Testing the Variation of Fundamental Constants with the Cosmic Microwave Background

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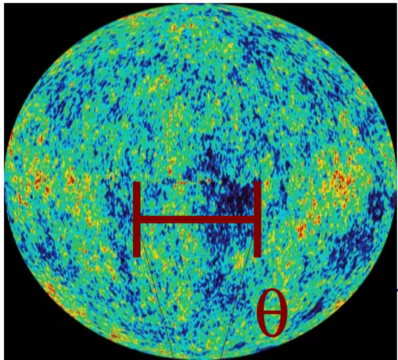
Outline

- Theory:
  - CMB and Standard Recombination
  - Variation of the fine structure constant
  - Variation of Newton's constant G.
- Results
  - Constraints from WMAP5+others.
  - Constraints from future experiments.
- Conclusions

CMB

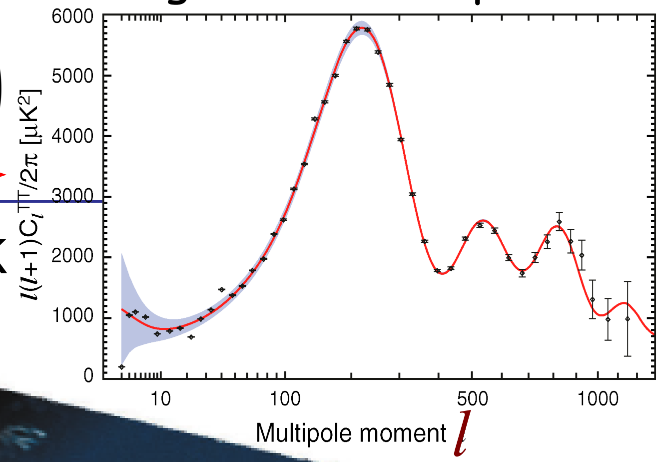


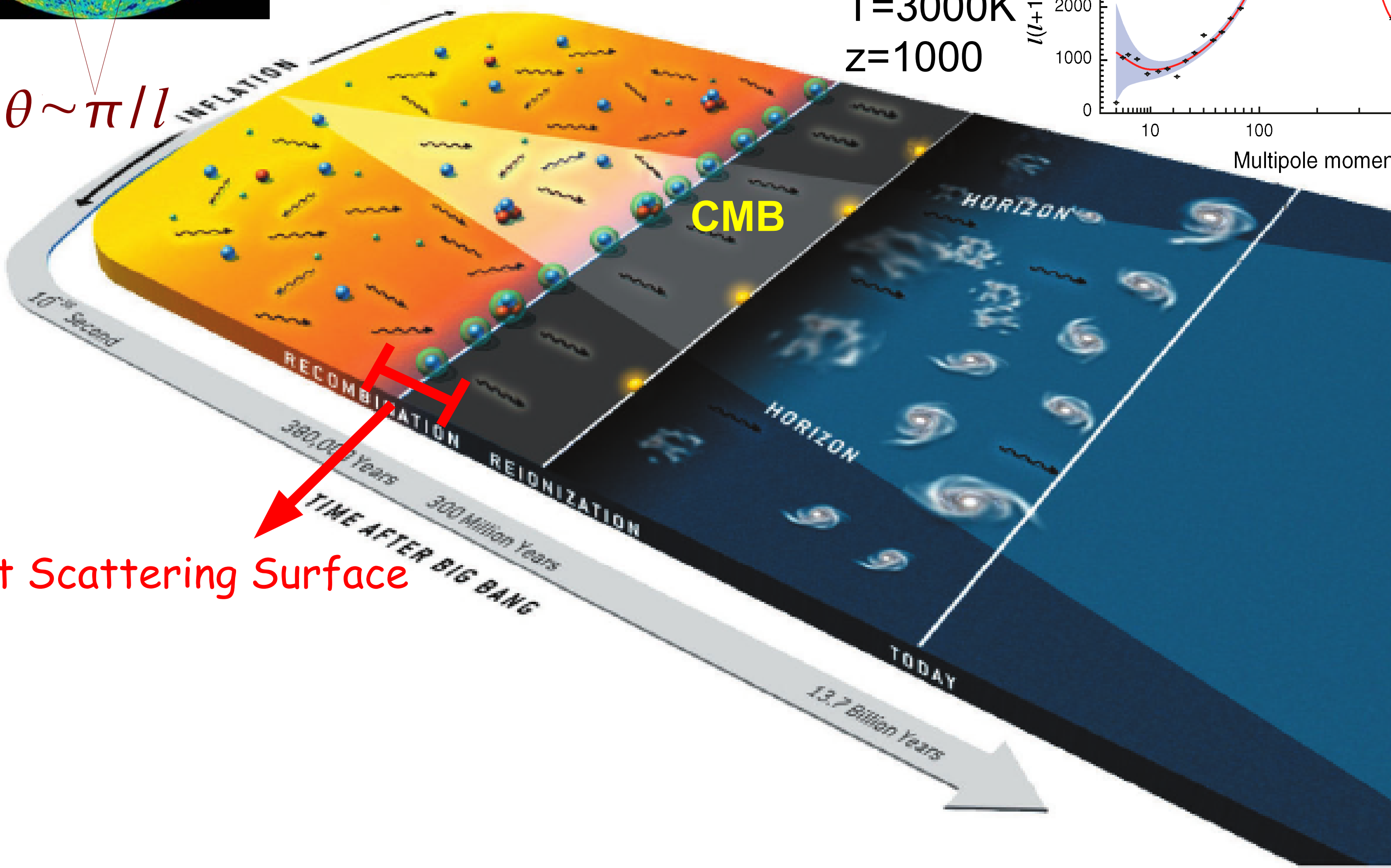
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

$\theta \sim \pi / l$

T=3000K
z=1000

Angular Power Spectra





Primary Anisotropies of CMB

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

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

These effects are convoluted with the **visibility function** which is defined as the probability density that a photon is last scattered at redshift z:

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

Gravity (Ψ) Adiabatic (Θ_0) Doppler ($\vec{n} \cdot \vec{v}_b$)

Visibility function

The visibility function rappresents the probability density that a photon is last scattered at η. Broadened by the finite thickness of the LSS.

