Beyond the Concordance Model

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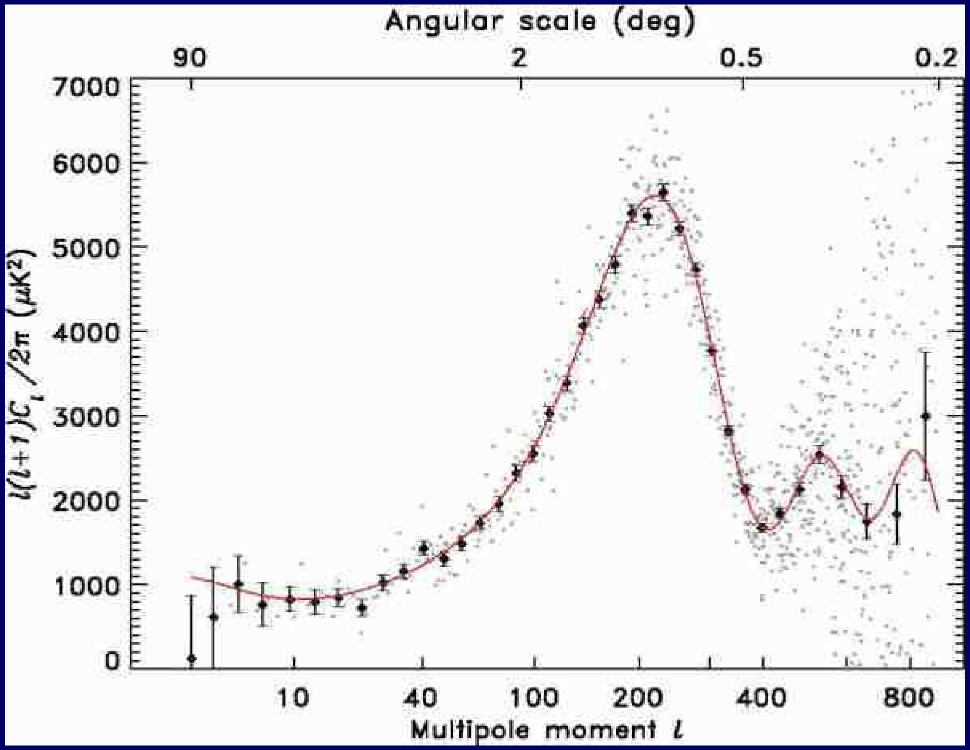
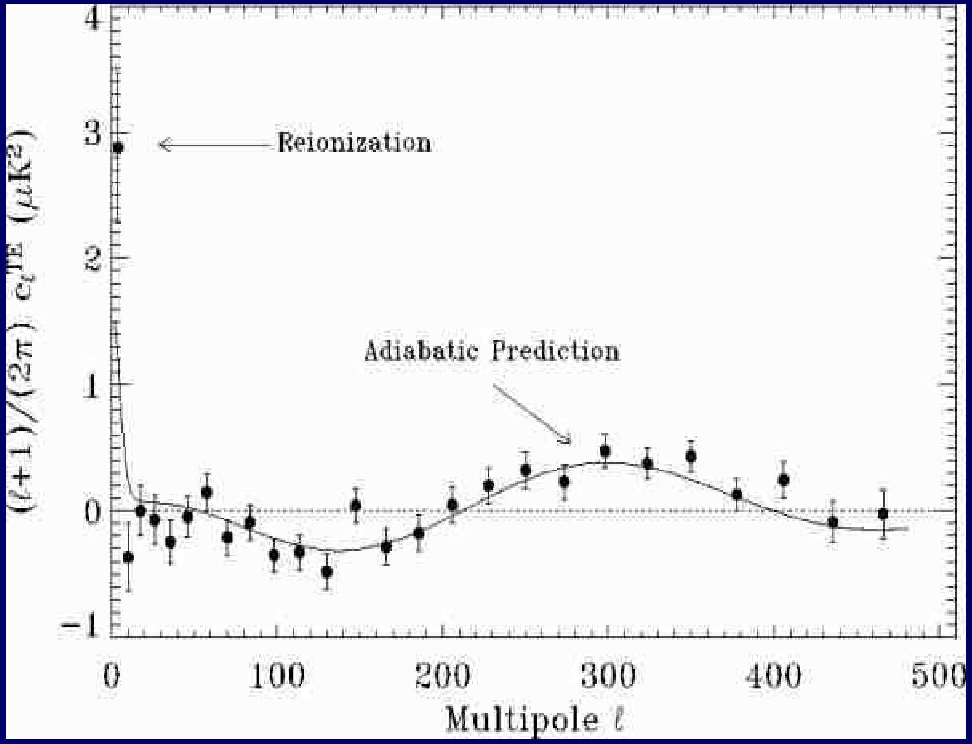
Recent CMB experiments such as Boomerang, MAXIMA, DASI, CBI, VSA among others and most recently WMAP seem to validate, apart some intriguing discrepancies, the so-called concordance model of cosmology. This emerging standard model of cosmology is $\longrightarrow$
flat-Λ dominated universe with initial 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 - no experimental evidence for a stochastic background of gravitational waves.

- 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.

- 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.

- 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?

- 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.

Is the CMB field Gaussian?

The CMB field might be itself Non-Gaussian
Foregrounds contamination from our own Galaxy + discrete radio sources + systematics $\longrightarrow$ leave a Non-Gaussian imprint on the CMB maps

How can we test the hypothesis of Gaussianity?

- Frequentist tests Skewness + kurtosis of t.d.; Three-point correlation function of t.d.; Statistics of maxima + minima in the CMB map; Topological properties of the 2-dim CMB t.d.; Minkowsky functionals of t.d.; k-statistics of the wavelets transforms coefficients

- Bayesian test - the challenge! How does the assumption of Gaussianity affect the Bayesian estimation of the power spectrum, C_l? - Which is the effect of allowing non-Gaussian degress of freedom into the likelihood? - Which framework for a Bayesian joint estimation of non-Gaussianity and the power spectrum ?

Attempts $\hookrightarrow$ Edgeworth expansion

Our solution $\hookrightarrow$ Hilbert space of an harmonic oscillator $\hookrightarrow$ Likelihood (C_l, α_i) where α_i are generalized cumulants.

