Constraints on the variation of the fine structure constant from recent CMB measurements

Graca Rocha
Cavendish Astrophysics, University of Cambridge

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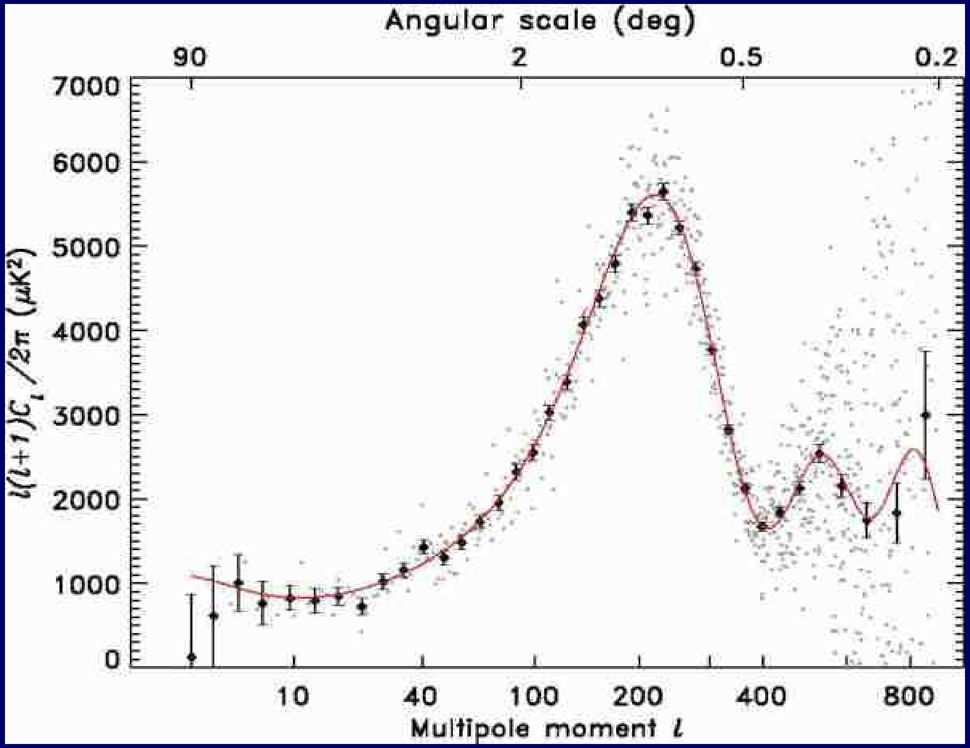
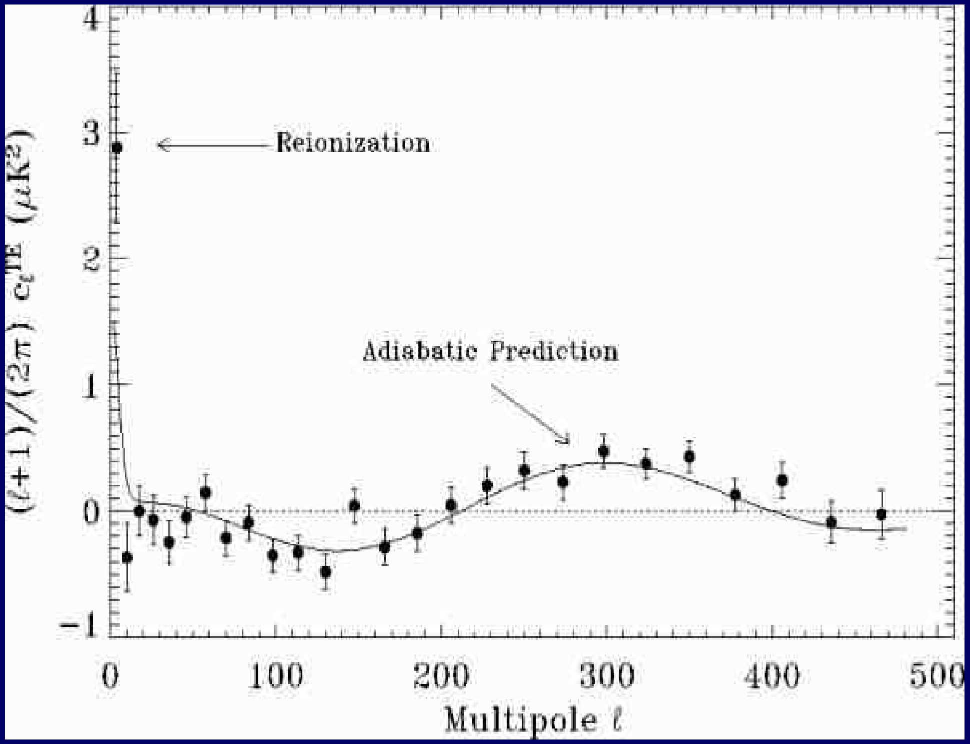
Recent CMB experiments such as Boomerang, MAXIMA, DASI, CBI, VSA among others and most recently WMAP seem to validate, apart some intriguing discrepancies, the so-called concordance model of cosmology. This emerging standard model of cosmology is $\rightarrow$ flat-Λ dominated universe with initial nearly scale invariant adiabatic Gaussian fluctuations.





(Left) best fit power law Λ-CDM model to the WMAP temperature angular power spectrum, and (right) with TE power spectrum (Spergel et al.,astro-ph/0302209)

- What is the origin of the CMB fluctuations?

- Are there Tensor fluctuations? - Is there a stochastic background of Gravitational Waves? - Recent WMAP results limit the amplitude of these tensor modes but no experimental evidence for a stochastic background of gravitational waves.

- Are the primordial fluctuations Gaussian? - Is the CMB Gaussian? Most CMB experiments don't show Non-Gaussianity - what does this tell us about Inflation? Cosmic strings? Anisotropic universes?

- What can we learn with Secondary Anisotropies? - The SZ effect, gravitational lensing, etc - tell us about the intervening material between us and the early universe.

- How complex is the Reionization history of the Universe? - The universe is highly ionized today, we know now from WMAP observations that the universe reionized at redshifts $z \sim 17$ and that tell us when first stars formed.