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

Scattering rate

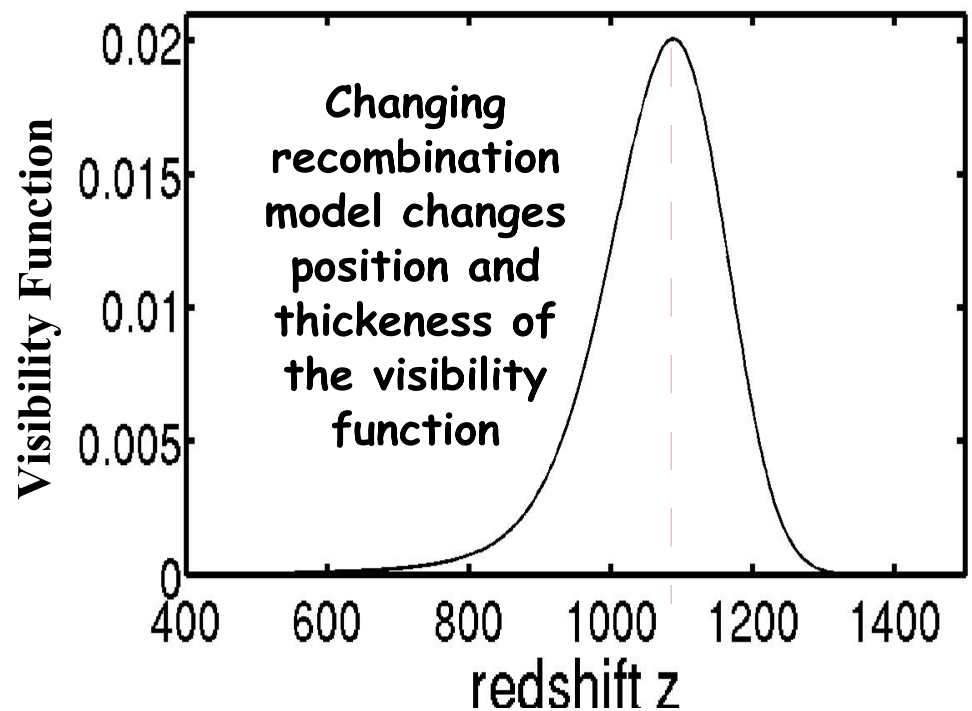
$$\dot{\tau}(\eta) = n_H x_e a \sigma_T$$

Optical Depth

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

$x_e = n_e / n_H$

The evolution of xe with time affects the optical depth and the scattering rate, therefore g(η) and the Angular Power Spectra!



Physics of recombination (Peebles (1968) and Zeldovich, Kurt & Sunyaev (1968))

Direct Recombination but NO NET recombination

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

2-photon decay from metastable 2s states

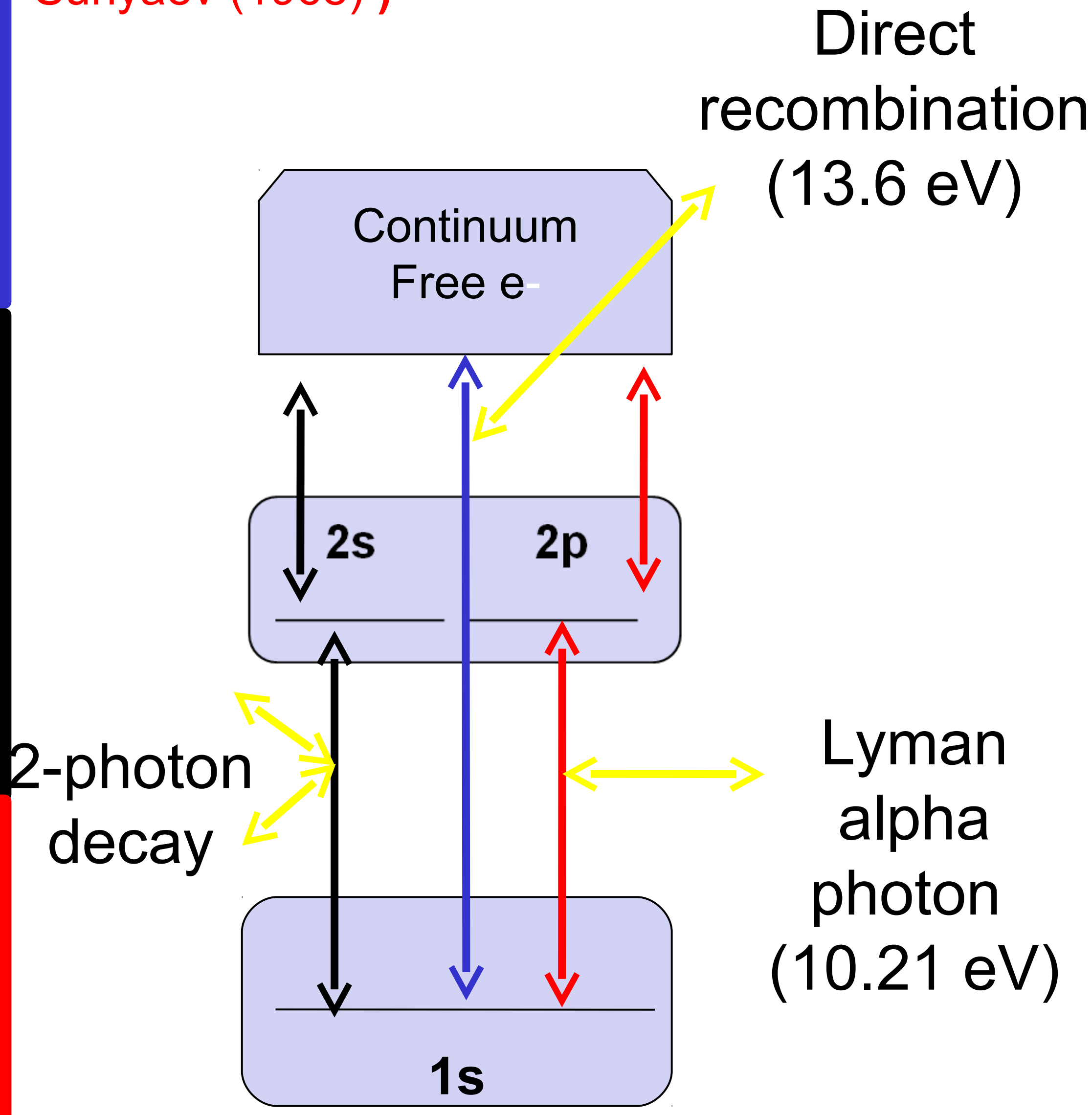
$$H^+ + e^- \leftrightarrow H_{2s} + \gamma$$