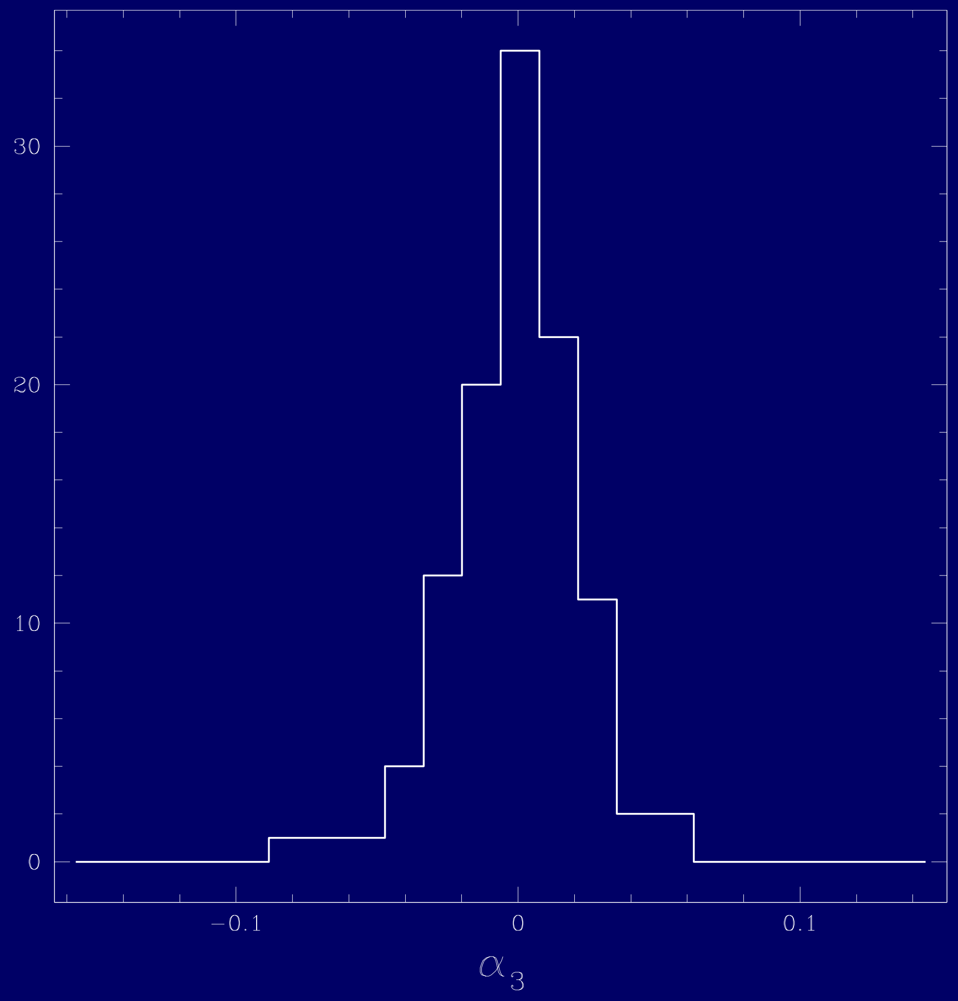
$$P = |\psi|^2 = e^{-\frac{\xi^2}{2\sigma_o^2}} \left| \sum_n \alpha_n C_n H_n \left(\frac{\xi}{\sqrt{2}\sigma_o} \right) \right|^2$$

where $H_n(\xi)$ - Hermite polynomials. The only constraint upon the amplitudes α_n is:

$$\sum_n |\alpha_n|^2 = 1$$

The generalization of this distribution to the multidimensional case is trivial in the signal-to-noise eigenmode basis.

(Rocha et al., Phys. Rev. D64, 063512, 2001 (astro-ph/0008070), Savage et al., astro-ph/0308266)



Application to simulated Very Small Array (VSA) observations of a Gaussian CMB realization $\longrightarrow$ our method is not biased!

This method has been applied to real data.

An interesting feature of this formalism is that it can assist in generating non-Gaussian simulations.

The main achievement of this work is to convert testing Gaussianity into a problem of Bayesian estimation. For the first time a general form of the likelihood has been derived in a rigorous, non-perturbative, Bayesian framework to jointly test Gaussianity and estimate the power spectrum

Frequentist approch $\longrightarrow$ the Bispectrum a natural follow on from the Power Spectrum.

Expression of temperature fluctuations of the CMB on the celestial sphere, in terms of an expansion in spherical harmonics:

$$\frac{\Delta T}{T}(\alpha,\phi) = \sum_{l=2}^{\infty}\sum_{m=-l}^{l} a_{lm}Y_{lm}(\alpha,\phi)$$

where (α, ϕ) are the polar coordinates of a point on the spherical surface.