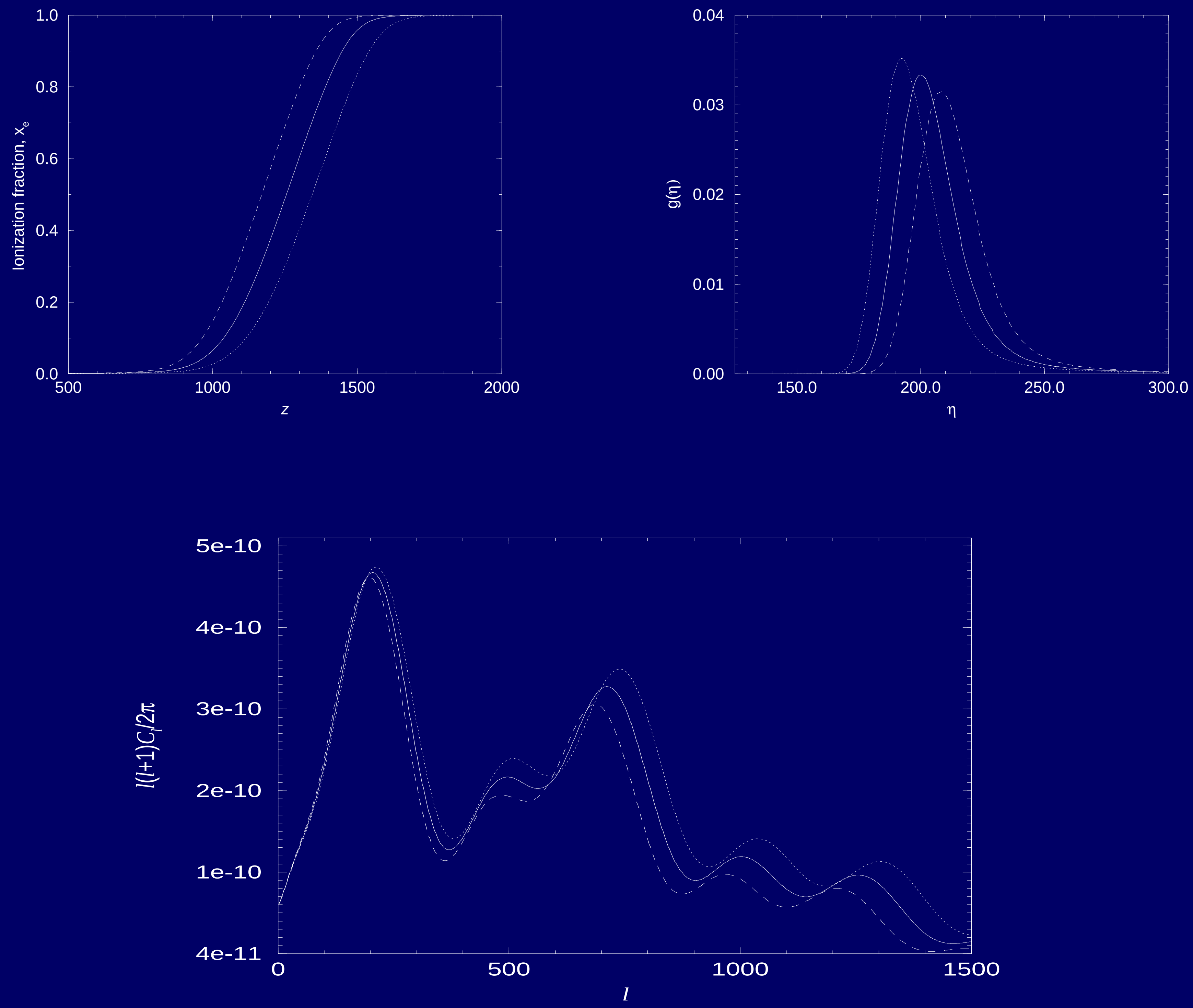
- Is the Universe finite after all? - Why is the quadrupole for both COBE and WMAP lower then that predicted by the concordance model? - Cosmic variance? Systematics/foreground contamination ?

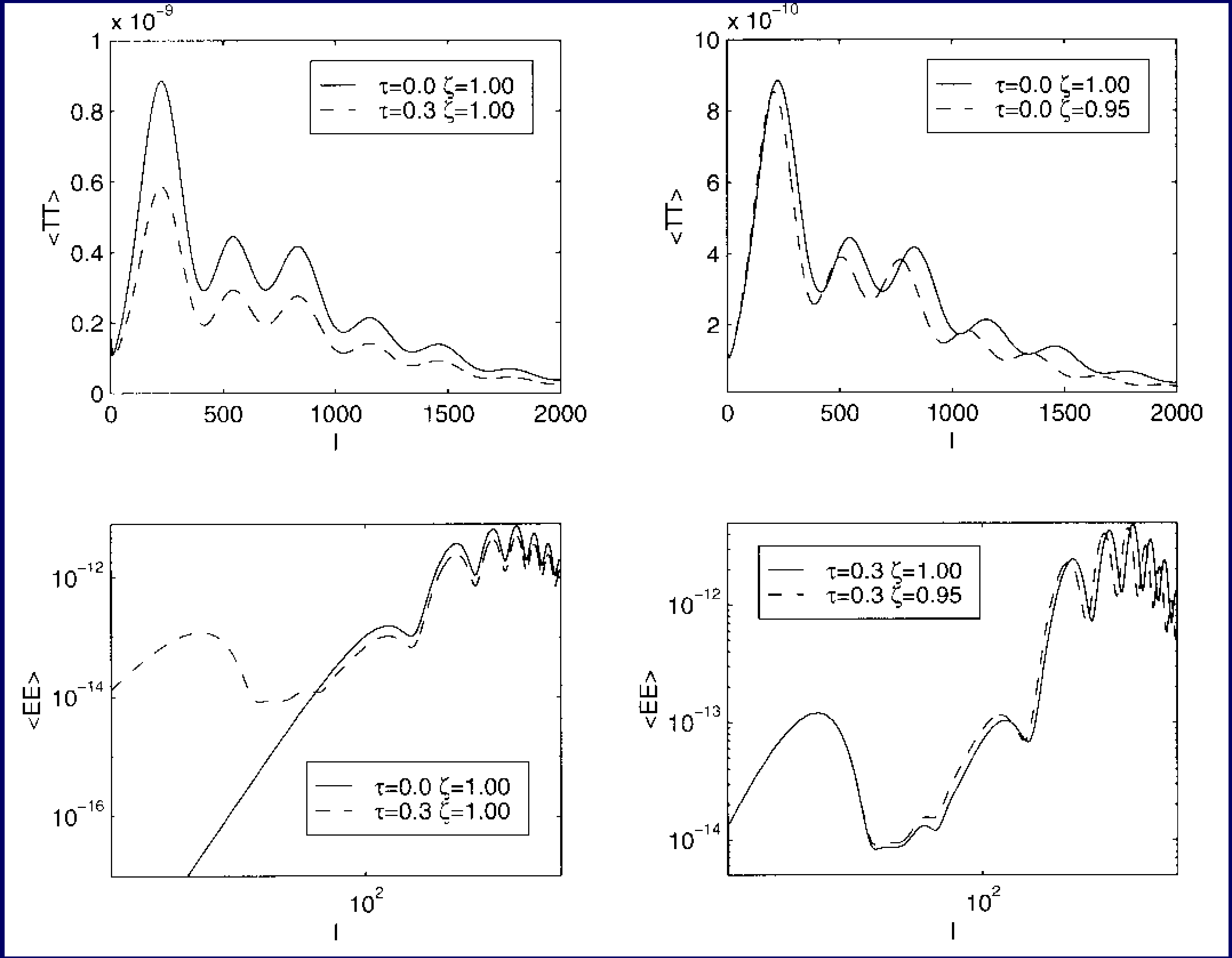
- Do fundamental constants vary? - Current unification theories predict the existence of additional space-time dimensions, which have observable consequences, including modifications in the gravitational laws on very large (or very small) scales and space-time variations of the fundamental constants of nature - There is already observational evidence of a fine-structure constant that was smaller in the past as measured in quasar absorption systems.