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

Cosmological redshift of the **Lyman alpha** photons

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

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



Non Standard Recombination

- Extra Injection of new Ionizing and Lyman Alpha photons:
  - Dark Matter Decay and annihilation
  - Evaporating Black Holes
  - Cosmic string decays,magnetic monopoles etc...
- **Variation of Fundamental Constants**

The Fine Structure Constant

Variation of The Fine Structure Constant

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

- The fine structure constant modifies the visibility function through the thompson scattering rate and xe:

$$\dot{\tau} = x_e(a) n \sigma_T a$$

Free electron Fraction

Thompson scattering cross section

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

1

The Evolution of the Free Electron Fraction

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

Ionization coefficient

$\beta_H \rightarrow R_H$

Recombination coefficient 2

$$R_H \rightarrow \sigma_{nl} \approx \alpha^{-1} m_e^{-1} f'(h\nu / B_1)$$

Ionization cross section nl state

Peebles coefficient

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

Rate of decay 2s a 1s 3

$$\Lambda_{2s} \propto m_e \alpha^8$$

Constant K $K = n_e \lambda_\alpha^3 / (8\pi H)$ 4

Lyman-alpha

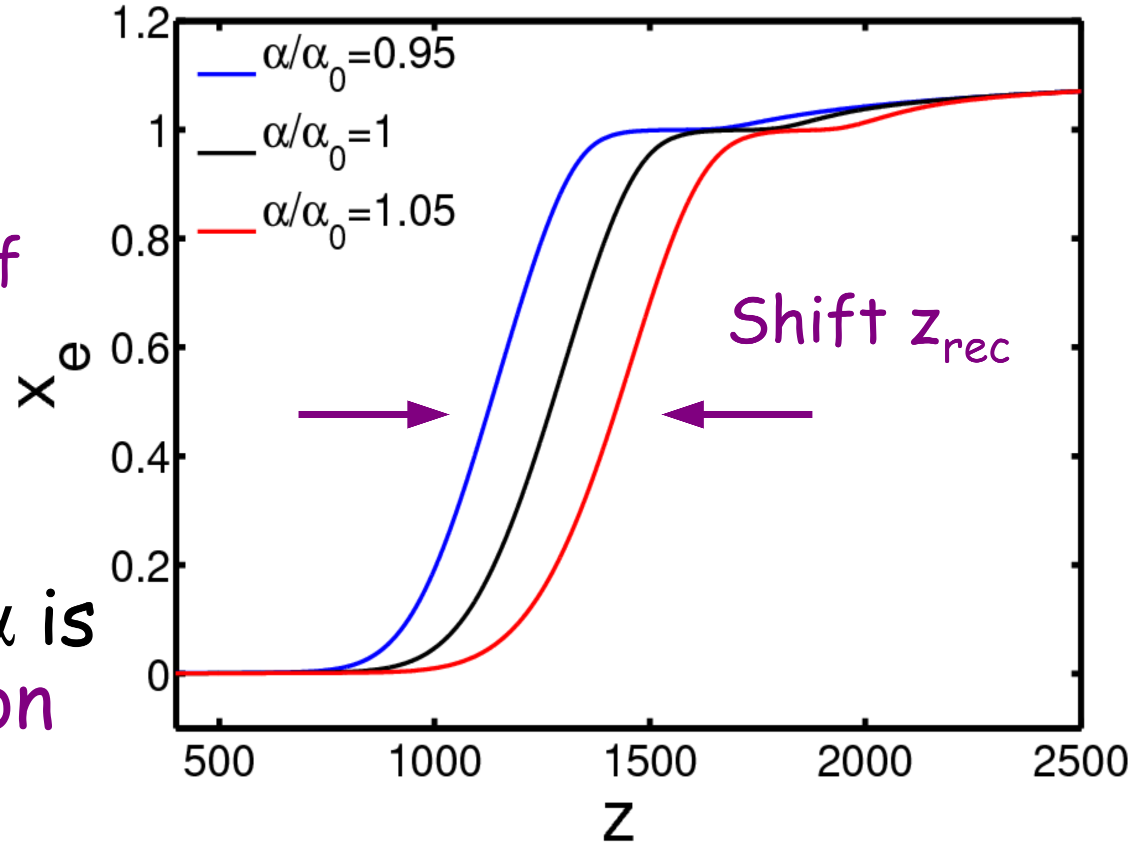
$$\lambda_\alpha = 16\pi\hbar / (3 m_e c^2) \alpha^{-2}$$

Variation of free electron fraction with α

Different values of α change the evolution of the free electron fraction.