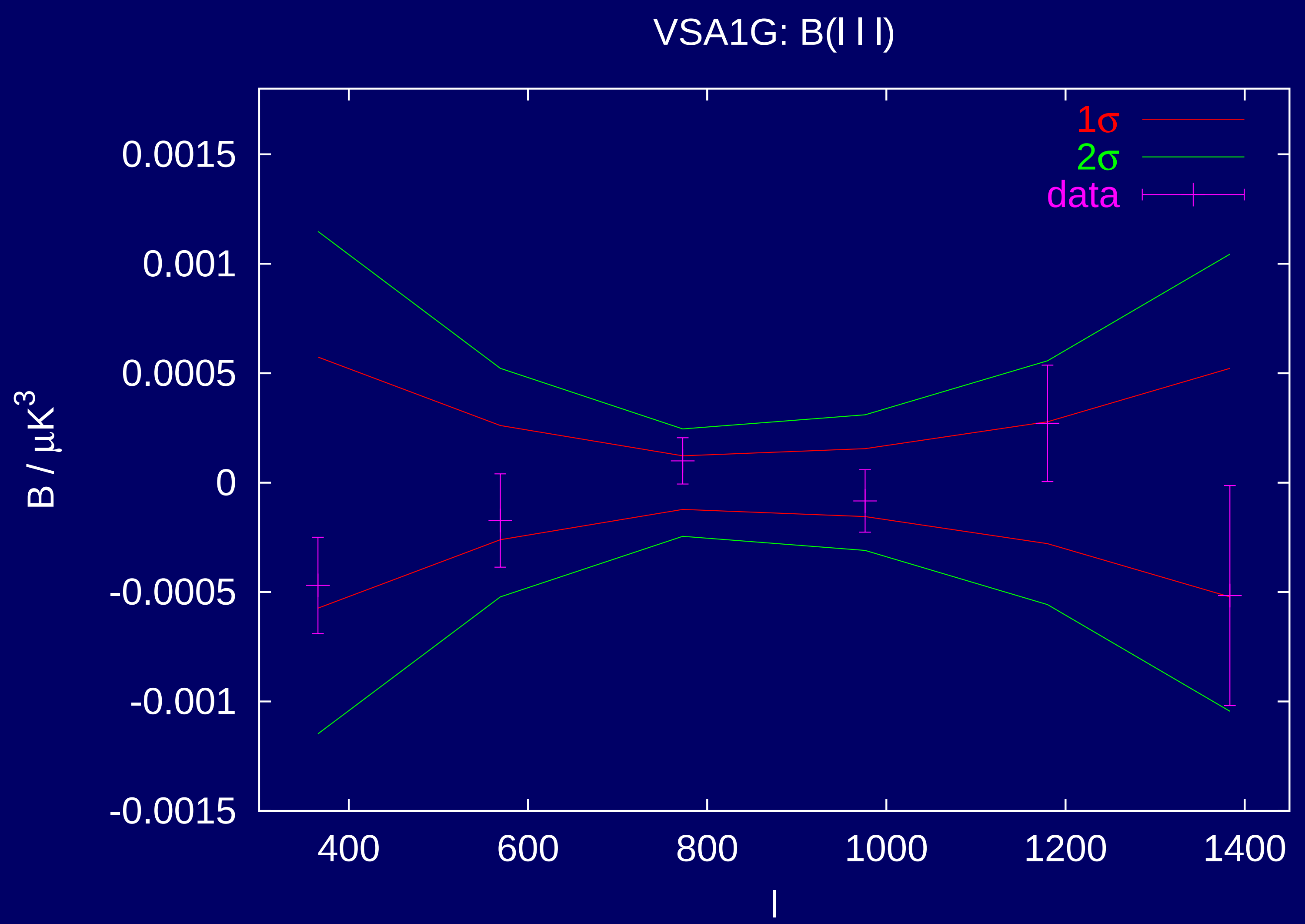
The angular power spectrum $\longrightarrow$ $C_l = \langle |a_{lm}|^2 \rangle$

The Bispectrum $\longrightarrow$ $\langle B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} \rangle \equiv \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$

The harmonic transform of the 3-point correlation function $\longrightarrow$ gives a scale-dependent measure of skewness $\longrightarrow$ it ensemble averages to zero for Gaussian fluctuations.

For VSA experiment $\longrightarrow$ use the flat sky approximation.

(Smith et al., 2003)



Diagonal bispectrum estimate with variance from Gaussian simulations for compact array field VSA1G.

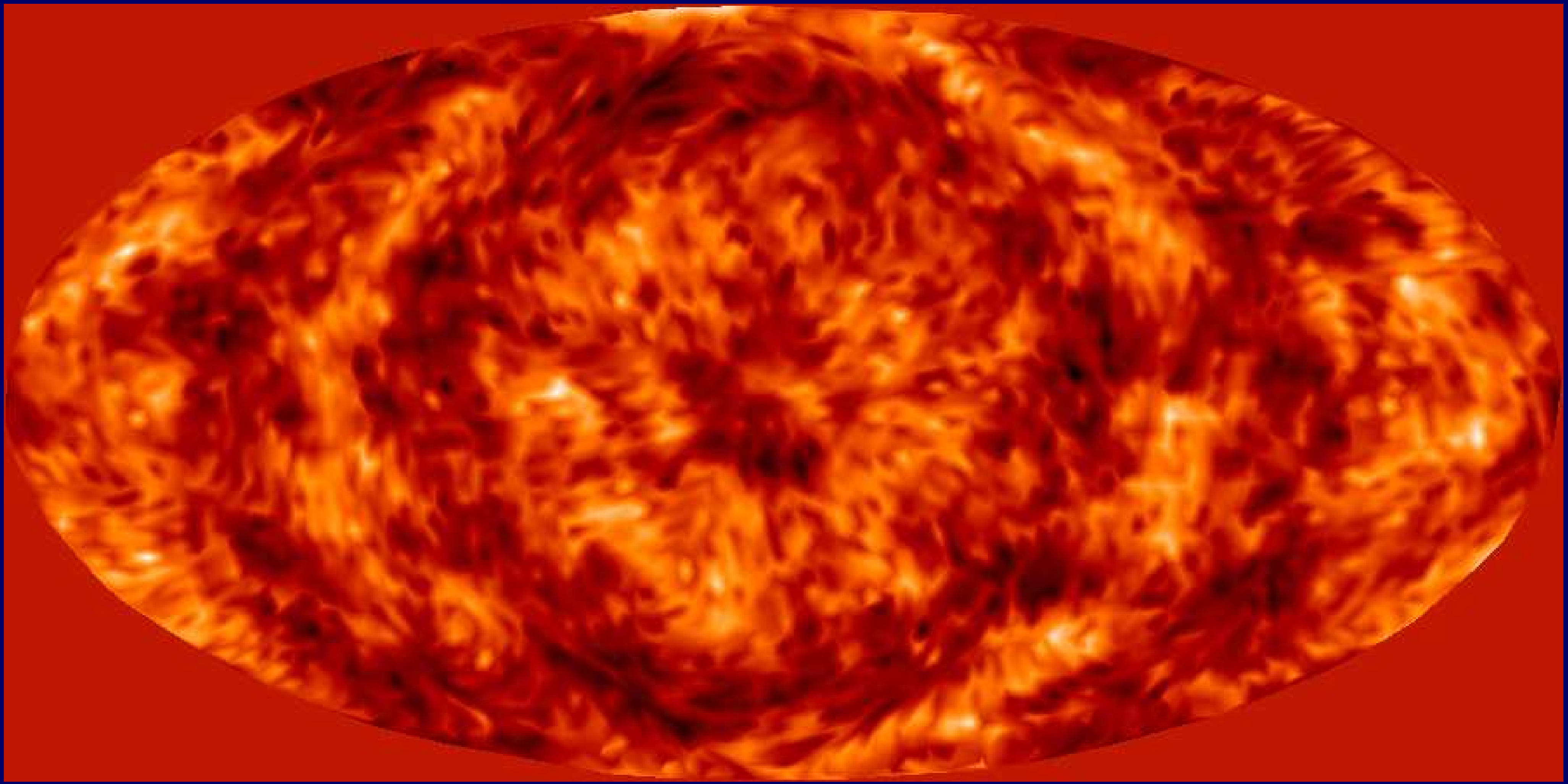
Conclusion → No Non-Gaussianity Yet!