- What does CMB polarization tell us? - DASI and WMAP detected the polarization of the CMB via the temperature polarization (scalar E-mode) cross power-spectrum (TE).

- Are there any pseudo-scalar B-modes of the polarized CMB radiation? - One source of B-modes could be a background of gravitational waves.

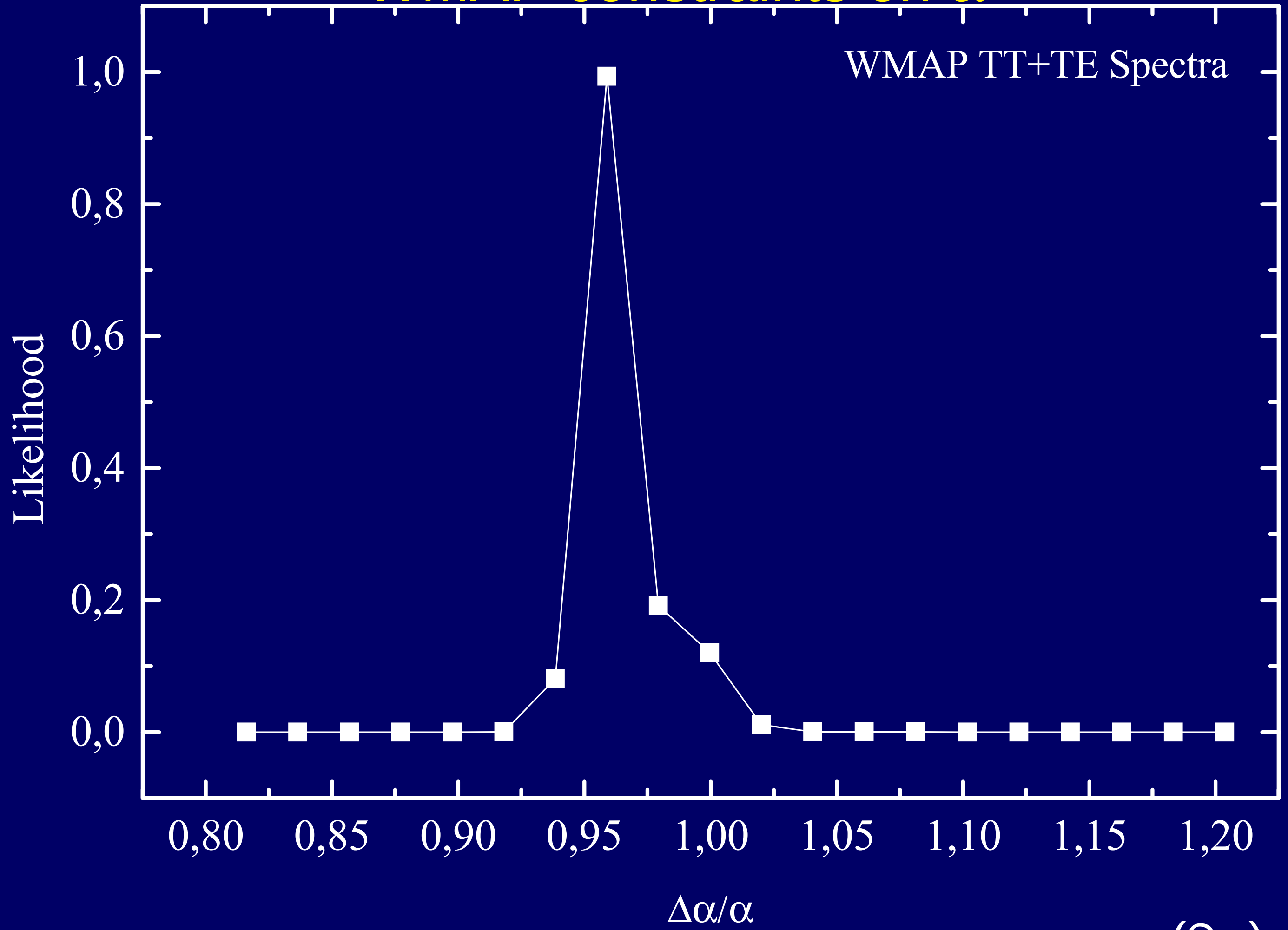
Does the fine structure constant α vary with time?





Contrasting the effects of varying α and reionization on the CMB temperature and polarization. Here $\zeta = \alpha_{dec}/\alpha_0$.

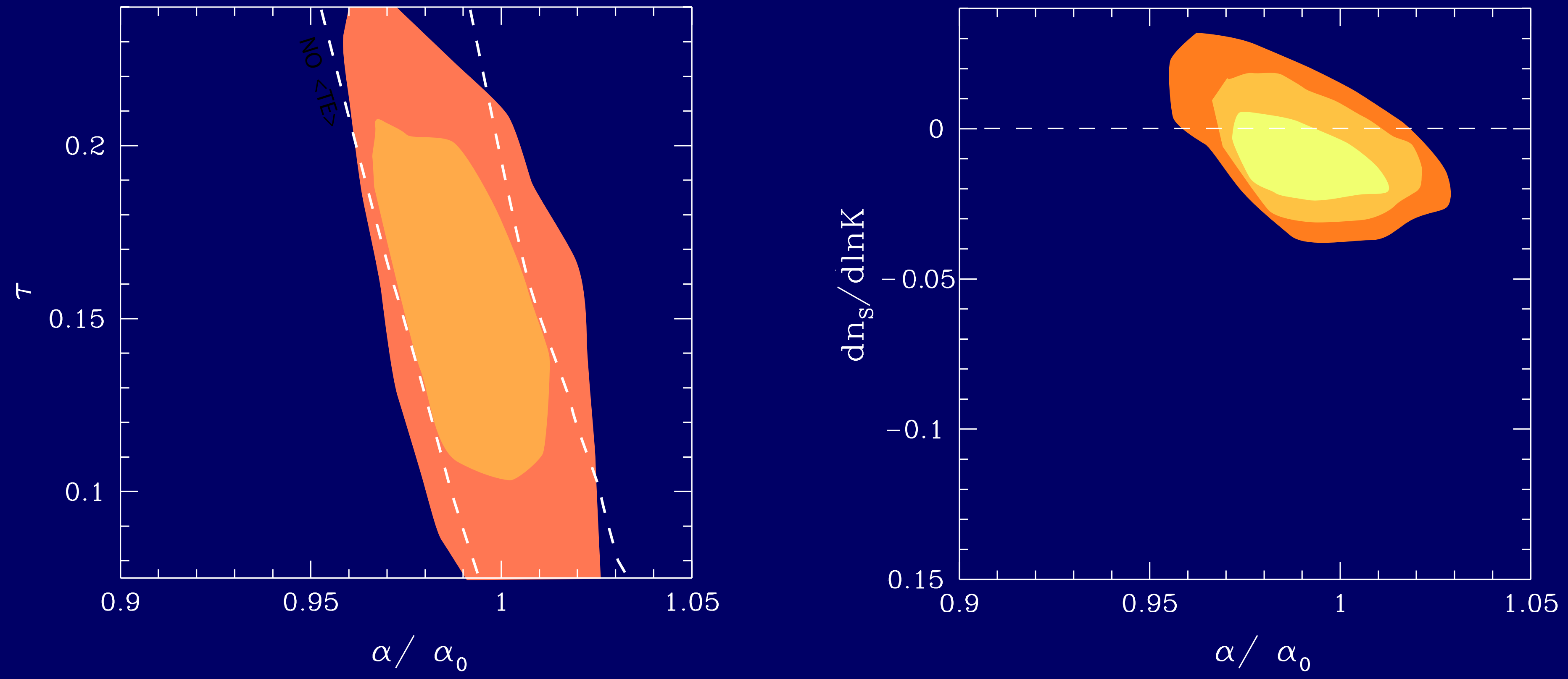
WMAP constraints on α



$$0.94 \leq \alpha_{dec}/\alpha_0 \leq 1.01 \qquad (2\sigma)$$

Conclusion → A variation of α at decoupling with respect to the present-day value is bounded to be smaller than 2% (6%) at 95% confidence level.

