Testing Fundamental Physics with the Cosmic Microwave Background

Silvia Galli
Laboratoire APC, Paris VII
University of Rome La Sapienza

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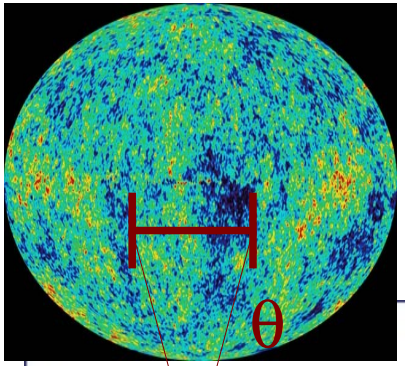
Outline

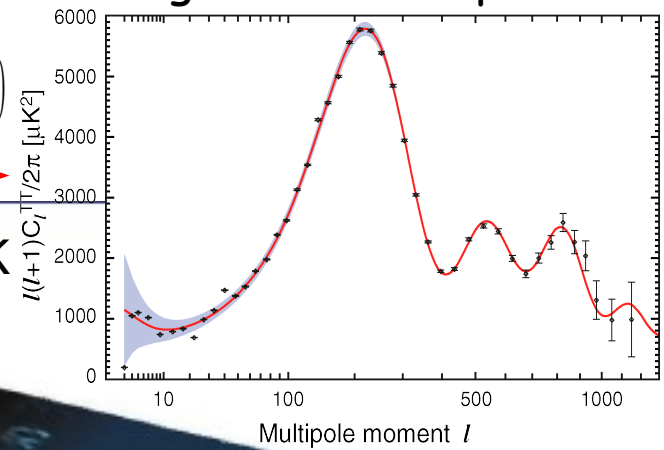
- Overview on CMB and standard recombination
- Changing std. recombination:
  - Dark Matter Annihilation
  - Variation of Fundamental constants
    - The Fine Structure Constant
    - The Gravitational Constant
- Conclusions

CMB

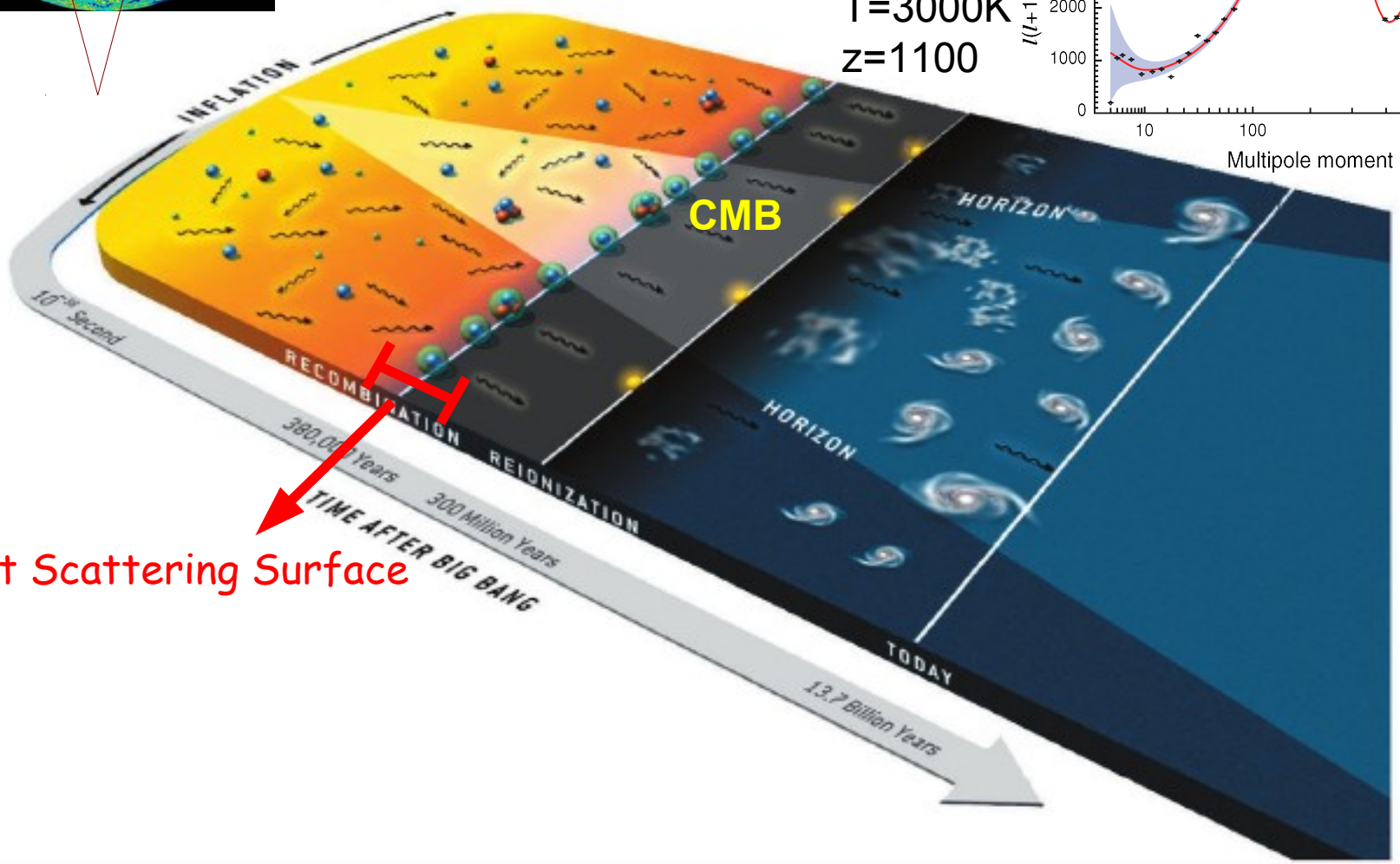


$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

Angular Power Spectra



T=3000K
z=1100



Last Scattering Surface

Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

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:

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

Gravity Adiabatic Doppler

η= conformal time

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

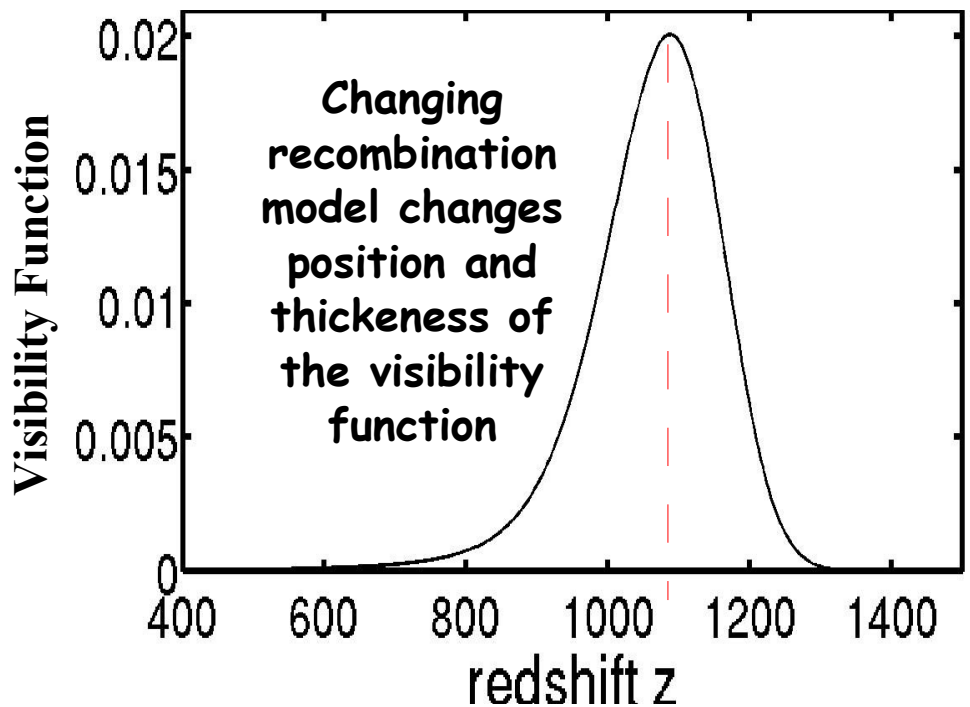
$$\dot{\tau}(\eta) = n_H x_e a \sigma_T$$