Extension and implementation of previous Non-Gaussianity estimators for Planck instrument.

Effect of Systematics on the time ordered data (TOD) in Planck satellite $\longrightarrow$ detection and removal of non-stationary signals - use of a new technique a Non-Comutative Tomography method (NCT) - This method obtains information on time-frequency by looking at the marginal distributions along rotated directions in the (time,frequency) plane - in phase of implementation.

The NCT technique is particularly suitable for detection of Gravitational Waves (non stationary and possibly short-lived signals)

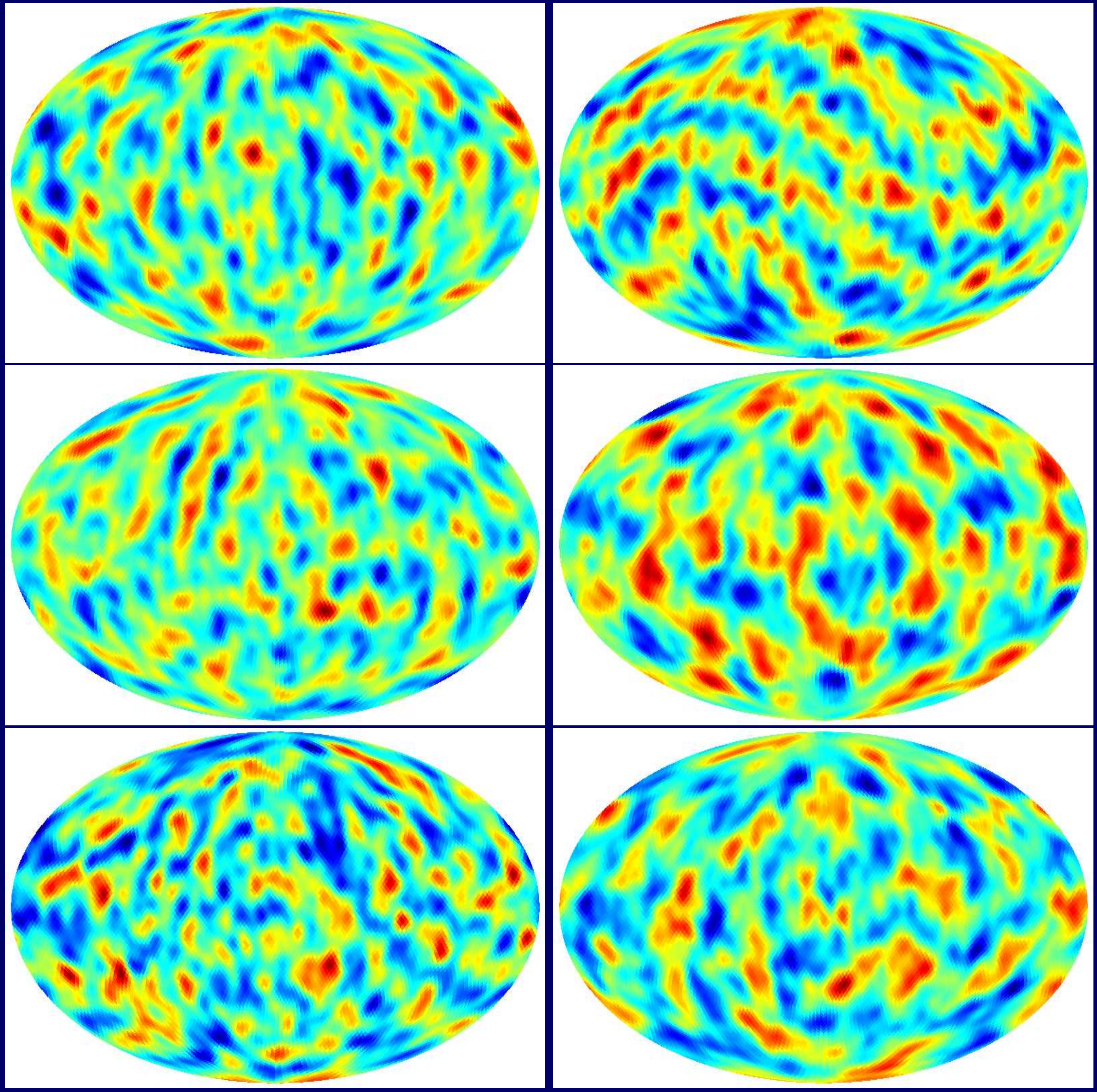
How big is the Universe?