(Martins et al., astro-ph/0302295)



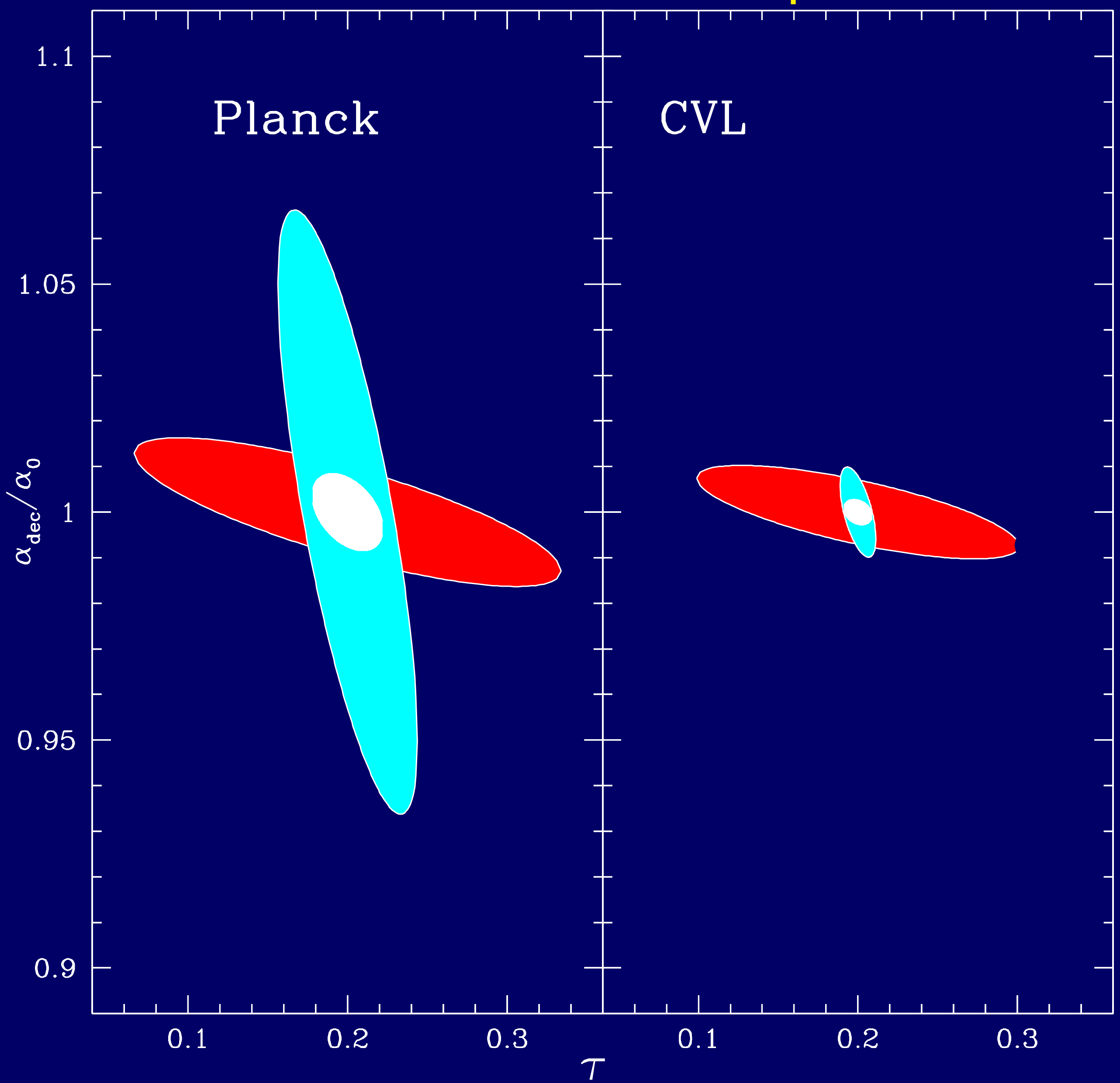
Including the running of the spectral index

Correlation between α and spectral index (lower $\alpha/\alpha_0 \longrightarrow$ lower n)

Better consistency with zero running if we lower α

(Rocha et al., astro-ph/0309211,0309205)