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

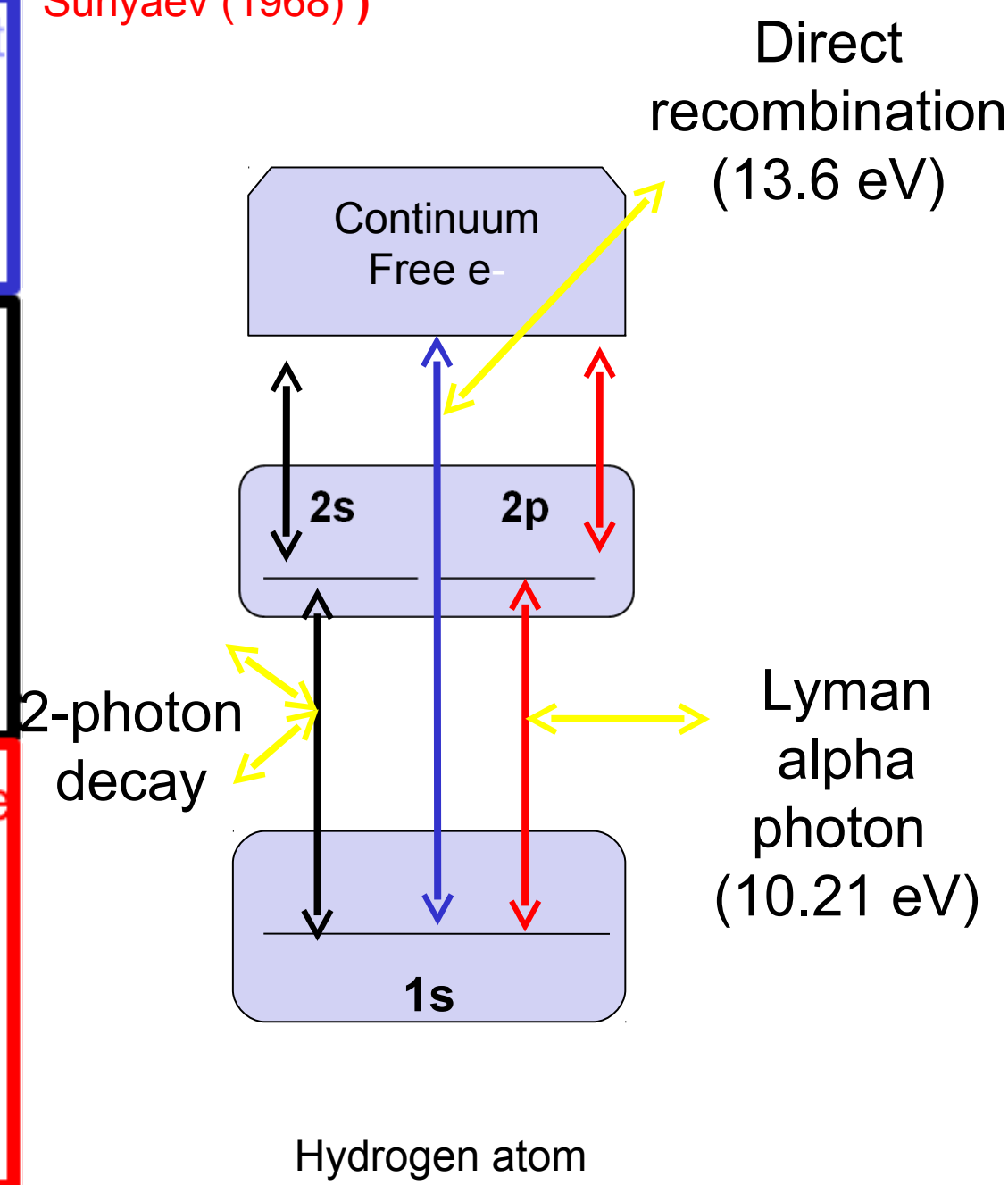
$$H^{+} + e^{-} \leftrightarrow H_{2s} + \gamma$$

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

Cosmological redshift of the **Lyman alpha** photons

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

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



Non Standard Recombination

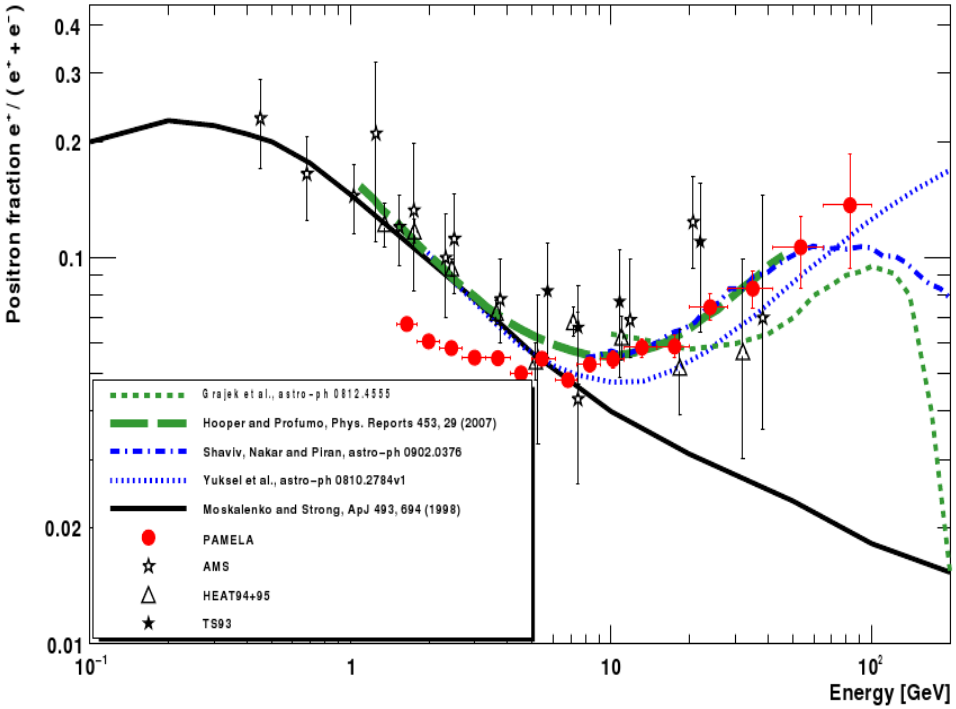
- Extra Injection of new Ionizing and Lyman Alpha photons:
  - **Dark Matter Annihilation** and Decay
  - Evaporating Black Holes
  - Cosmic string decays,magnetic monopoles etc...
- **Variation of Fundamental Constants**

Dark Matter Annihilation

Motivations

- **Anomalies:** excess in the positron electron fraction and in the energy spectrum of electrons.
- Several explanations: pulsar emission, dark matter decay, **dark matter annihilation** etc…