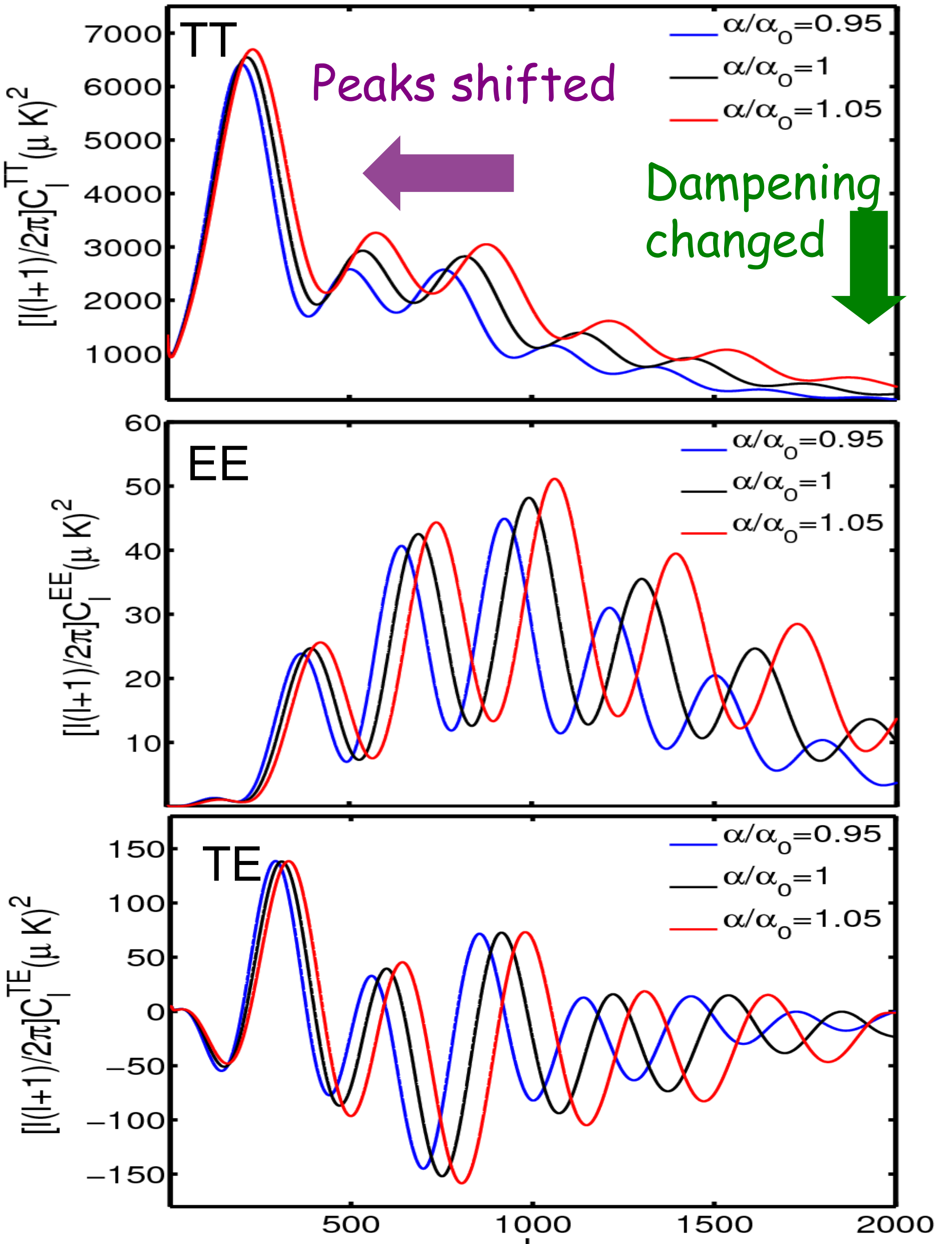
They **Shift the redshift** of recombination.
The shift is almost rigid.

In particular when α is **smaller,** recombination takes place later at smaller z.



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

The Angular Power Spectra with α



If the fine structure constant is **smaller:**

- Recombination is delayed, the size of the sound horizon $r_s \sim c_s \eta_{dec}$ at recombination is larger ($\eta_{de=}$conformal time at decoupling, c_s sound speed)
  - peaks of the CMB angular spectrum are shifted at lower l (larger angular scales).

$$l \approx \frac{n \pi \eta_0}{r_s}$$

  - The Frequency r_s of the oscillations is larger.
  - Larger Silk Dampening Scale k_D

Constraints on the fine structure constant

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

~2%

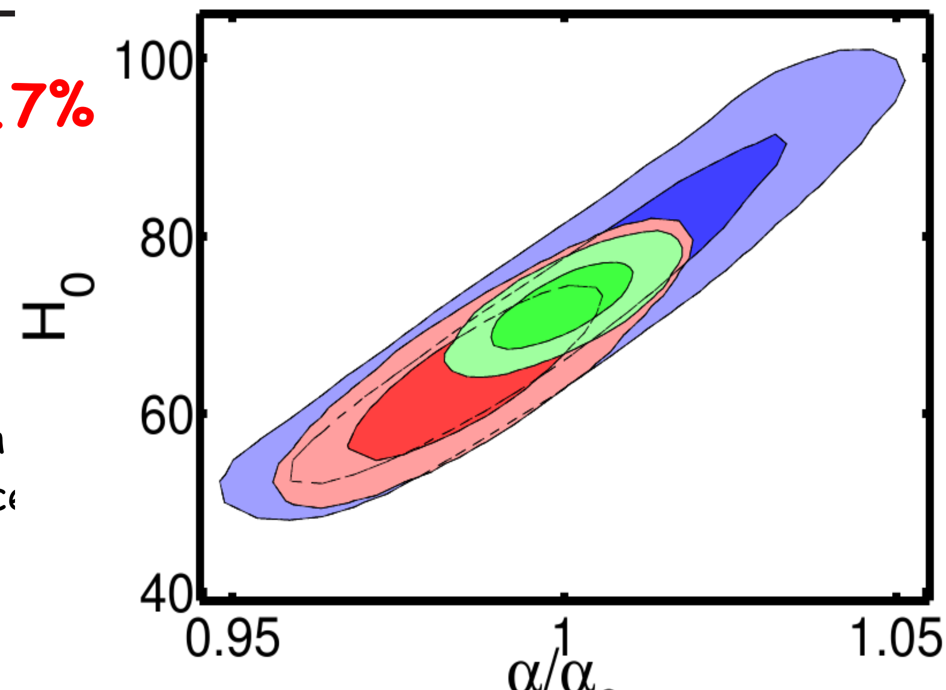
~0.7%

WMAP5 + prior 40<H0<100 Km/s/Mpc

All CMB: WMAP5+ACBAR+ +QUAD+CBI+BOOMERANG + prior 40<H0<100 Km/s/Mpc

HST: prior H0=74.7 ± 3.6 Km/s/Mpc

- Constraints from current CMB data far to be competitive with CODATA relative error=6.8x10^{-10} at 68% cl.
- BUT we test different space-time scales!
- Constraining power limited by degeneracy with H0, that changes the angular diameter distance at recombination as well and therefore shifts the peaks.