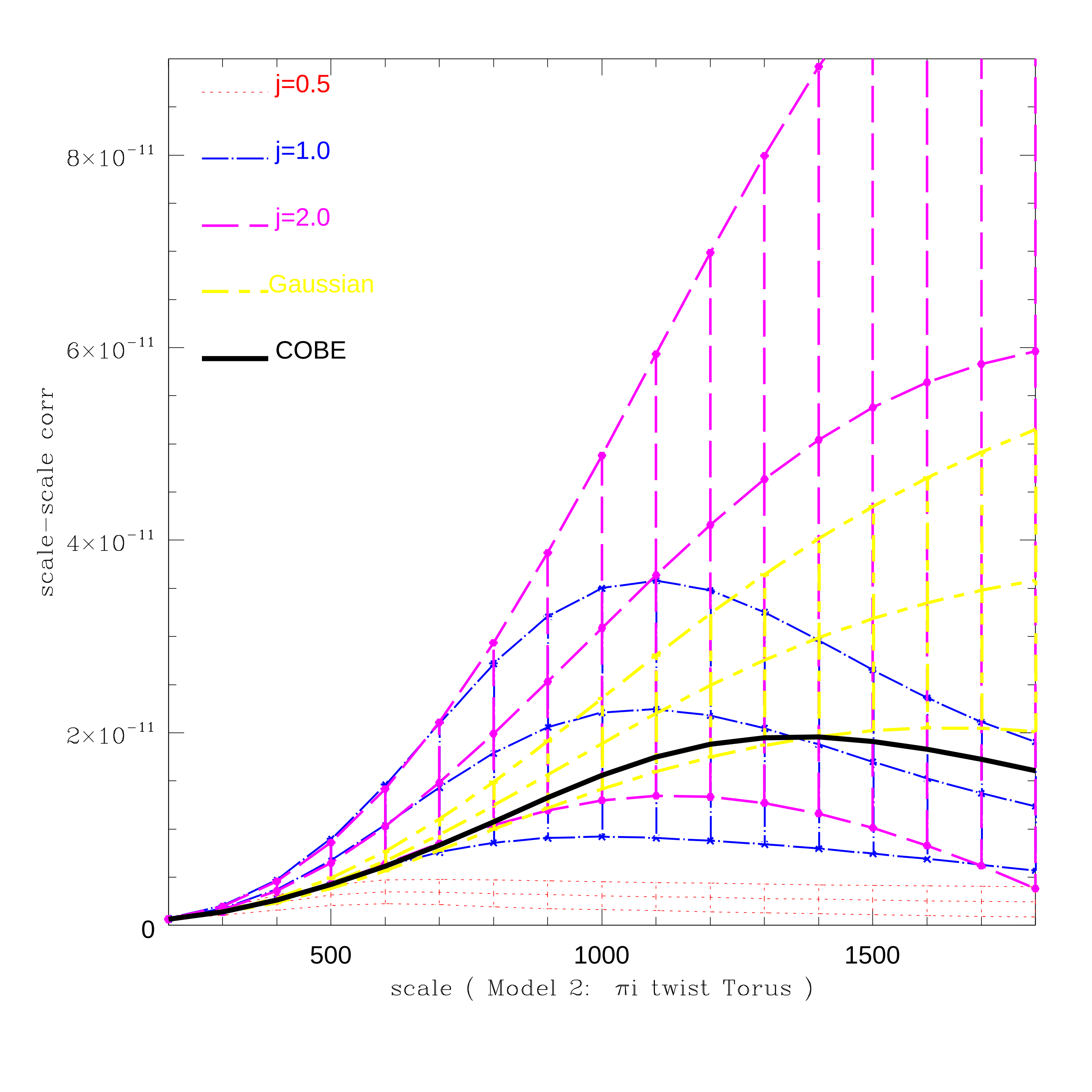
Simulation of the CMB sky for a Finite Topology Universe

While General Relativity specifies the local curvature of space-time the global geometry still remains undefined!

Repeated spatial structures $\hookrightarrow$ pattern formation $\rightarrow$ location, number and distribution of repeated points allow the recontruction of the Geometry



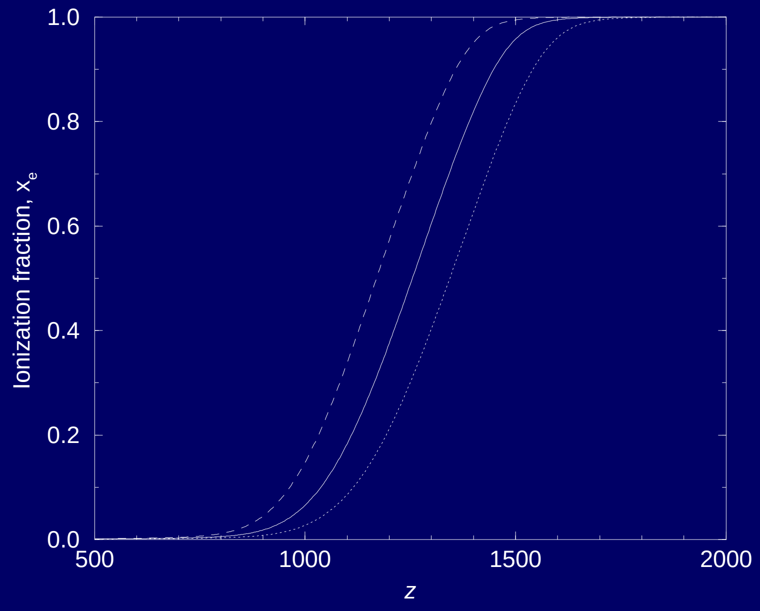
Simulations for a Torus, π twist Torus, $\pi/2$ twist Torus, triple twist Torus, $\pi/3$ Hexagon, $2\pi/3$ Hexagon, for j=0.5. The maps are in HEALPix pixelization with Nside=32 and COBE-DMR resolution.