Positron Electron Fraction

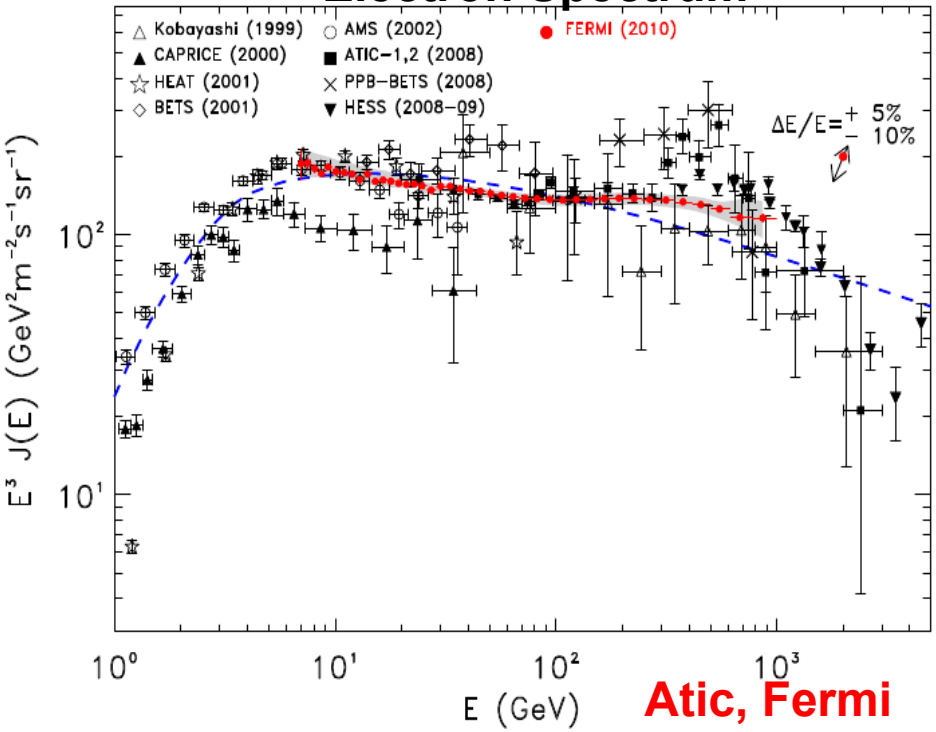


Adriani, O., et al.2009, Nature, 458, 607

Pamela

Mocchiutti, E., et al.\ 2009, arXiv:0905.2551

Electron Spectrum



Atic, Fermi

Fermi Lat-collaboration arXiv:1008.3999

Motivations

→ **Thermal production of DM:**

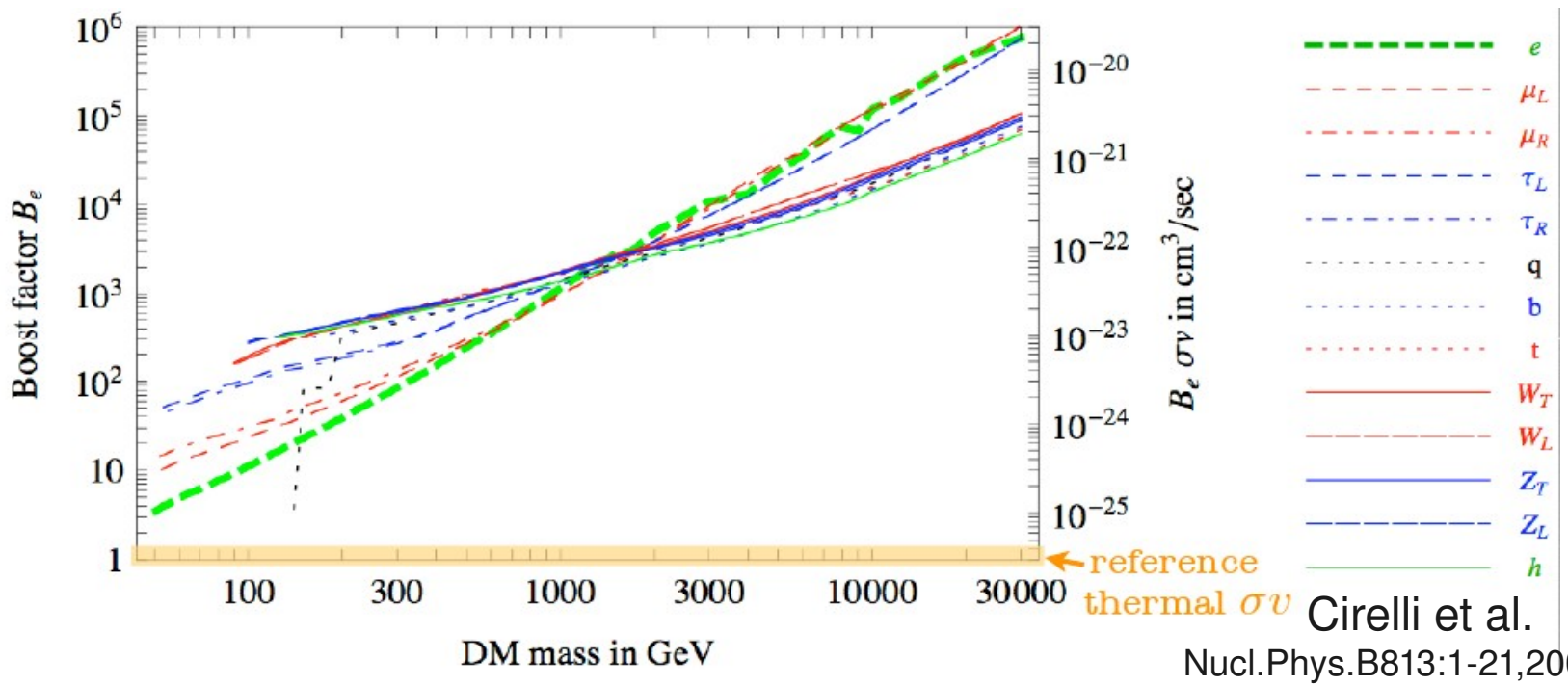
$\langle\sigma v\rangle \sim 10^{-26}\ cm^3/s.$ **(WIMP)**

→ **Annihilation rate:**

$\Gamma \propto n^2 \langle\sigma v\rangle$. n from dm simulations, models, observations

Astrophysical or Particle Physics **BOOST** to explain the data.

Profumo, S. 2005, PRD, 72, 103521



Cirelli et al.
Nucl.Phys.B813:1-21,2009

Motivations

→ **Thermal production of DM:**

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BOOST of the cross section to explain the data, depends on mass of DM and annihilation channel.

Dark Matter annihilation should leave a signature in CMB:

➜ At (z~1000), when CMB forms, the homogenous dark matter density is $n(z=1000) = n_{today}\,(1+z)^3 \sim n_{today} \times 10^9$

➜ DM mean velocity $\beta \sim 10^{-8}$. Favours Sommerfeld Enhancement.

Testing a specific Model: Dark Matter annihilation

- Lyman alpha and ionizing photons affects xe and temperature

$$dE/dt = \rho_c^2 c^2 \Omega_{DM} (1+z)^6 \left[f \frac{\langle \sigma v \rangle}{m_\chi} \right]$$

Energy injection rate

p_{ann}

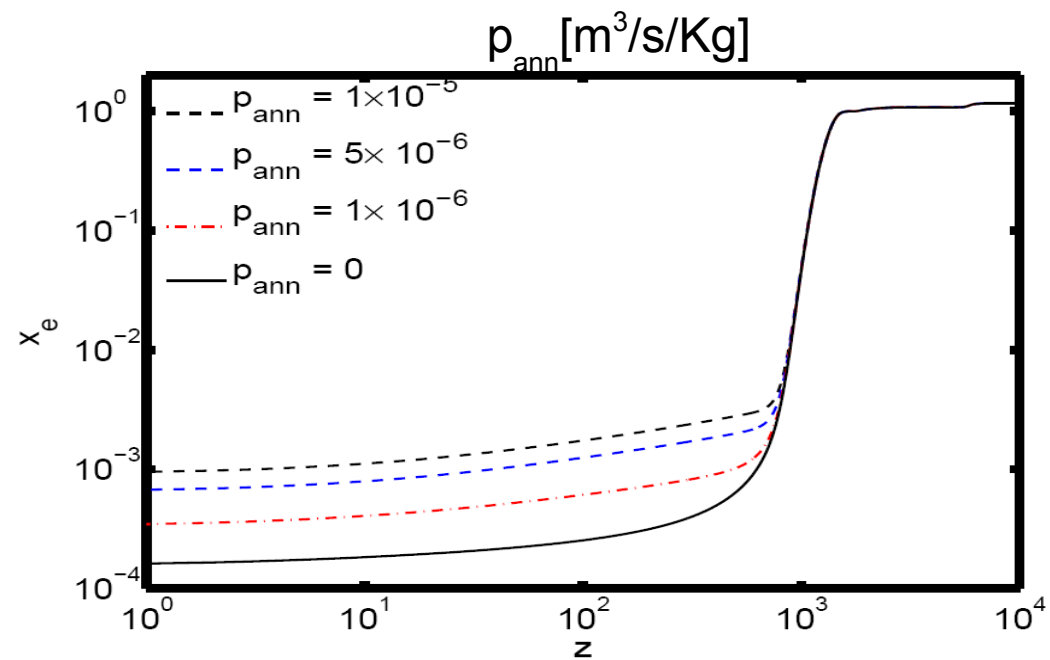
Redshift dependence of the injection rate of Lyman alpha (εα), ionizing (εi) photons and
heating term that changes matter temperature