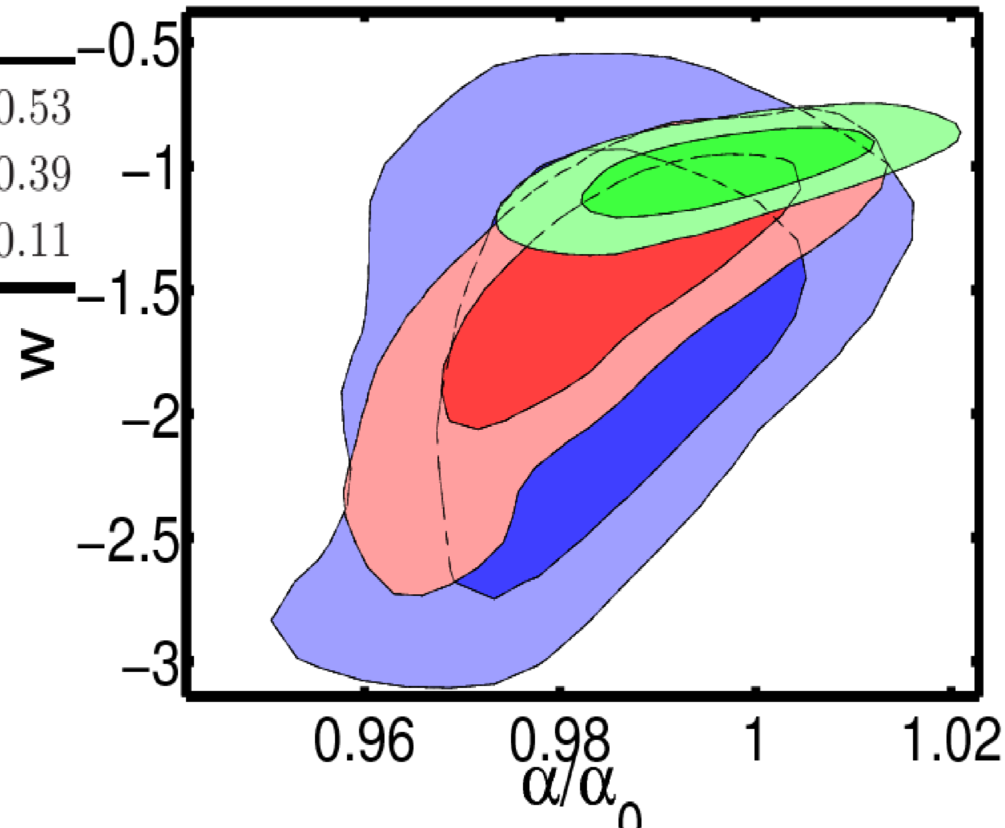
E. Menegoni, S.Galli, J. Bartlett, C. J. A. P. Martins, A. Melchiorri et al.
arXiv:0909.3584v1 Phys. Rev. D *80 08/302 (2009)*

DE Equation of state and α

Dark energy equation of state different from w=-1, would lead to a change in the angular diameter distance of the LSS, shifting the peaks. This causes a degeneracy with α.

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

1.1%



CMB: WMAP5+ACBAR+
+QUAD+CBI+BOOMERANG + prior
40<H0<100 Km/s/Mpc

HST: prior H0=74.7 ± 3.6 Km/s/Mpc
SN-Ia: Union Catalog

Menegoni, E.,, Pandolfi, S., Galli, S., Lattanzi, M., Melchiorri, A.
2010, I. J.M. P. D, 19, 507

The Gravitational Constant

Variation of the Gravitational constant G

$$G = \lambda_G^2 G_0$$

Dimensional constants do not have physical significance BUT if one assumes particle masses to be constant, constraints on the gravitational constant G are in fact constraining the dimensionless product of G and the nucleon mass squared.

$$\alpha_G = G \underbrace{m_p^2 / (\hbar c)}_{\text{constant}}$$

Variation of the Gravitational constant G

The variation of G modifies:

1.) **The Friedmann equation:**

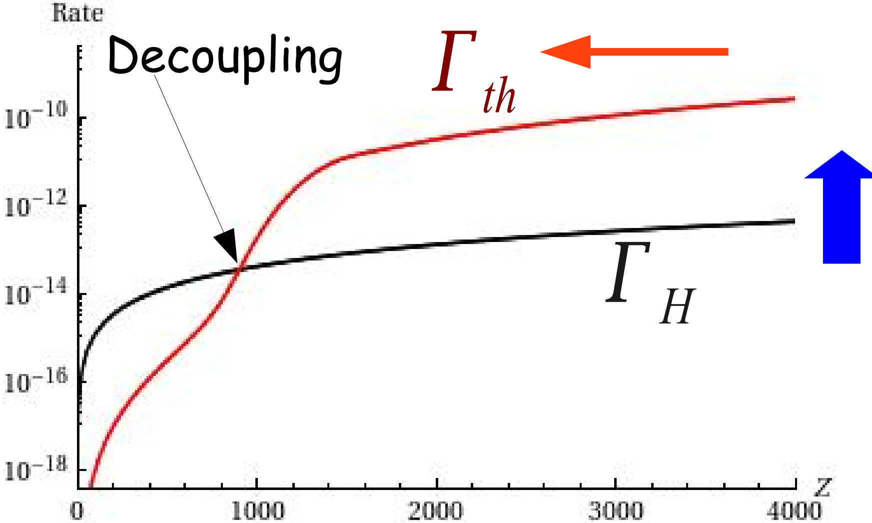
REDSHIFT of Decoupling is changed, i.e. the moment when the expansion rate equals the Thompson scattering rate.

If G is **larger**, decoupling will happen earlier → zdec is larger and the sound horizon is smaller.

BUT! The recombination evolution and therefore the scattering rate are affected as well......