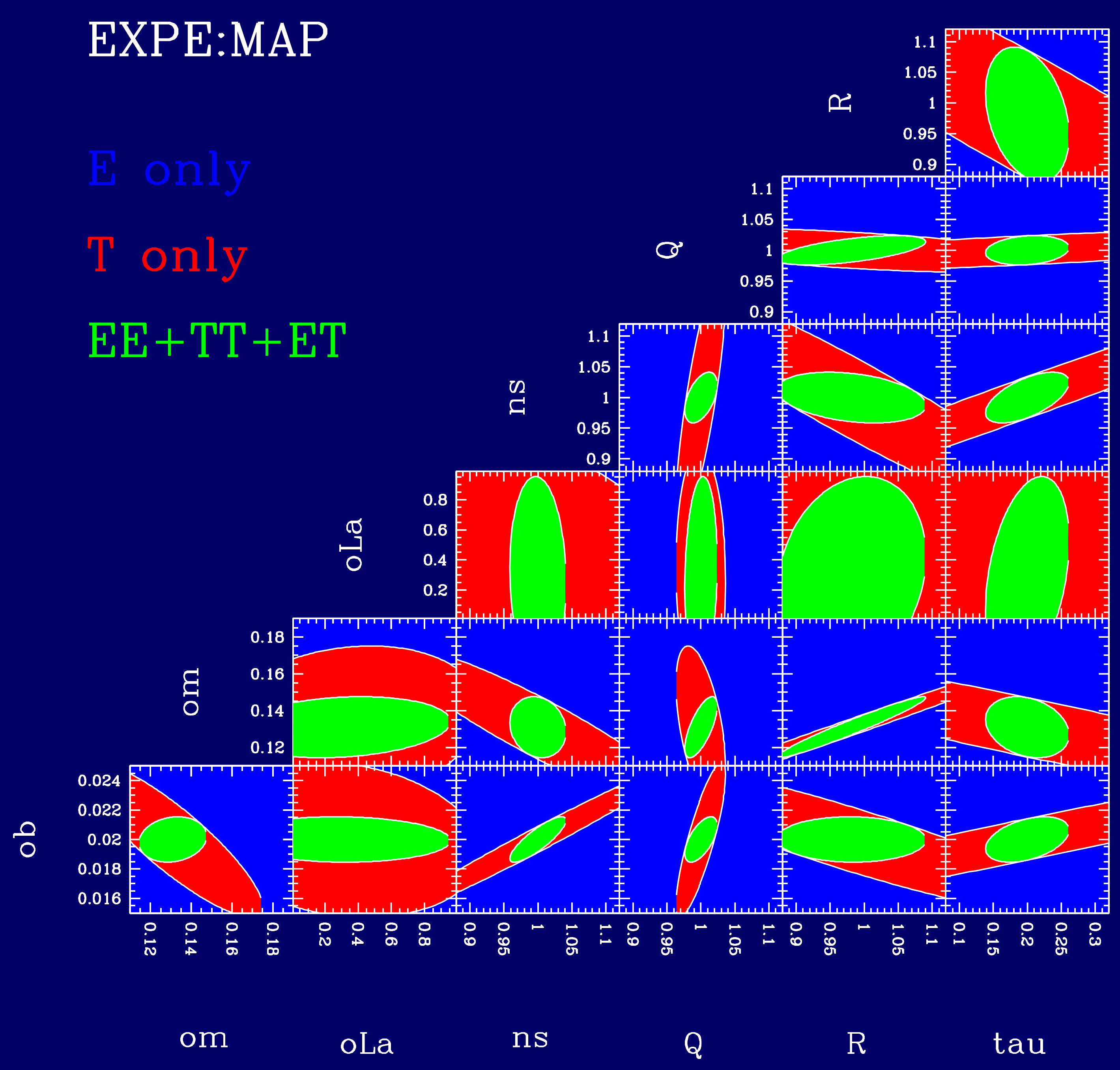
Predictions for future experiments



Ellipses containing 95.4% (2σ) of joint confidence in the α vs. τ plane (all other parameters marginalized), for the Planck and cosmic variance limited (CVL) experiments, using temperature alone (dark gray), E-polarization alone (light gray), and both jointly (white).