One new parameter that contain:
f = energy fraction to plasma
<σv> = cross section
m_χ = mass of the annihilating particle

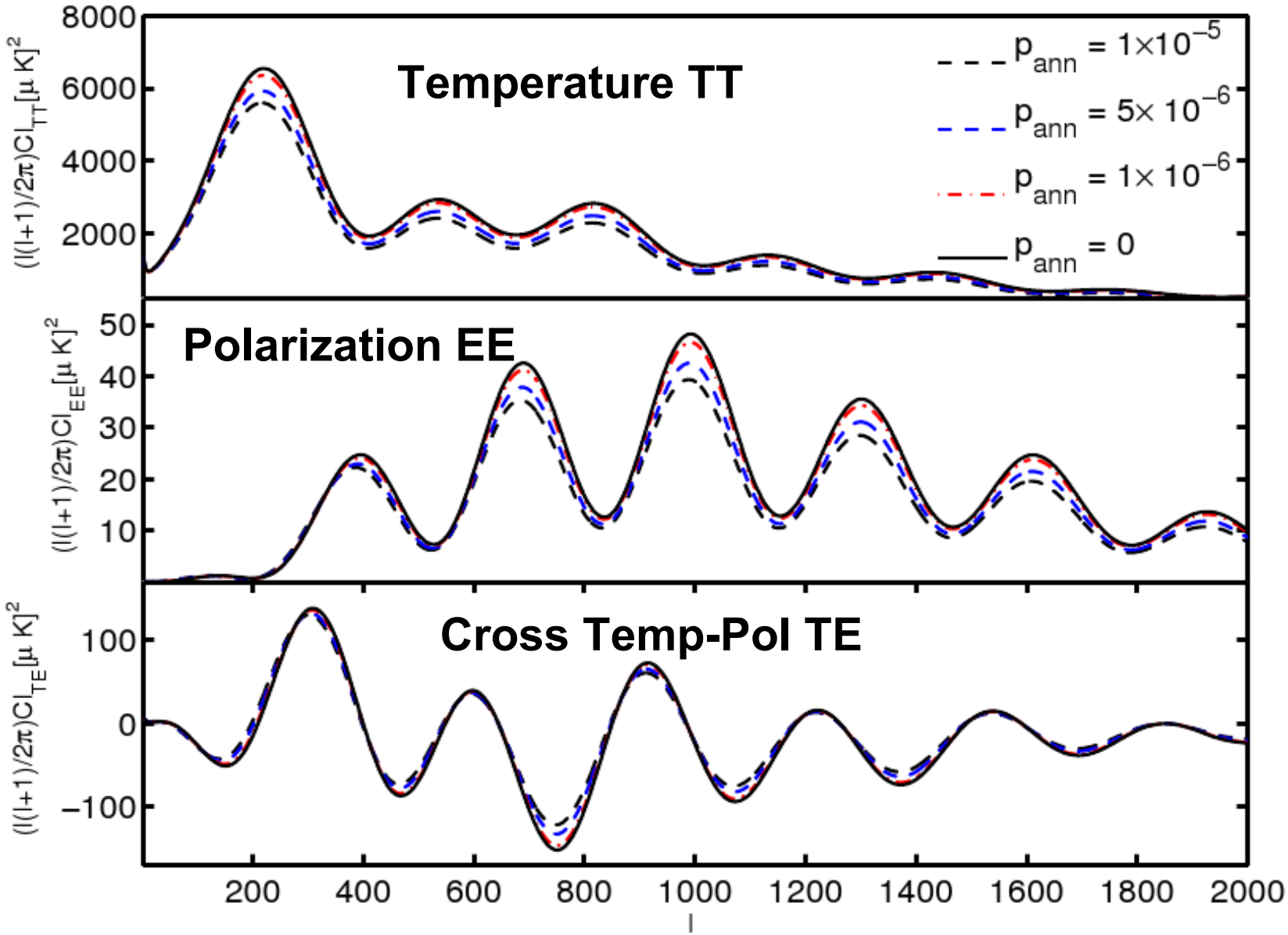
$$\varepsilon_\alpha(z) = C \chi_\alpha \frac{dE/dt}{n_H(z) E_\alpha H(z)}$$

$$\varepsilon_i(z) = C \chi_i \frac{dE/dt}{n_H(z) E_i H(z)}$$

$$\kappa_h = \chi_h \frac{dE/dt}{n_H(z)}$$



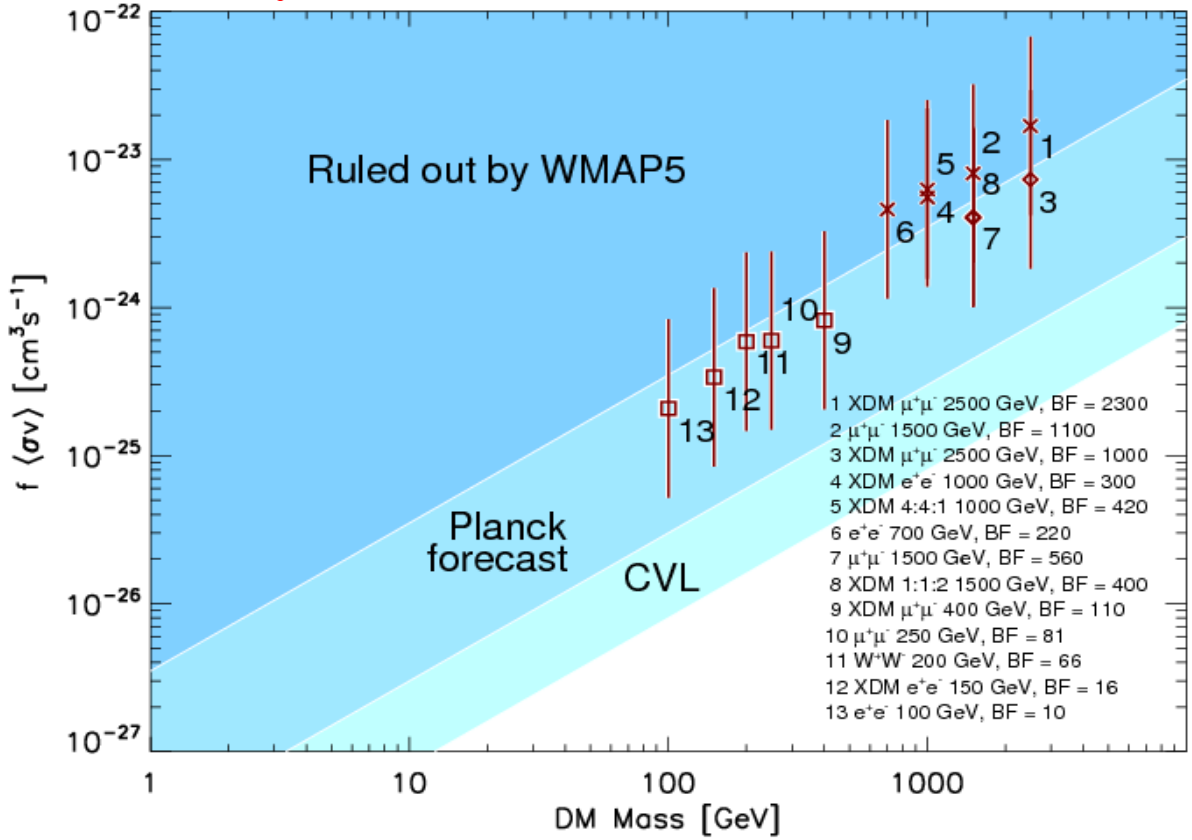
CMB Angular Power Spectra



Results on dark matter annihilation

Constraints on the p_ann parameter =fraction of DM annihilation energy that goes into the plasma times DM cross section divided by DM mass using Wmap5 data, Planck mock and a hypotetical Cosmic Variance limited experiment