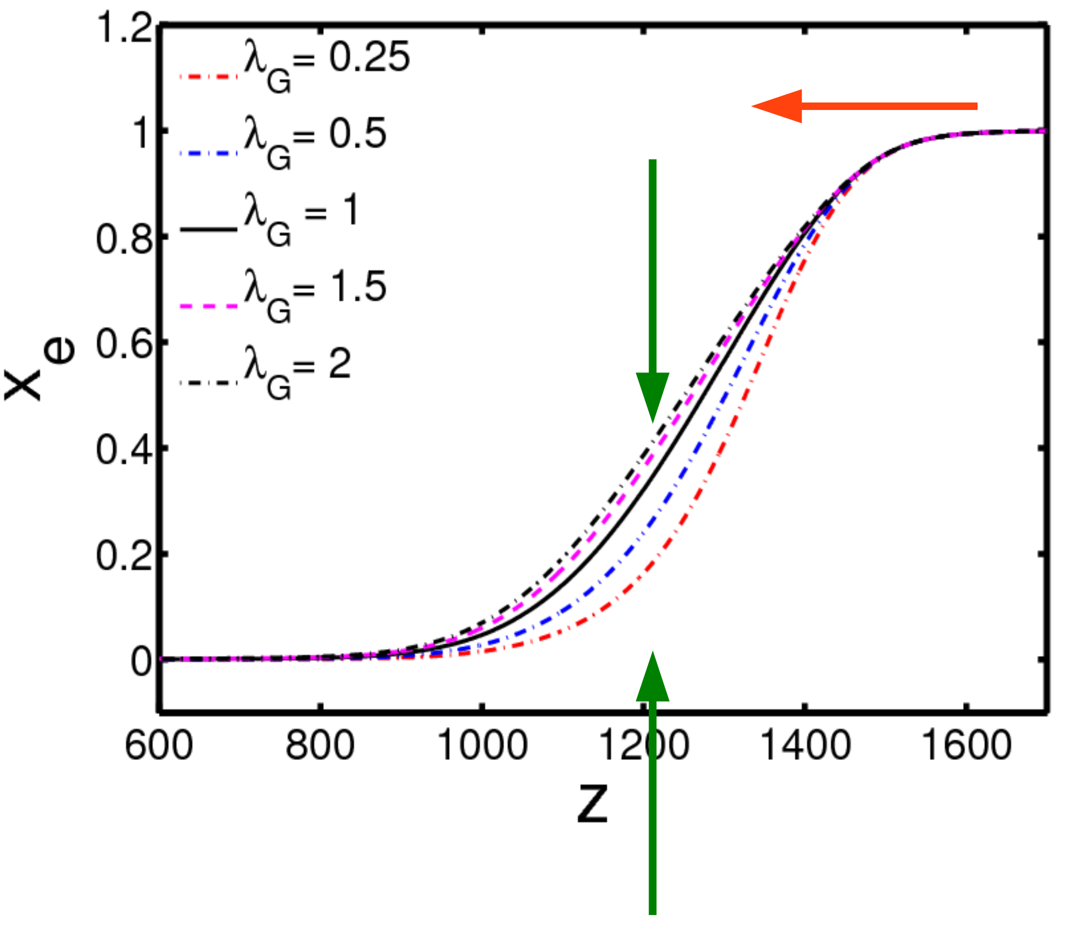
$$\Gamma_H = H(z) = \sigma_{th} n_e(z) c = \Gamma_{th}$$

$$H(z) = \frac{8\pi G}{3} \Sigma_i \rho_i(z)$$



Evolution of the Free Electron Fraction with G

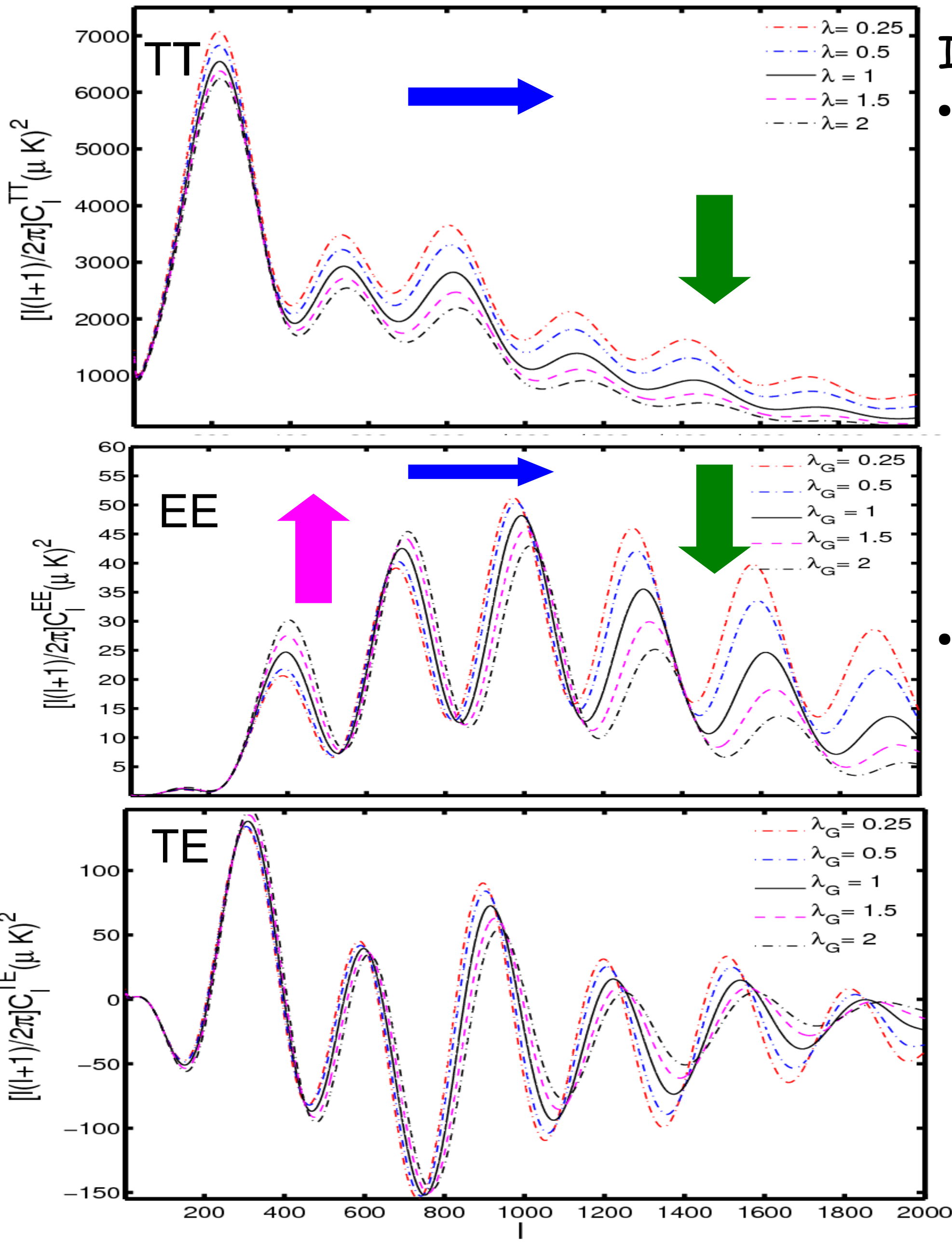
1) **<u>Larger</u>** values of G makes recombination of Hydrogen more difficult, as the expansion of the universe is increased. Recombination is delayed. BUT remember this only PARTIALLY compensates the fact that the expansion rate of the universe is larger.