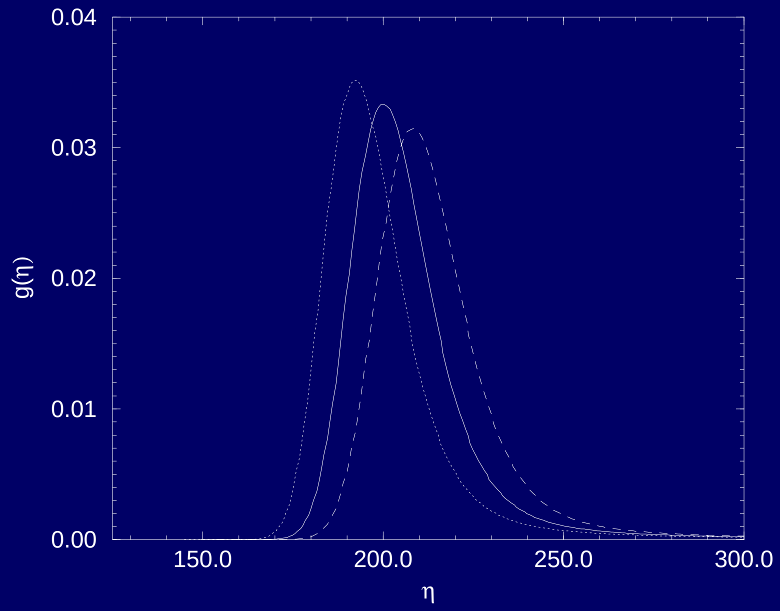


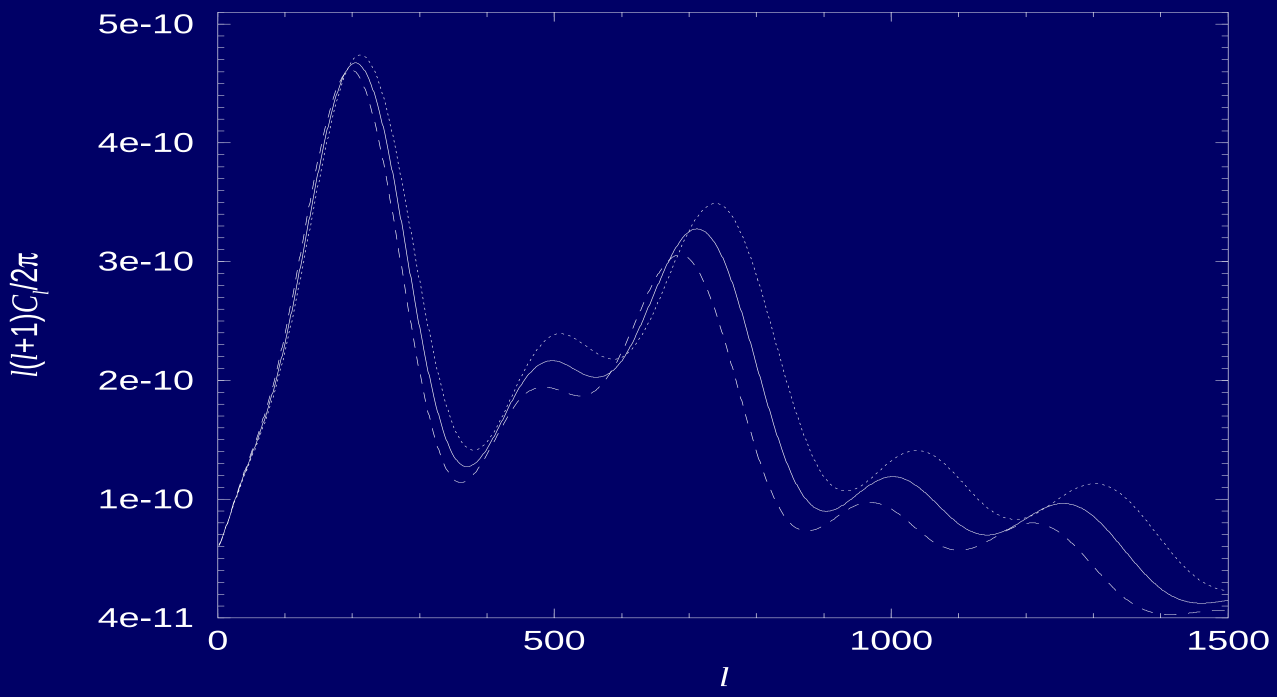
Mean $\pm$ 1σ scale-scale correlations for a π twist Torus (Rocha et al., astro-ph/0205155)

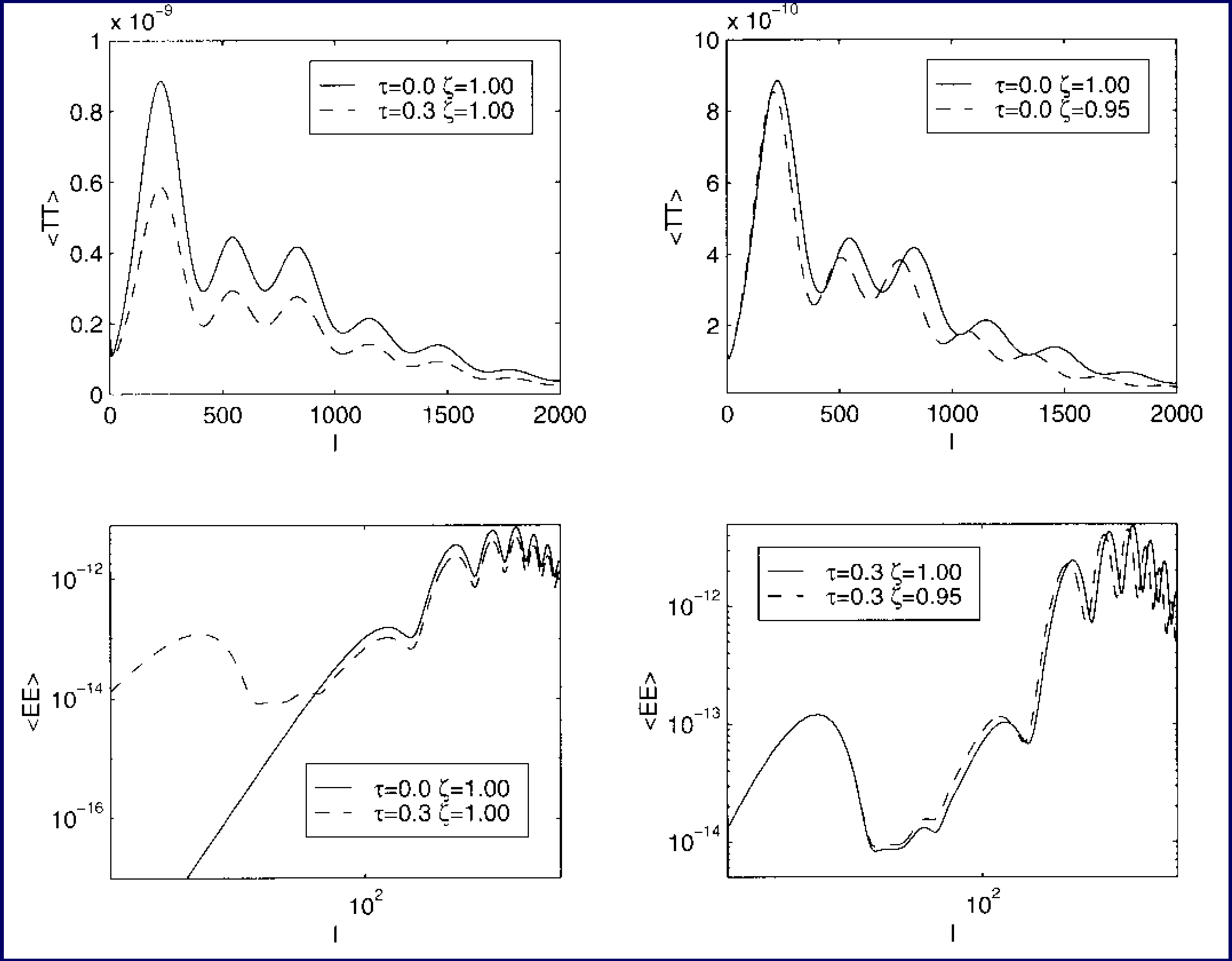
Conclusion $\longrightarrow$ Compact orientable flat topologies with appropriate topological sizes are as consistent with the *COBE*-DMR data as an infinite universe. Among the finite models the data seems to prefer a Universe which is about the size of the horizon for all but the hypertorus and the triple-twist torus. This analysis allows us to find a best fit topological size for each model, although cosmic variance might limit our ability to distinguish some of the topologies.