$$p_{ann} = f \frac{\langle \sigma v \rangle}{m_\chi}$$

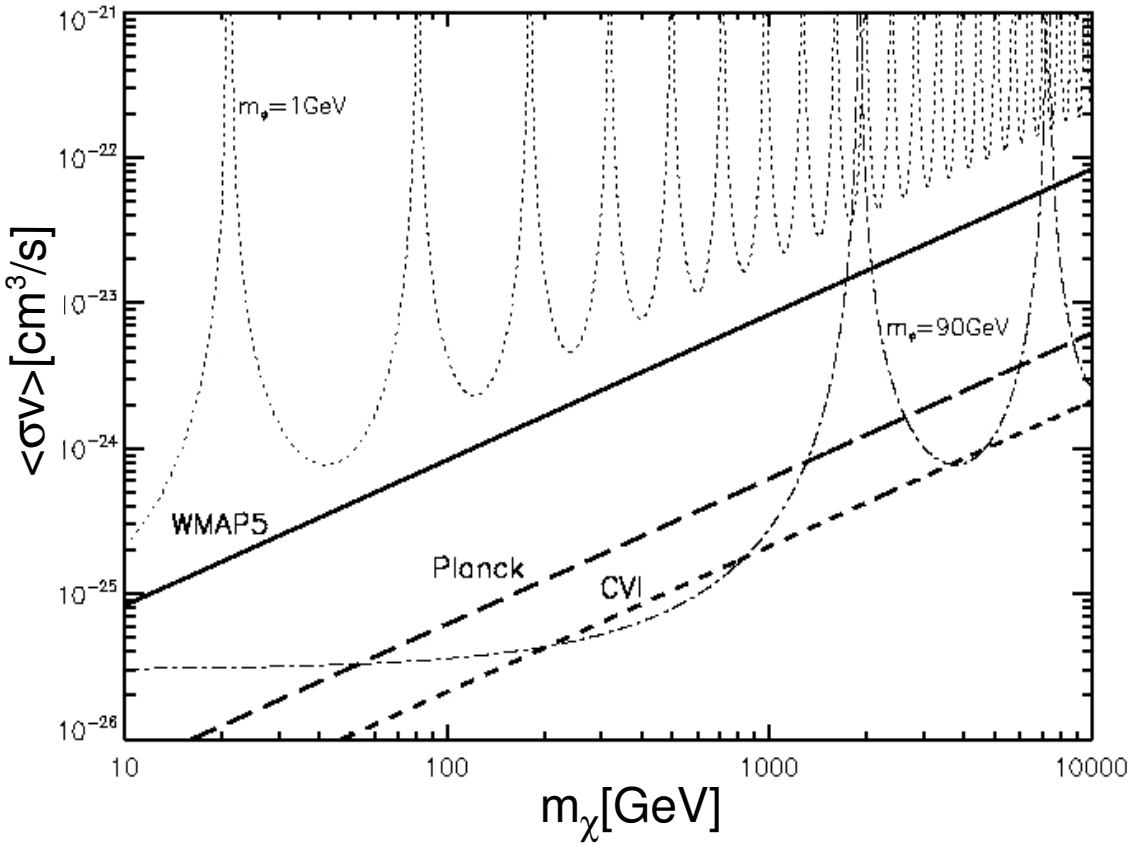


Experiment	p_{ann} 95% c.l.
WMAP	$< 2.4 \times 10^{-6} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
Planck	$< 1.7 \times 10^{-7} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
CVl	$< 5.9 \times 10^{-8}\ \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$

Points from Slatyer et al. arXiv:0906.1197

S. Galli, F. Iocco, G. Bertone, A. Melchiorri, Phys. Rev. D, vol. 80, Issue 2, (arXiv:0905.0003), 2009.

Coupling with gas: constant f



- Assuming constants f=0.5
- Runs with a more proper redshift-variable coupling with the plasma are on going.
- Depends on annihilation channel, mass of the particle (Based on T.R. Slatyer, N. Padmanabhan, P. D. Finkbeiner, arXiv:0906.1197)

Future constraints

- Constraints improvable by exctracting the lensing signal with the Hu and Okamoto quadratic estimator. (Okamoto, T., & Hu, W. 2003, Phys. Rev. D, 67)

Adding lensing extration will improve Planck data by 10%.

ACTpol will provide info useful for CMB science till **TT lmax~2500** and **EE lmax~3500** (foregrounds limited). ACT will improve Planck Data by 20%.

CMBpol with lensing extraction will constrain DM annihilation to a level comparable to the CVI case.

Experiment	p_{ann} 95% c.l.
Planck	$< 1.5 \times 10^{-7} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
Planck+ACT	$< 1.2 \times 10^{-7} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
CMBpol	$< 6.3 \times 10^{-8}\ \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$

Galli S., Martinelli M., Melchiorri A., Pagano L., Sherwin B., Spergel D., arXiv:1005.3808

Conclusions on Dark Matter annihilation

- CMB = very good DM annihilation probe as indipendent from the knowledge of DM distribution
- WMAP already puts strong constraints
- More accurate model needed to improve constraints
- Planck will improve constraints by one order of magnitude.

Variation of Fundamental Constants

Variation of fundamental constants

- Variation of Fundamental Constants predicted by different theories.
- Testable with CMB, as gravitational constant or of the fine structure constant change the history of recombination.
- A first approach to the problem is to test how much CMB can constrain the constant value of G and α.

The Fine Structure Constant ?

Evidence for spatial variation of the fine structure constant

J. K. Webb[1], J. A. King[1], M. T. Murphy[2], V. V. Flambaum[1], R. F. Carswell[3], and M. B. Bainbridge[1]
[1] *School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*
[2] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H39, PO Box 218, Victoria 3122, Australia and*
[3] *Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, England.*
(Dated: August 25, 2010)

We previously reported observations of quasar spectra from the Keck telescope suggesting a smaller value of the fine structure constant, α, at high redshift. A new sample of 153 measurements from the ESO Very Large Telescope (VLT), probing a different direction in the universe, also depends on redshift, but in the opposite sense, that is, α appears on average to be larger in the past. The combined dataset is well represented by a spatial dipole, significant at the 4.1σ level, in the direction right ascension 17.3 ± 0.6 hours, declination -61 ± 9 degrees. A detailed analysis for systematics, using observations duplicated at both telescopes, reveals none which are likely to emulate this result.

PACS numbers: 06.20.Jr, 95.30.Dr, 95.30.Sf, 98.62.Ra, 98.80.-k, 98.80.Es, 98.80.Jk

Webb, J. K., King, J. A., Murphy, M. T., Flambaum, V. V., Carswell, R. F., Bainbridge, M. B. 2010, arXiv:1008.3907

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

Thomson 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

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

2

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

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

3

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

Lyman-alpha

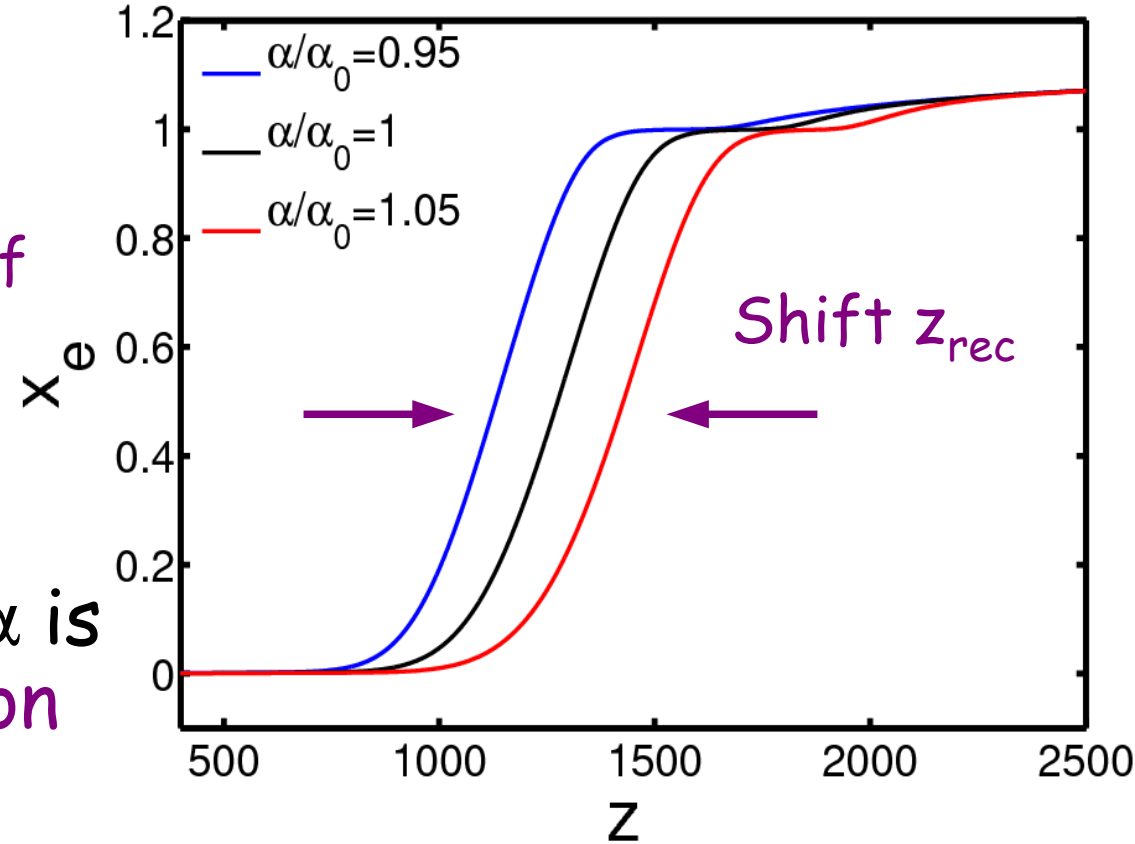
$$\lambda_\alpha = 16\pi \hbar / (3 m_e c^2) \alpha^{-2}$$