2) Recombination takes LONGER!

<u>The thickness of the last scattering surface is then larger</u>.

Power Spectra with G



If G is **larger:**

- Decoupling happens earlier, so the sound horizon is smaller:
  - peaks of the CMB angular spectrum are shifted at higher l (larger angular scales), but small change due to compensations.
  - The Frequency r_s of the oscillations is smaller.

- The width of the LSS is THICKER:
  - CMB photons come from different times, fluctuations less in phase. Amplitudes of the peaks smothed, more on small scales.
  - Polarization amplitude is enhanced by the wider thickness of the LSS, but small scales are smothed as TT.

Constraints on the gravitational constant

Experiment	Constraints on λ_G at 68% c.l.
WMAP	1.01 ± 0.16
WMAP+POL	0.97 ± 0.13
WMAP+ACBAR	1.03 ± 0.11
WMAP+BBN	0.98 ± 0.03
PLANCK	1.01 ± 0.015
CVL	1.002 ± 0.004

~10%

0.4%

WMAP5

POL :CBI+BOOM

BBN:Deuterium

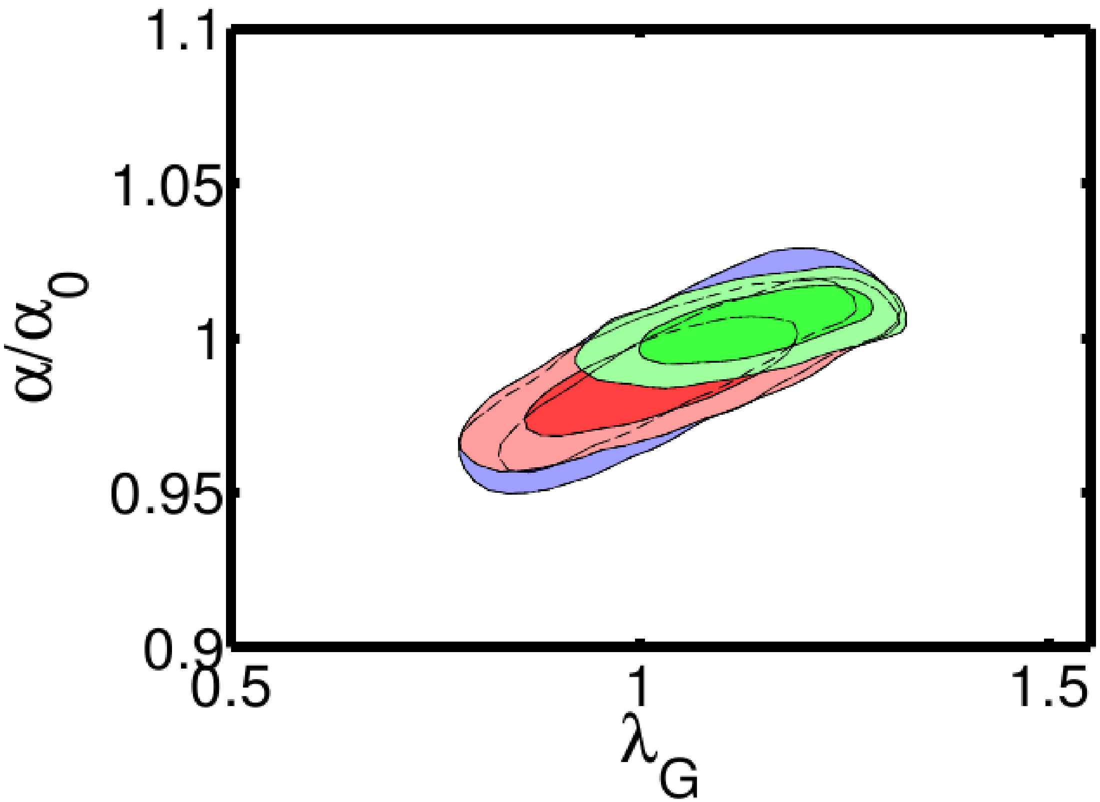
- Constraints from current CMB data are not competitive with laboratory constraints.

S. Galli, A. Melchiorri, G. Smoot,O. Zahn 2009, PRD, 80, 023508 arXiv:0905.1808v2

There is a degeneracy between the fine structure constant and gravitational constant

Rolling of couplings expected to be due to the same underlying mechanism in most theories (e.g. dynamical, fundamental scalar field), the rates of change of the couplings will be related.