Does the fine structure constant α vary with time?



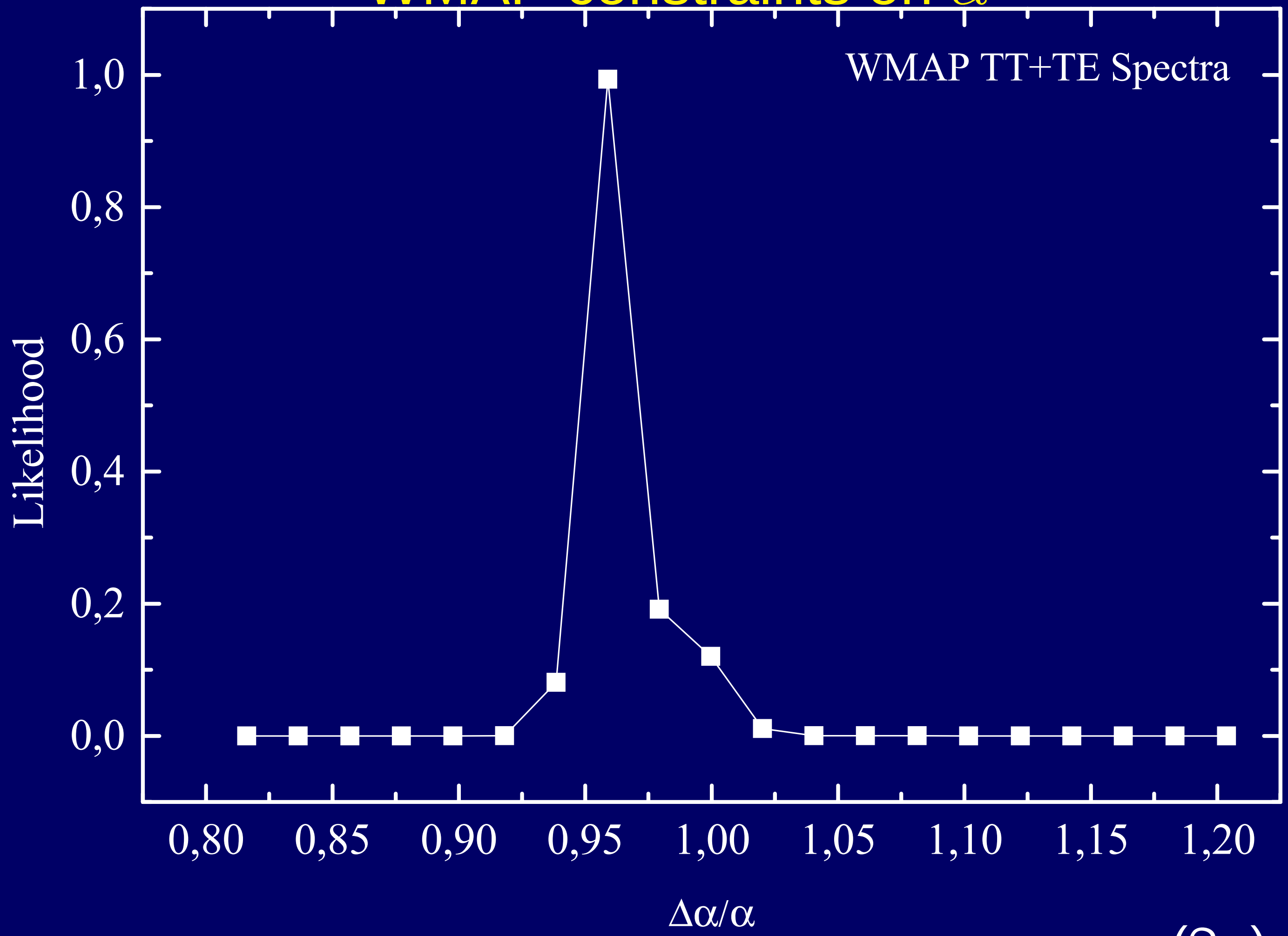






Contrasting the effects of varying α and reionization on the CMB temperature and polarization. Here $\zeta = \alpha_{dec}/\alpha_0$.