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

CMB *alone* can only constrain variations of α up to $\mathcal{O}(10^{-3})$ at $z \sim 1100$ (to be contrasted with the variation measured in quasar absorption systems (Webb et al. 2001), $\delta\alpha/\alpha_0 = \mathcal{O}(10^{-5})$ at $z \sim 2$.) - But variations in α should be larger at higher redshifts.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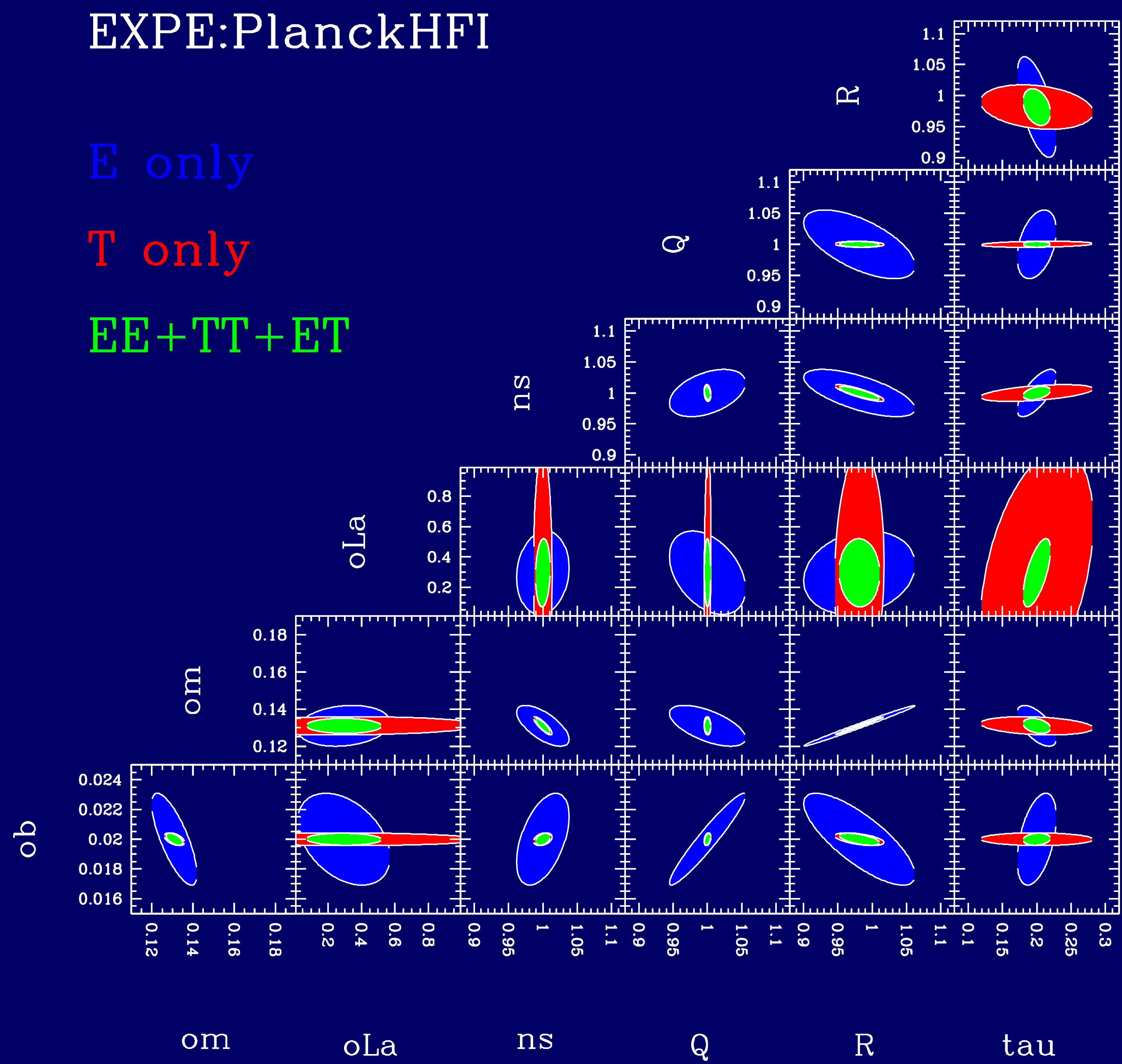
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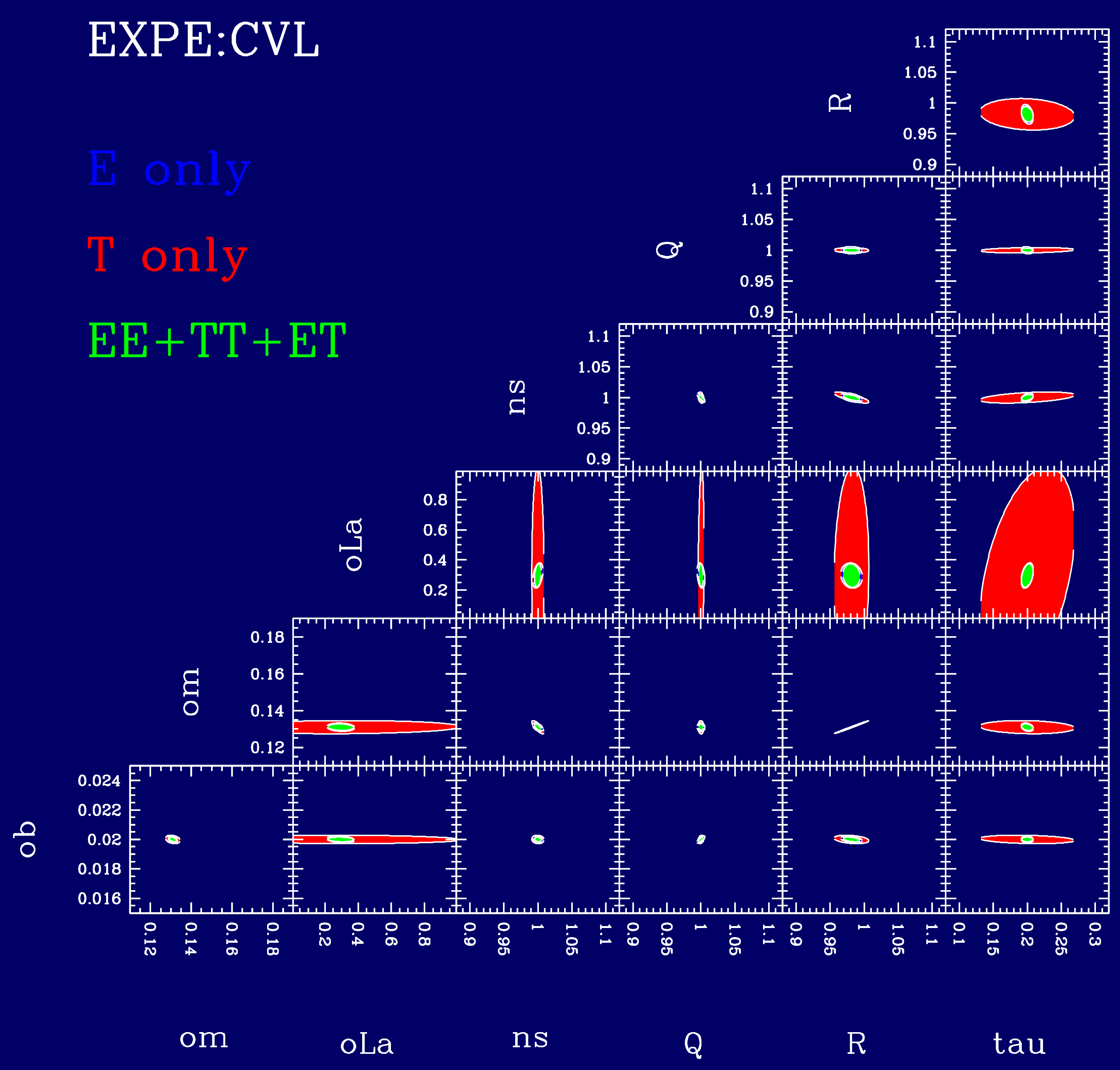
