HST prior on the Hubble constant, $h = 0.748 \pm 0.036$ (third row). We report errors at 68% and 95% confidence level.

$\approx 0.7\%$



Menegoni, Galli, Bartlett, Martins, Melchiorri, arXiv:0909.3584v1
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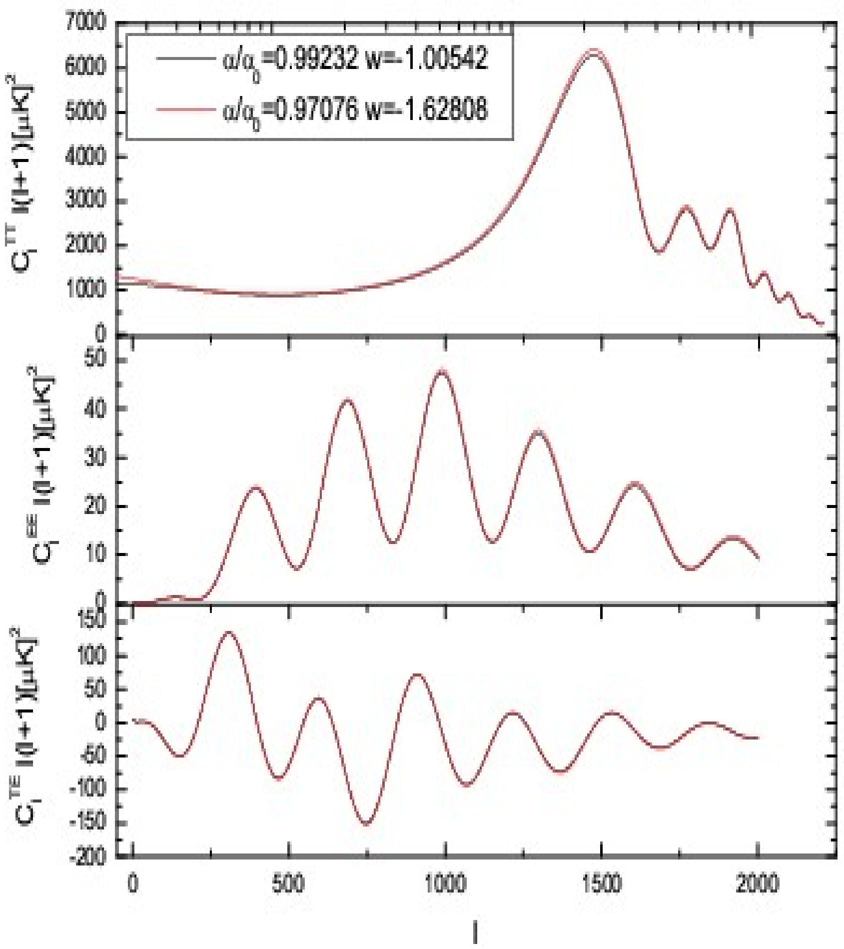
The degeneracy between the fine structure constant with the dark energy equation of state w



If we vary the value of w we change the angular distance at the Recombination. Again this is degenerate with changing the sound horizon at recombination varying the fine structure constant.

$$d_A = \frac{cH_0^{-1}}{(1+z)} \int_0^{1100} \frac{dz'}{E(z')}$$

$$E(z) = \left[\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_X (1+z)^{[3(1+w)]}\right]^{1/2}$$