4

Variation of free electron fraction with α

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

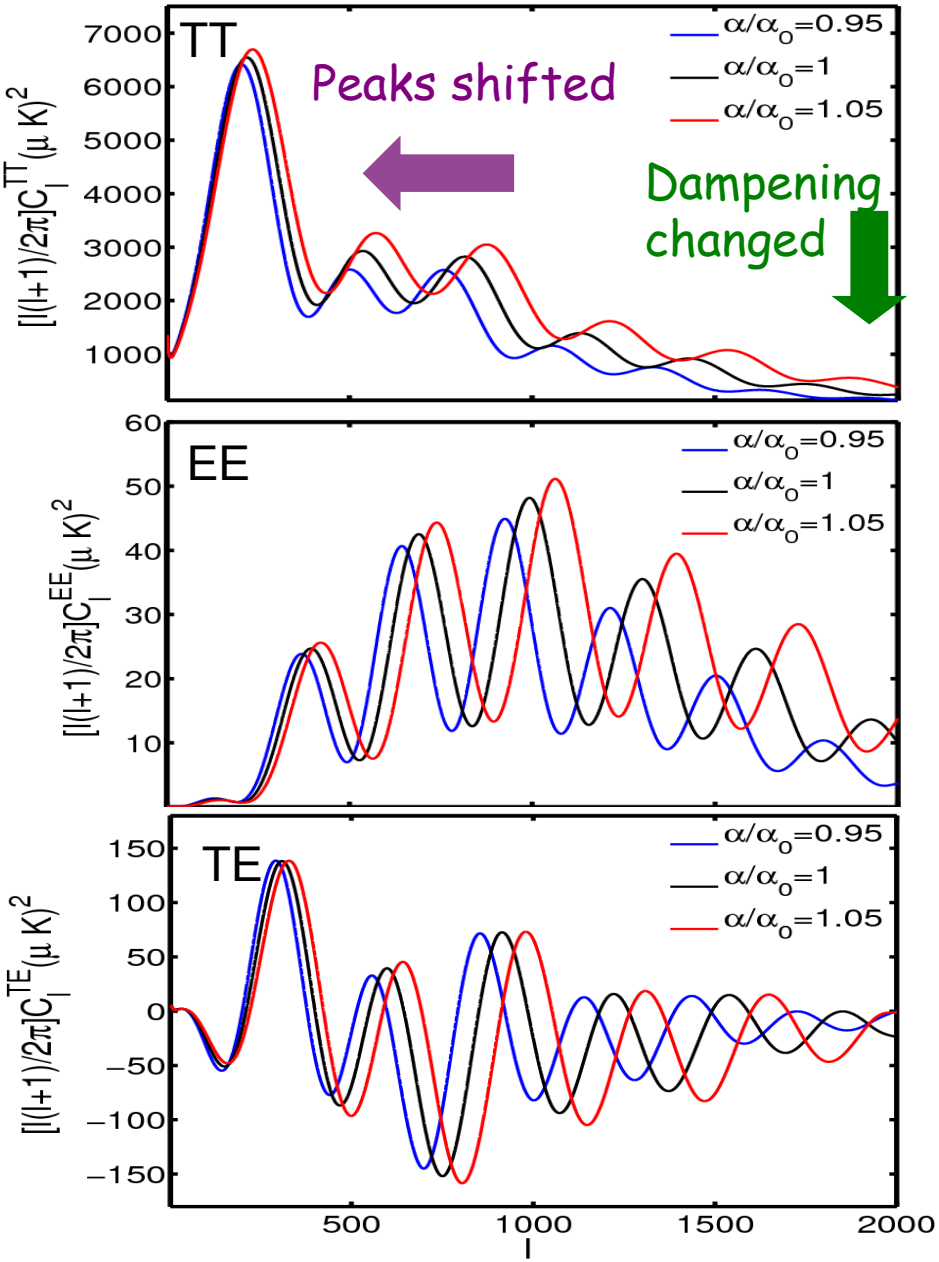
They **Shift the redshift** of recombination.
The shift is almost rigid.



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

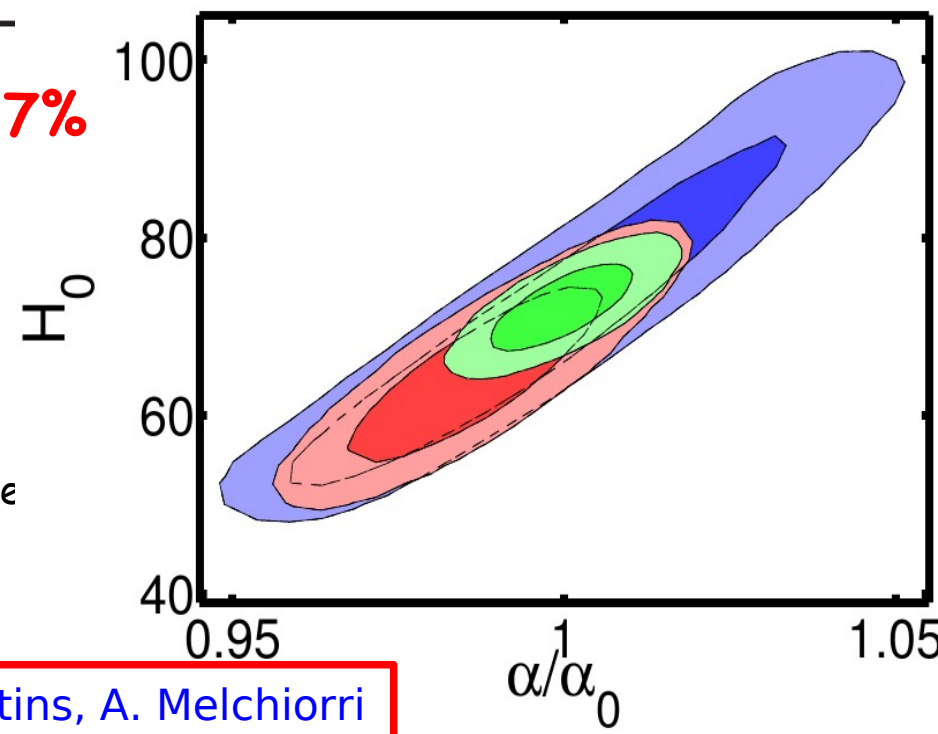
~2%

~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=6.8×10^{-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)*

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:

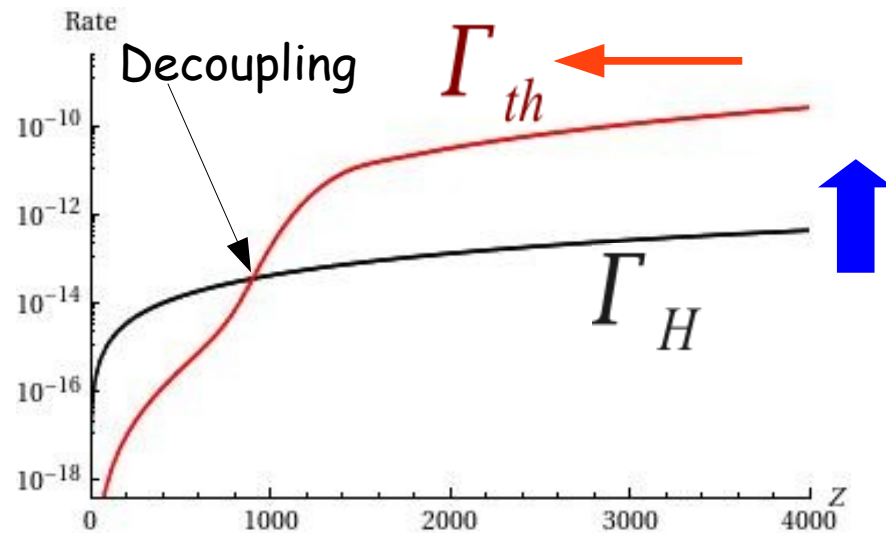
1.)**The Friedmann equation:**

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.

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

$$H^2(z) = \frac{8\pi G}{3} \Sigma_i \rho_i(z)$$



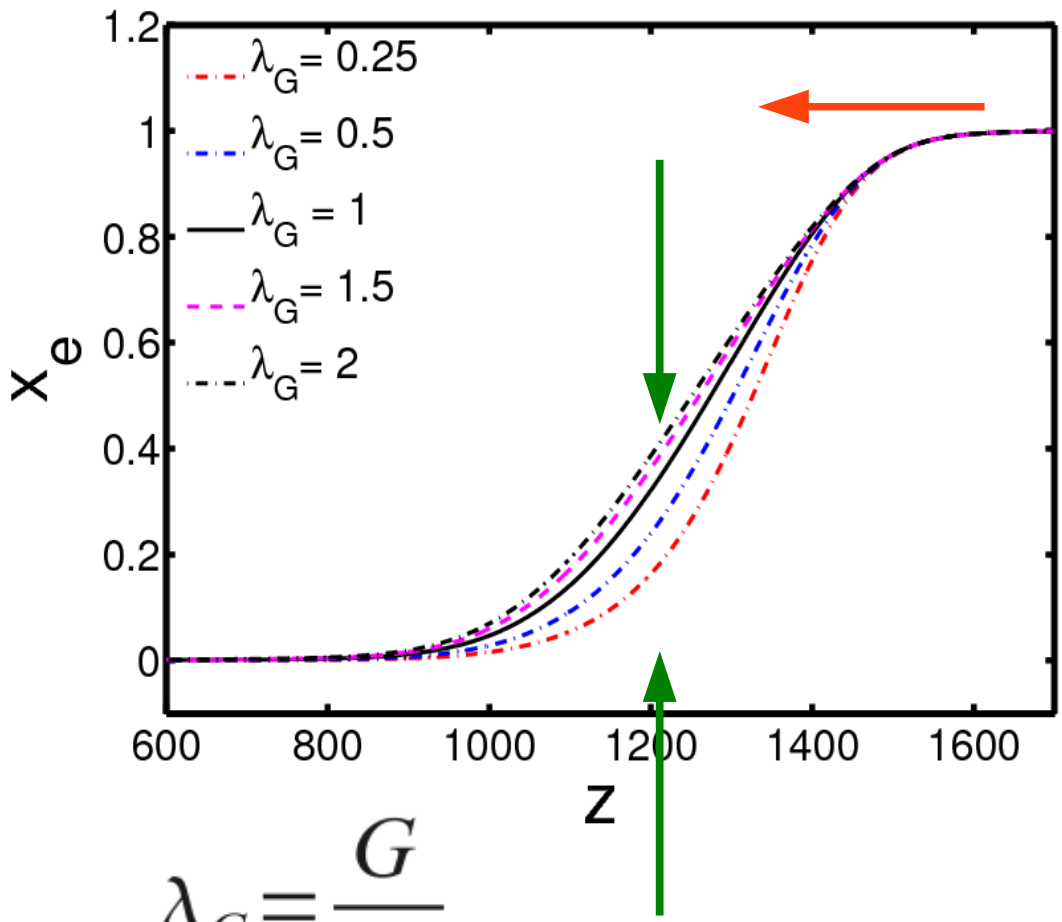
BUT! The recombination evolution and therefore the scattering rate are affected as well.....

Umezu, K.-I., Ichiki, K., & Yahiro, M. 2005, PRD, 72, 044010

Zahn, O., & Zaldarriaga, M. 2003, PRD, 67, 063002

Evolution of the Free Electron Fraction with G

1) **Larger** 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.



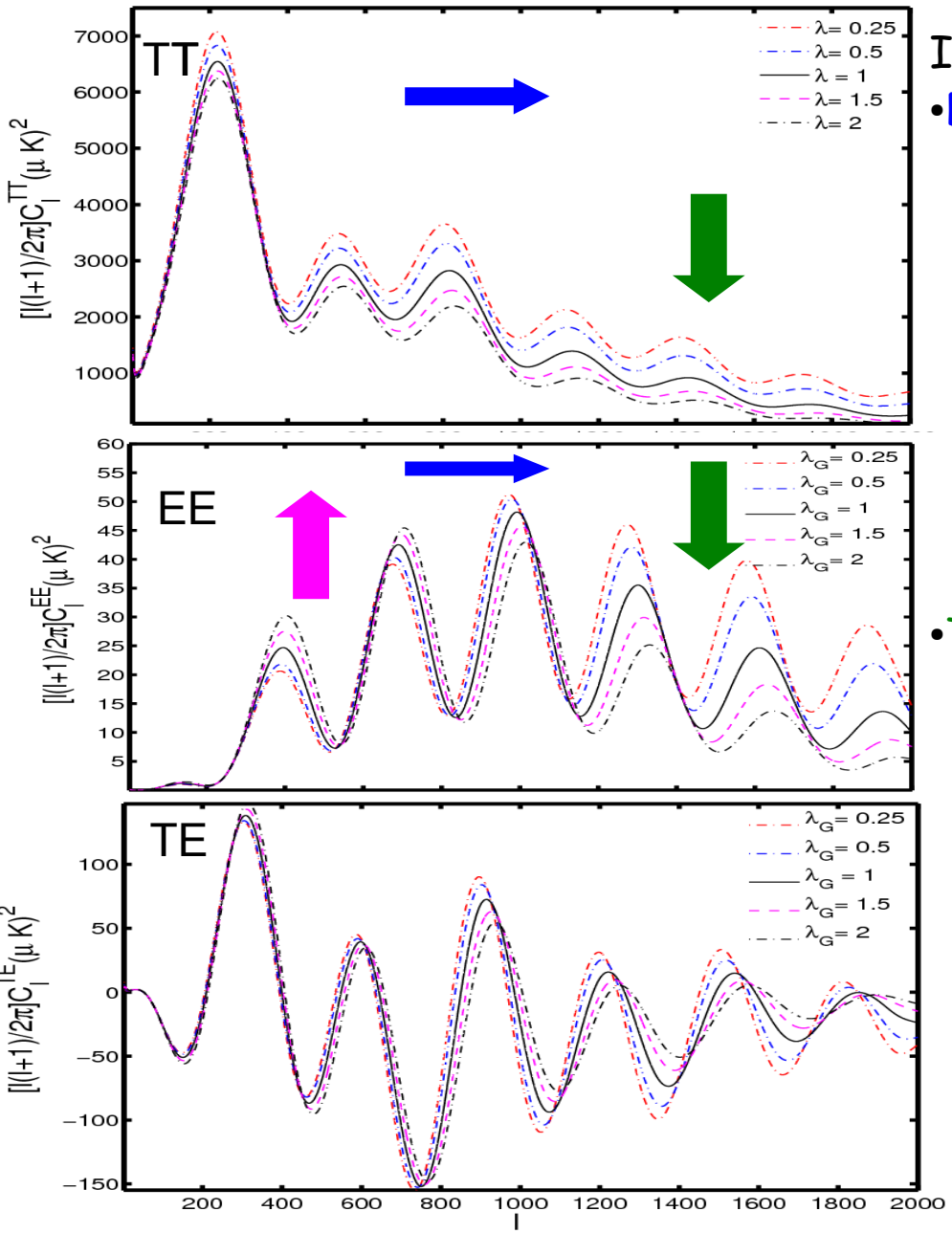
$$\lambda_G = \frac{G}{G_0}$$

2)Recombination takes LONGER!