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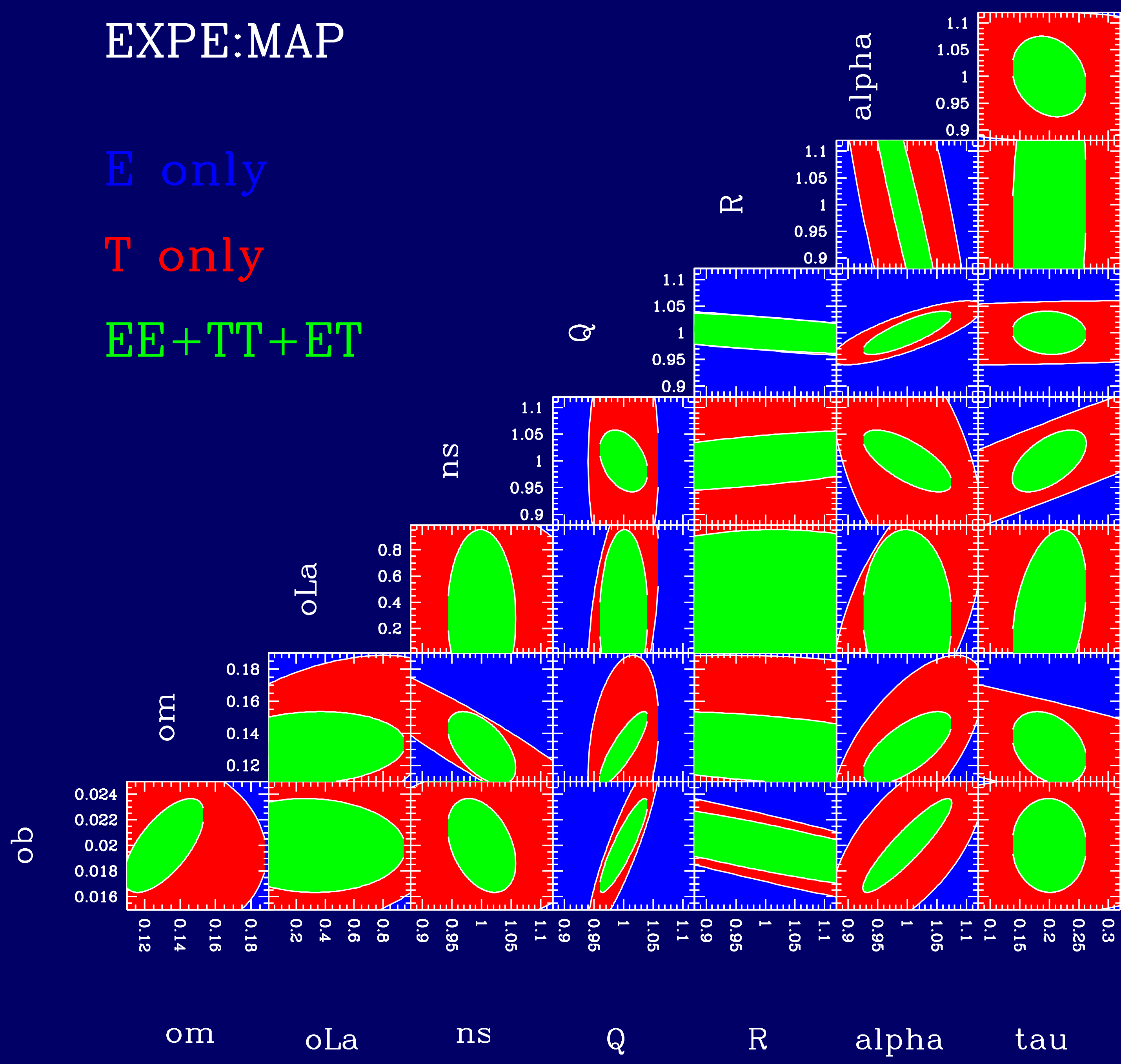
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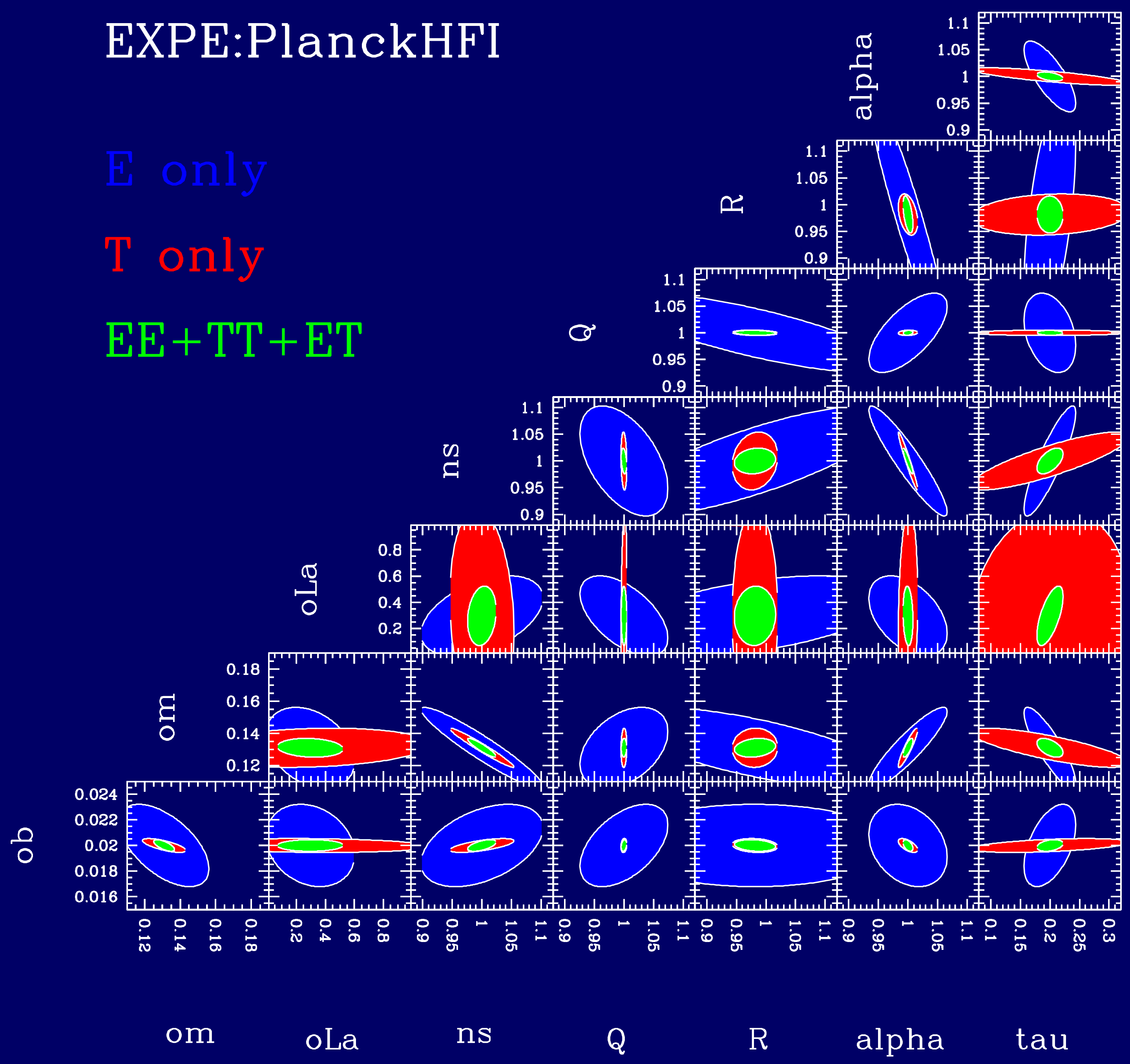
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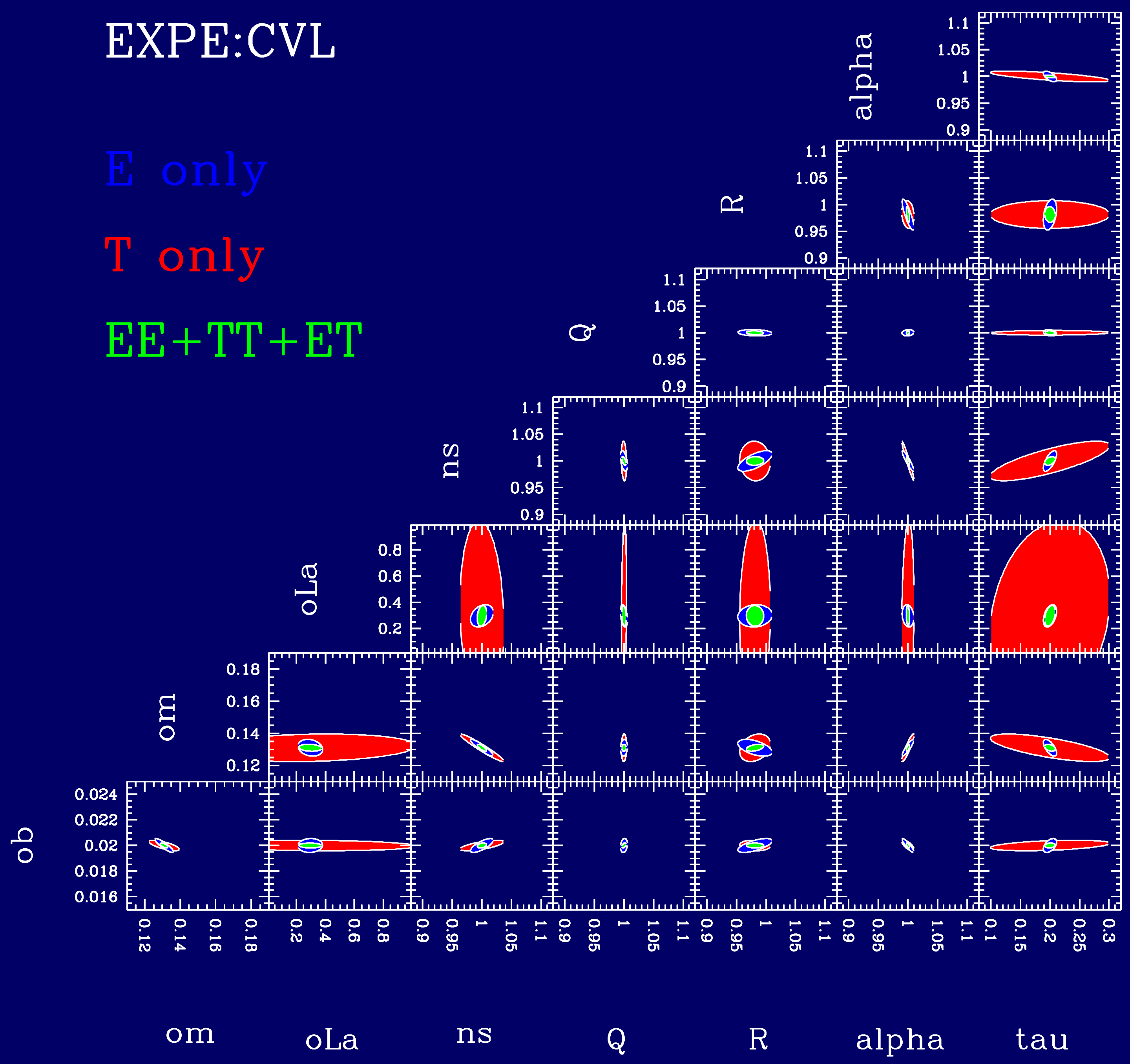
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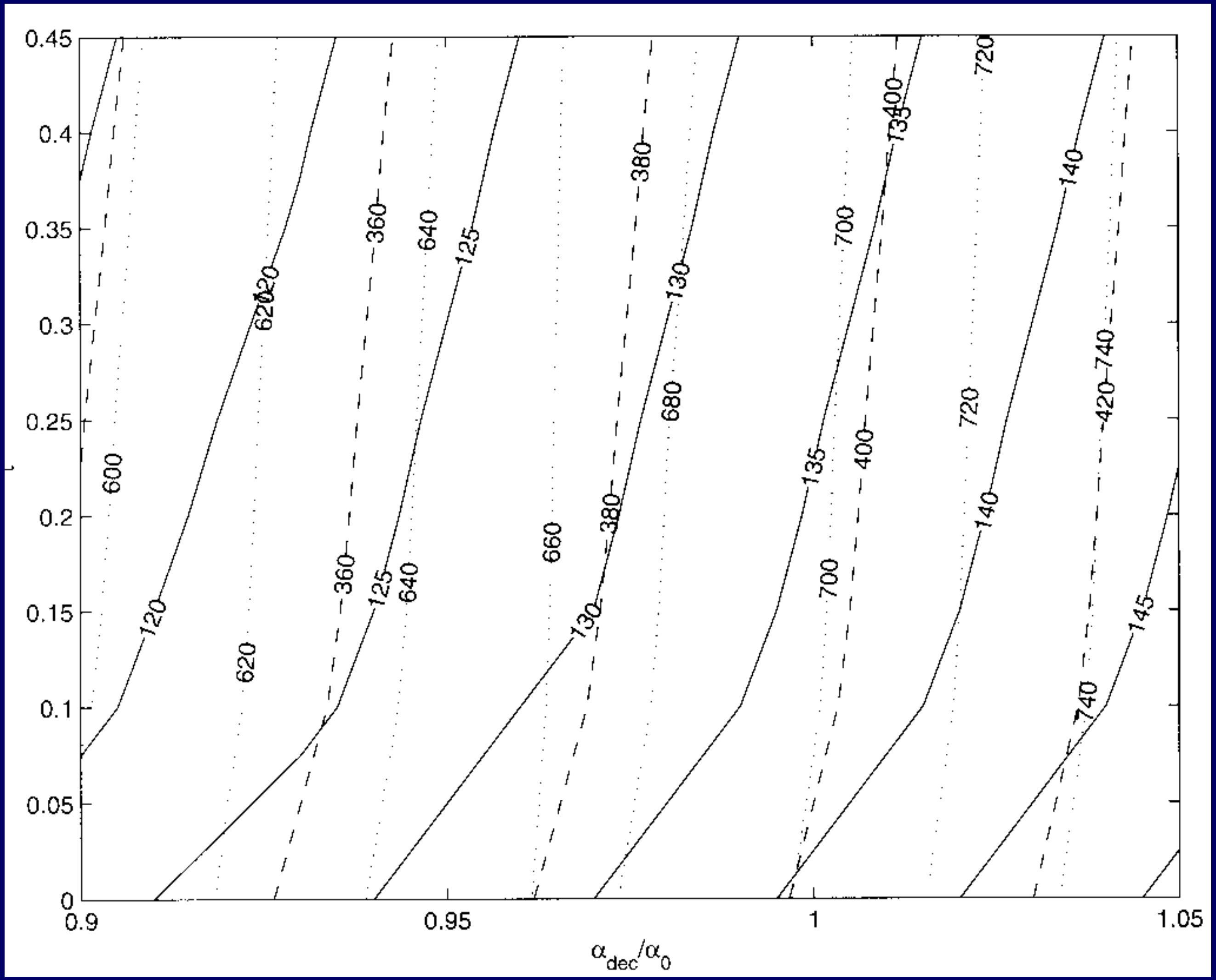
Conclusion $\longrightarrow$ Planck is essentially cosmic variance limited for temperature but there will still be considerable room for improvement in polarization .