Constraints on the dark energy parameter w

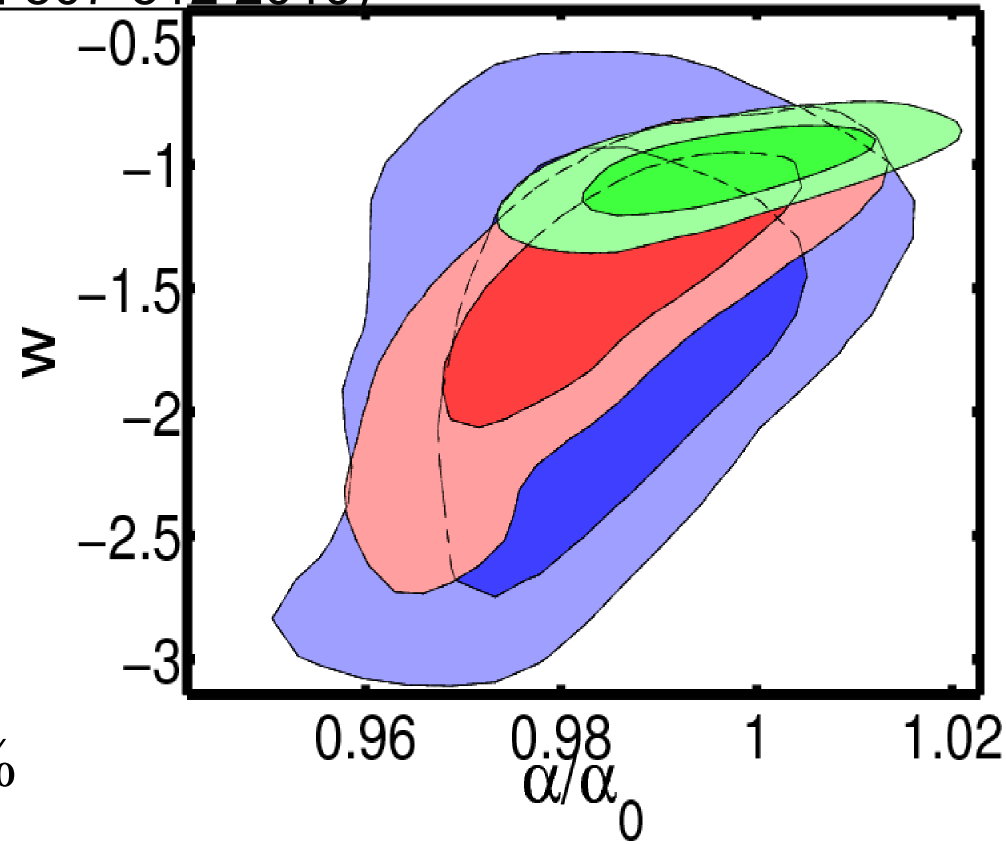
E. Menegoni, S. Pandolfi, S. Galli, M. Lattanzi, A. Melchiorri
(IJMPD, International Journal of Modern Physics D, Volume 19, Issue 04, pp. 507-512 2010)

Datasets	α/α_0	w
CMB	0.983 ± 0.012	-1.74 ± 0.53
CMB+ HST	0.983 ± 0.011	-1.52 ± 0.39
CMB+ HST+SN-Ia	0.996 ± 0.009	-1.02 ± 0.11

TABLE I: Limits on w and α/α_0 from CMB experiments (first row), from CMB plus the HST prior on the Hubble constant, $h = 0.748 \pm 0.036$ (second row), and from CMB+HST plus luminosity distances of supernovae type Ia from the UNION catalog. We report errors at 68% confidence level.

≈ 0.9%

≈ 1.1%



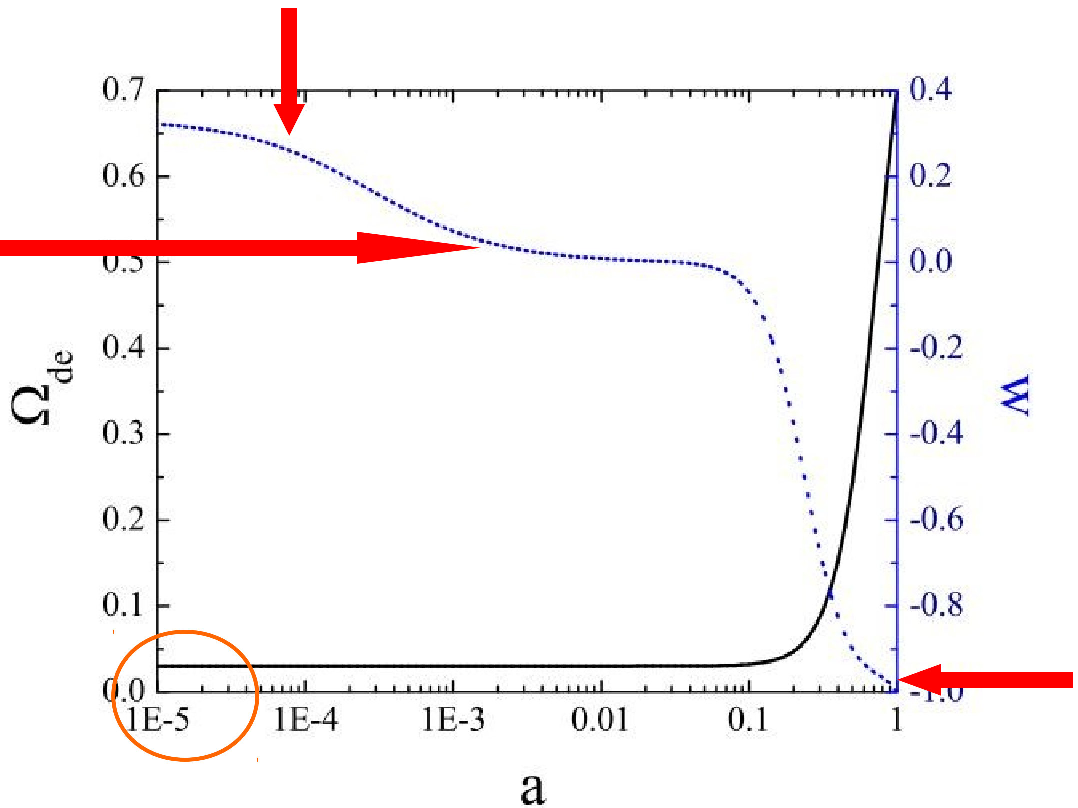
Varying fine structure constant: (possible) physical motivations