$$\frac{\alpha}{\alpha_0} - 1 = Q(\lambda_G^2 - 1)$$

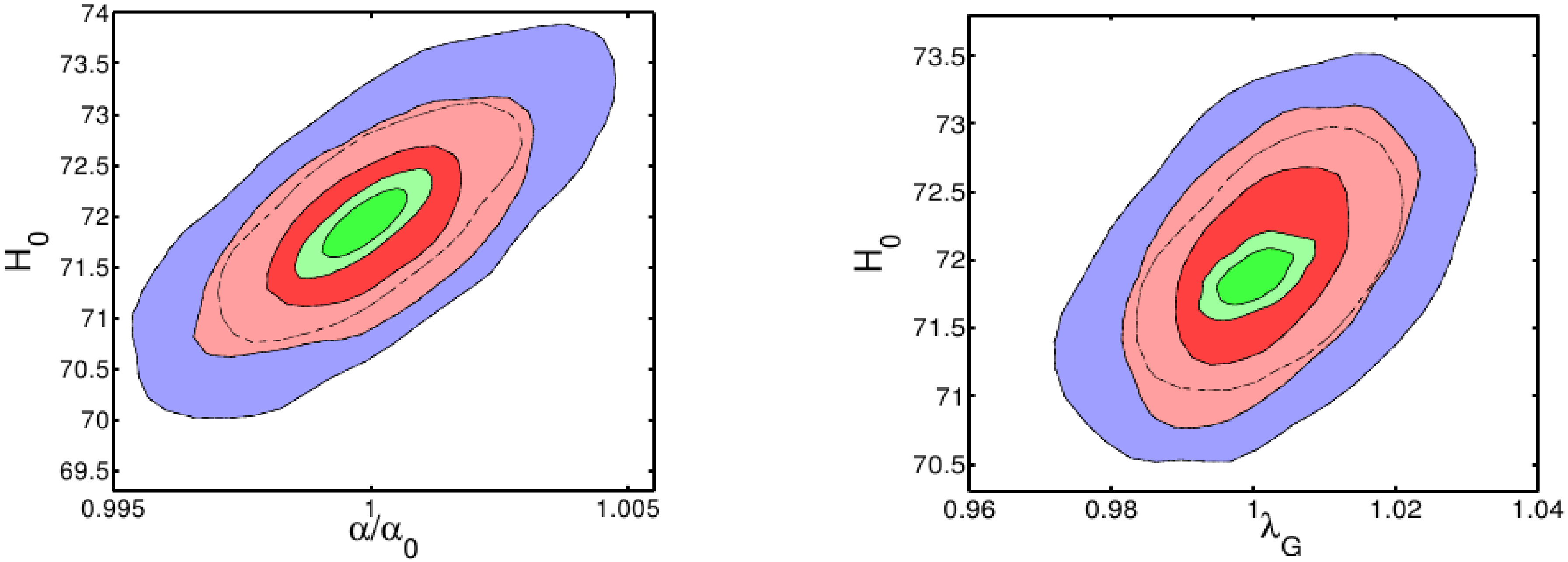


Experiment	α/α_0	68% c.l.	λ_G	68% c.l.
All CMB	0.999	±0.017	1.04	±0.12
All CMB+SN-Ia	0.989	±0.012	1.04	±0.11
All CMB+HST	1.003	±0.008	1.13	±0.09
ALL CMB+BBN	0.985	±0.009	1.01	±0.01
Planck only	1.000	±0.015	1.02	±0.09

All CMB:
WMAP5+ACBAR+
+QUAD+CBI+BOOMERA
NG + prior 40<H0<100
Km/s/Mpc

Martins, C.J.A.P., Menegoni, E., Galli, S., Mangano, G., Melchiorri, A. 2010, PRD, 82, 023532

Future Constraints



Planck= (blue)
Planck+ACT=(red),
CMBpol=(green)

Parameter uncertainty	Planck	Planck+ACTPol		CMBPol	
$\sigma(\alpha)$	0.0018	0.0013	(1.4)	0.00053	(3.7)
$\sigma(\lambda_G)$	0.012	0.0081	(1.5)	0.0030	(4.0)

0.8%

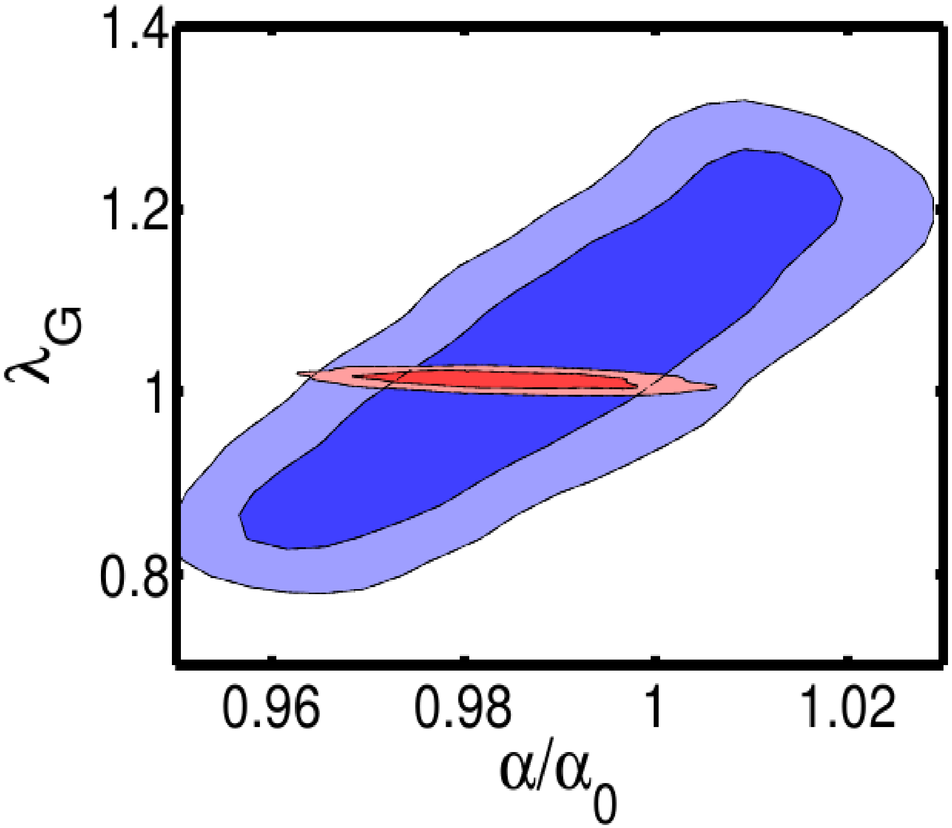
ACT will add small scales information on TT and EE polarization power spectra, improving the Planck data.

S. Galli, M. Martinelli, A. Melchiorri, L. Pagano, B. D. Sherwin, D. N. Spergel, 2010, arXiv:1005.3808, submitted to Phys. Rev. D.

Conclusions:

- We found a substantial agreement with the present value of the fine structure constant (~2% with WMAP, ~0.7% CMB+HST) and the Gravitational Constant (~10% CMB, ~3% CMB+BBN).
- When α and G are both let varying, current data give no clear indication about the relative sign of the variations, but prefers relative variations of the same sign for 1% variations G. Much tighter constraints by adding BBN data.
- Future experiments such as Planck combined with ACT will improve constraints of one order of magnitude.

If we include the BBN data the degeneracy between G and the fine structure constant can be broken



If we assume that the fine structure constant and G don't vary from BBN to recombination we can combine the CMB results with BBN analysis. Differently than for CMB, in case of BBN, variations of the fine structure constant and G are negatively correlated, since both Y_p and Deuterium are increasing functions of both parameters: this implies that the likelihood countours for BBN and CMB are almost orthogonal in that plane, thus leading to a tighter bound, in particular on λ_G .