Inclusion of polarization measurements help to better constrain some of the cosmological parameters, by probing the ionization history of the universe, (therefore better constraining the optical depth at reionization, τ_{reion}, and breaking degeneracies of this with other parameters) and by allowing the detection of gravity waves.

The existence of an early reionization epoch will, when more accurate cosmic microwave background polarization data is available, lead to considerably tighter constraints on α.

Summary

Now we have good measurements of the Cosmological Parameters, it is time to test the physics underlying the Standard Model and Inflation with future experiments such as Planck and Polarization experiments.



The separation in ℓ between the reionization bump and the first (solid lines), second (dashed) and third (dotted) peaks in the polarization spectrum, as a function of α at decoupling and τ. A (somewhat idealized) description of how α and τ can be measured using CMB polarization.

Predictions for future experiments

If the errors $\Theta - \Theta_0$ about the ML model are small, a quadratic expansion around this ML leads to the expression

$$\mathcal{L} \approx \mathcal{L}_m \exp\left[-\frac{1}{2}\sum_{ij} F_{ij}\delta\Theta_i\delta\Theta_j\right]$$

where F_{ij} is the Fisher matrix or curvature matrix, given by derivatives of the CMB power spectrum with respect to the parameters $\boldsymbol{\Theta}$.

In the more general case with polarization information included, instead of a single derivative we have a vector of four derivatives with the weighting given by the the inverse of the covariance matrix:

$$F_{ij} = \sum_{l}\sum_{X,Y} \frac{\partial \widehat{C}_{Xl}}{\partial \Theta_i} \mathrm{Cov}^{-1}(\widehat{C}_{Xl}\widehat{C}_{Yl}) \frac{\partial \widehat{C}_{Yl}}{\partial \Theta_j}$$

Cov^{-1} is the inverse of the covariance matrix, Θ_i are the cosmological parameters we want to estimate and X, Y stands for T (temperature),E, B (polarization modes),C (cross-correlation of the power spectra for T and E). For each l one has to invert the covariance matrix and sum over X and Y.

	1σ errors (%)					
	Planck HFI			CVL		
	marg.	fixed	joint	marg.	fixed	joint
	E-Polarization Only (EE)					
α	2.66	0.06	7.62	0.40	$<$ 0.01	1.14
τ	8.81	2.78	25.19	2.26	1.52	6.45
	Temperature Only (TT)					
α	0.66	0.02	1.88	0.41	0.01	1.18
τ	26.93	8.28	77.02	20.32	5.89	58.11
	Temperature + Polarization (TT+EE)					
α	0.34	0.02	0.97	0.11	$<$ 0.01	0.32
τ	4.48	2.65	12.80	1.80	1.48	5.15

Fisher matrix analysis results for a model with varying α and reionization: expected 1σ errors for the Planck satellite and for the CVL experiment. The column *marg.* gives the error with all other parameters being marginalized over; in the column *fixed* the other parameters are held fixed at their ML value; in the column *joint* all parameters are being estimated jointly.