- The Standard cosmological model is consistent with current data only if we admits the presence of a dark energy component.
- If dark energy is described by a scalar field, this scalar field can be couple to the electromagnetic sector and change the value of alpha
- In order to have variations of alpha at recombination we need a scalar field with energy density non-negligible at recombination, i.e. Early Dark Energy
- It is therefore interesting to constrain alpha in the context of Early Dark Energy

Dark Energy model with a EDE constant component in the past

$\approx 1/3$

≈ 0



≈ -1

Behaviour of early dark energy model in energy density (solid black line) and equation of state (dotted blue line) as a function of the scalar factor.

$\Omega_e \approx 0.03$

Analysis method with variation of the fine structure constant and Ω_e

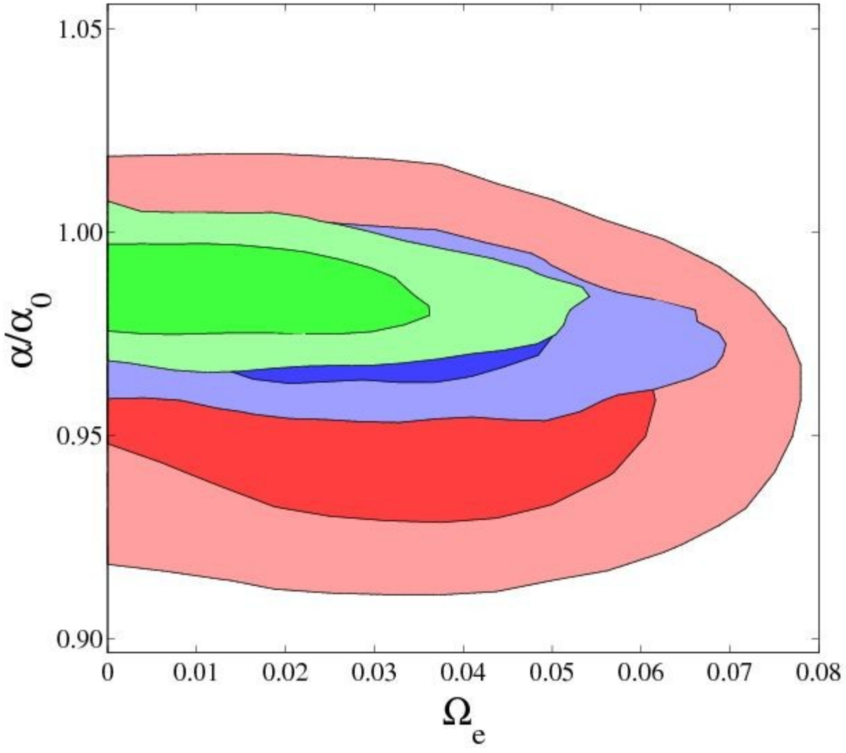
- We constrain variation in the fine structure constant and on the dark energy density parameter by sampling

  the following parameters: the baryon and cold dark matter densities, the Hubble constant, the scalar spectral index, the overall normalization of the spectrum, the optical depth to reionization, the variations on the fine structure constant and finally the variations in the primordial early dark energy density.

- This analysis is performed by modeling the EDE clustering proprieties through the effective sound speed and a viscosity parameter (which describes the possible presence of anisotropic stress).

- And also the equation state parameter w_0 is taken equal to -1 since the low redshift data are consistent with this value.

Constraints on the variations of the fine structure constant, EDE density parameter and on coupling



Experiment	α/α_0	Ω_e	ζ
WMAP7+HST	0.963 ± 0.044	< 0.064	< 0.047
WMAP7+ACT+HST	0.977 ± 0.010	< 0.051	< 0.028
WMAP7+ACT+HST+BAO	0.986 ± 0.014	< 0.043	< 0.024

Calabrese, Menegoni, Martins, Melchiorri and Rocha

CONCLUSIONS:

- We found a substantial agreement with the present value of the fine structure constant (we constrain variations at max of 2,5% at 68% level of confidence from WMAP-5 years and less than 0.7% when combined with HST observations).

- When we consider the equation of state parameter w, we notice a degeneracy that can alters the current constraints on w significantly.

- There is no clear degeneracy between the early dark energy density parameter and the fine structure constant, and we can reach tighter constraints on the fine structure constant with the future experimental data (Planck).