The thickness of the last scattering surface is then larger.

$$\lambda_G = \frac{G}{G_0}$$

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

$$\lambda_G = \frac{G}{G_0}$$

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
PLANCK	1.01 ± 0.015
CVL	1.002 ± 0.004

~10%

WMAP5

POL :CBI+BOOM

0.4%

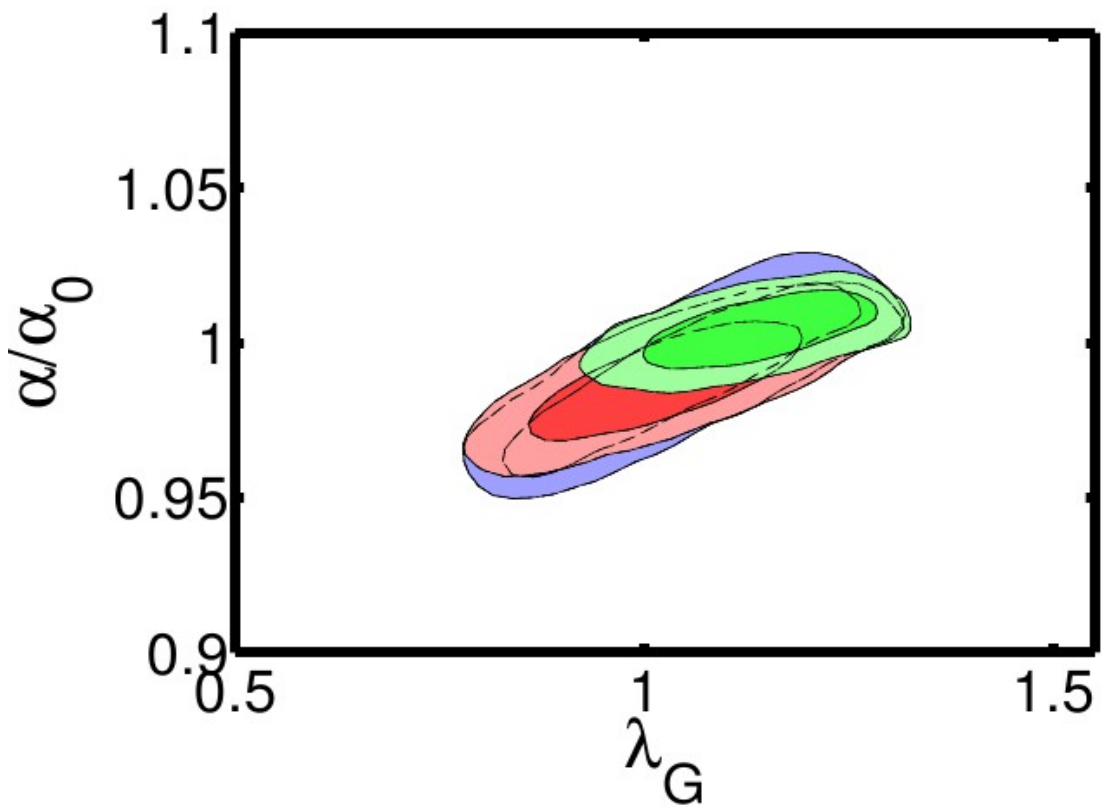
- Constraints from current CMB data are not competitive with laboratory constraints.

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.

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

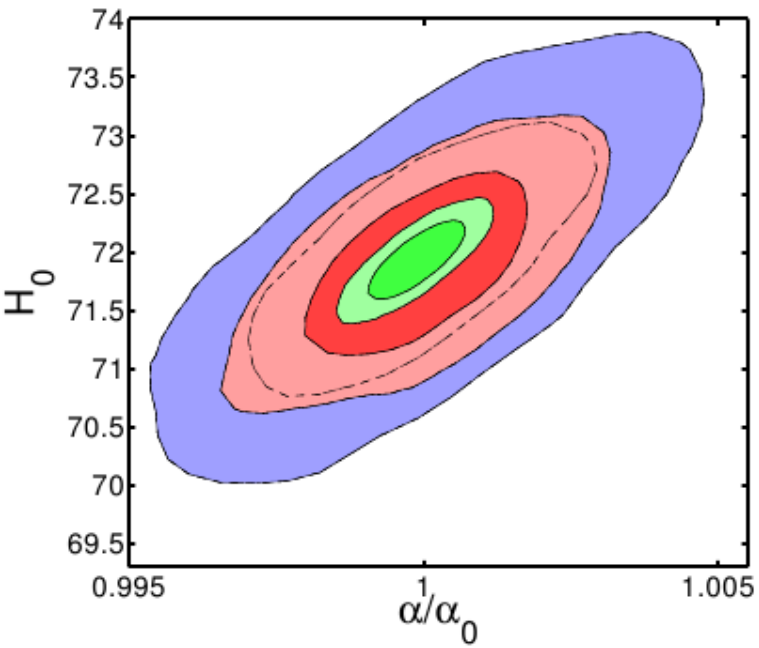


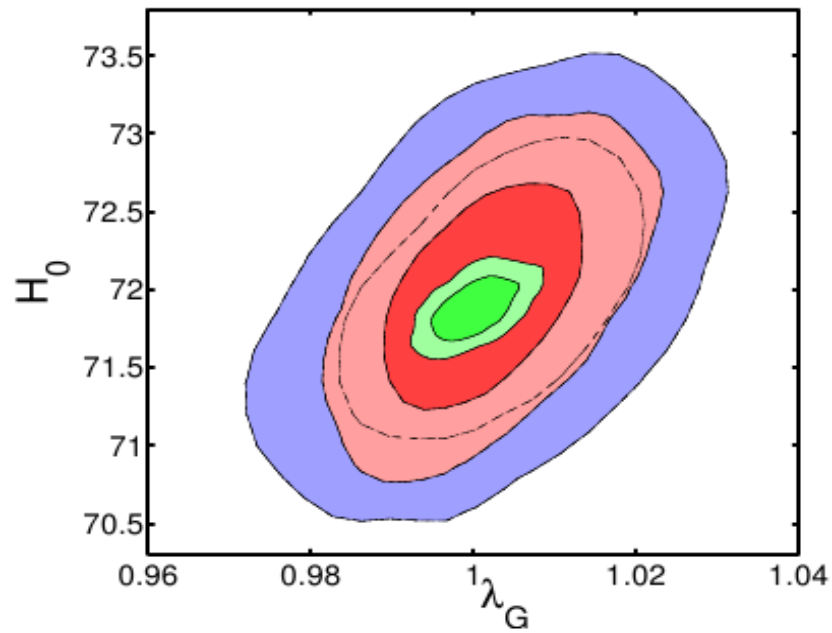
Experiment	α/α_0	68% c.l.	λ_G	68% c.l.
All CMB	0.999	±0.017	1.04	±0.12
All CMB+SN-Ia	0.989	±0.012	1.04	±0.11
All CMB+HST	1.003	±0.008	1.13	±0.09
ALL CMB+BBN	0.985	±0.009	1.01	±0.01
Planck only	1.000	±0.015	1.02	±0.09

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 on Variation of Fundamental Constants

- Current CMB data are far to provide constraints comparable to laboratory data, but test completely different time scales.
- Planck will improve constraints of one order of magnitude, priors on H_0 leads to further improvements.
- A study of more specific models for variation will lead to interesting constraints on theories such as modified gravity etc..

Conclusions

- CMB is a powerful probe of Fundamental Physics.
- Current data already strongly constrain Dark Matter Annihilation.
- Limits on the gravitational and fine structure constant test time/space ranges of the order of the age of the universe.
- Planck will improve constraints by one order of magnitude.