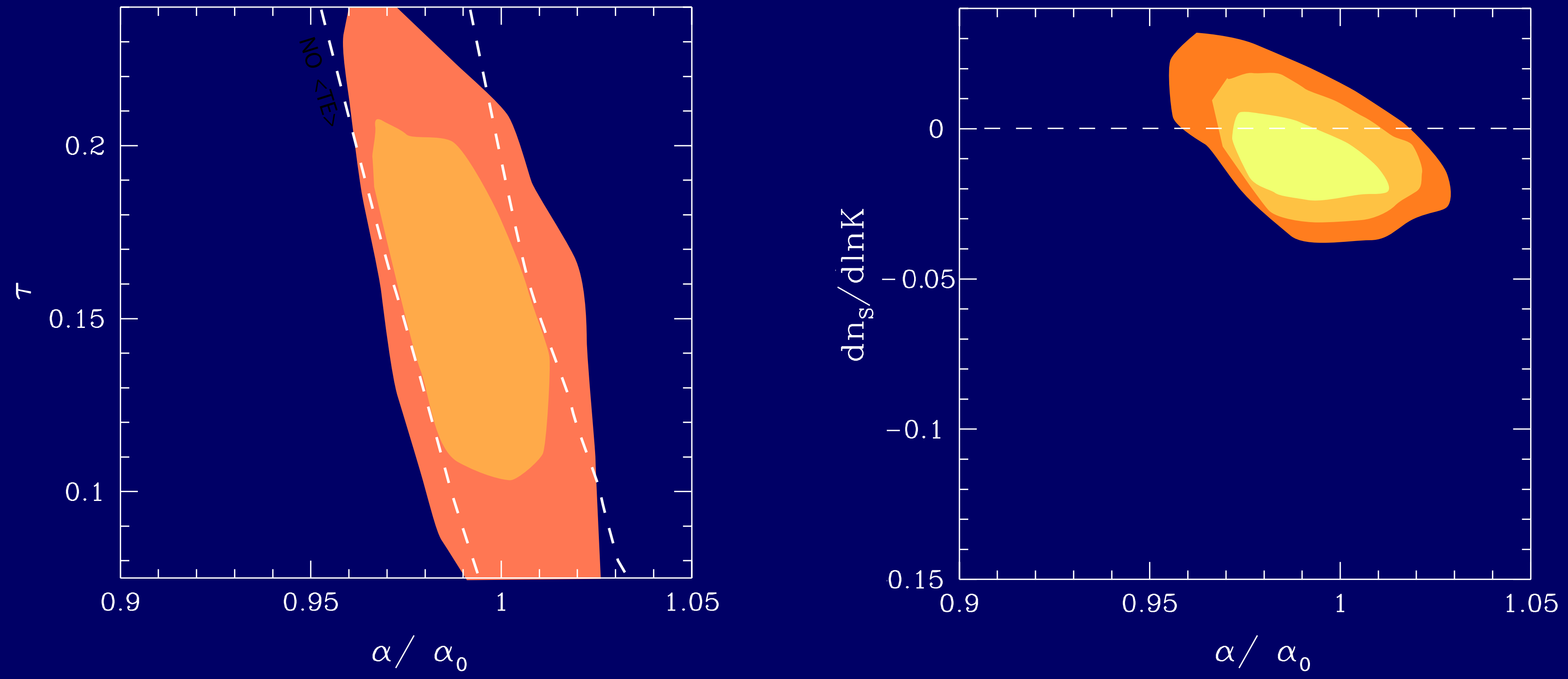
WMAP constraints on α



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

Conclusion $\rightarrow$ 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

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

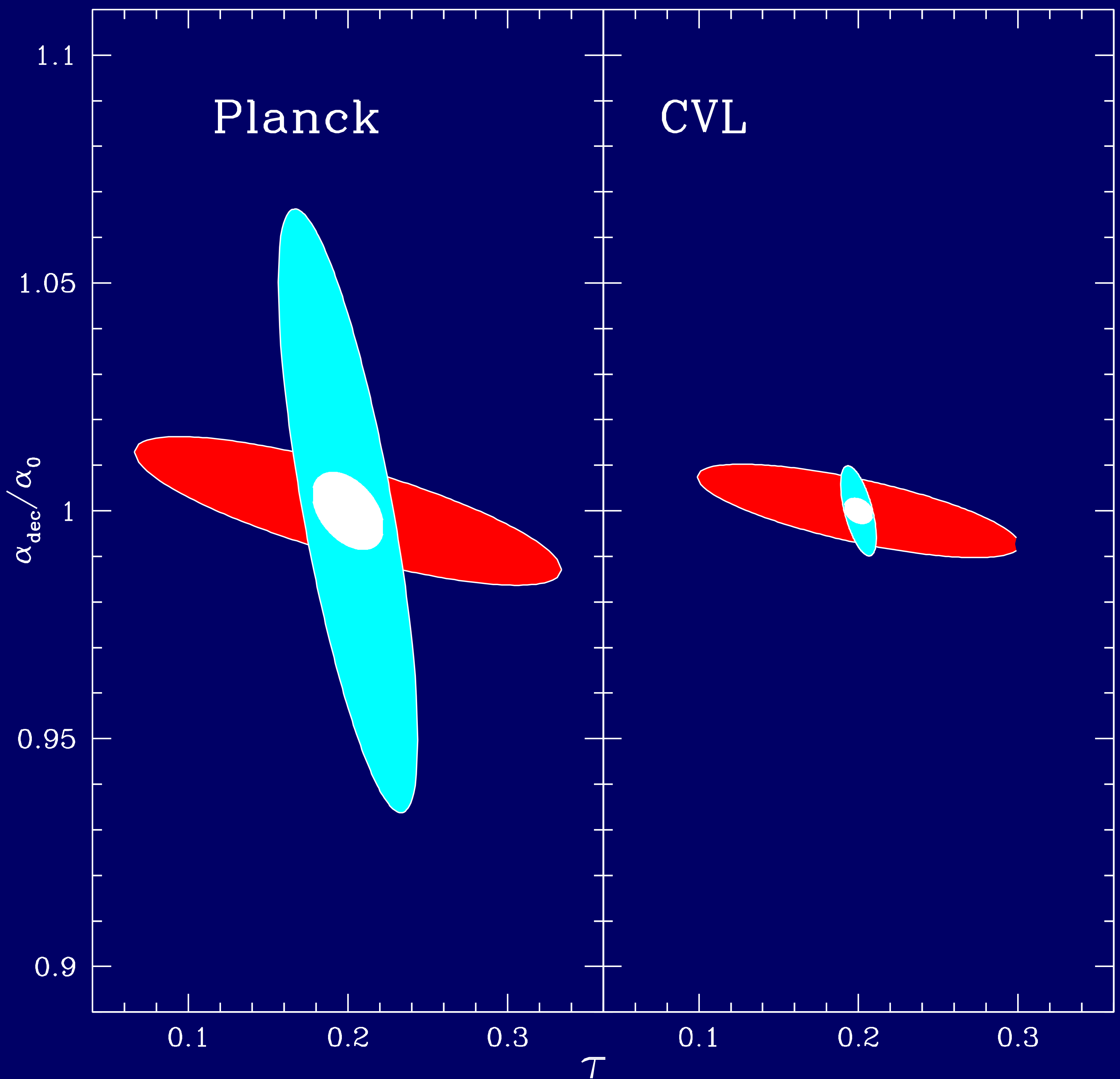
$$\mathcal{L} \approx \mathcal{L}_m \exp\left[-\frac{1}{2}\sum_{ij} F_{ij}\delta\Theta_i\delta\Theta_j\right]$$

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

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:

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

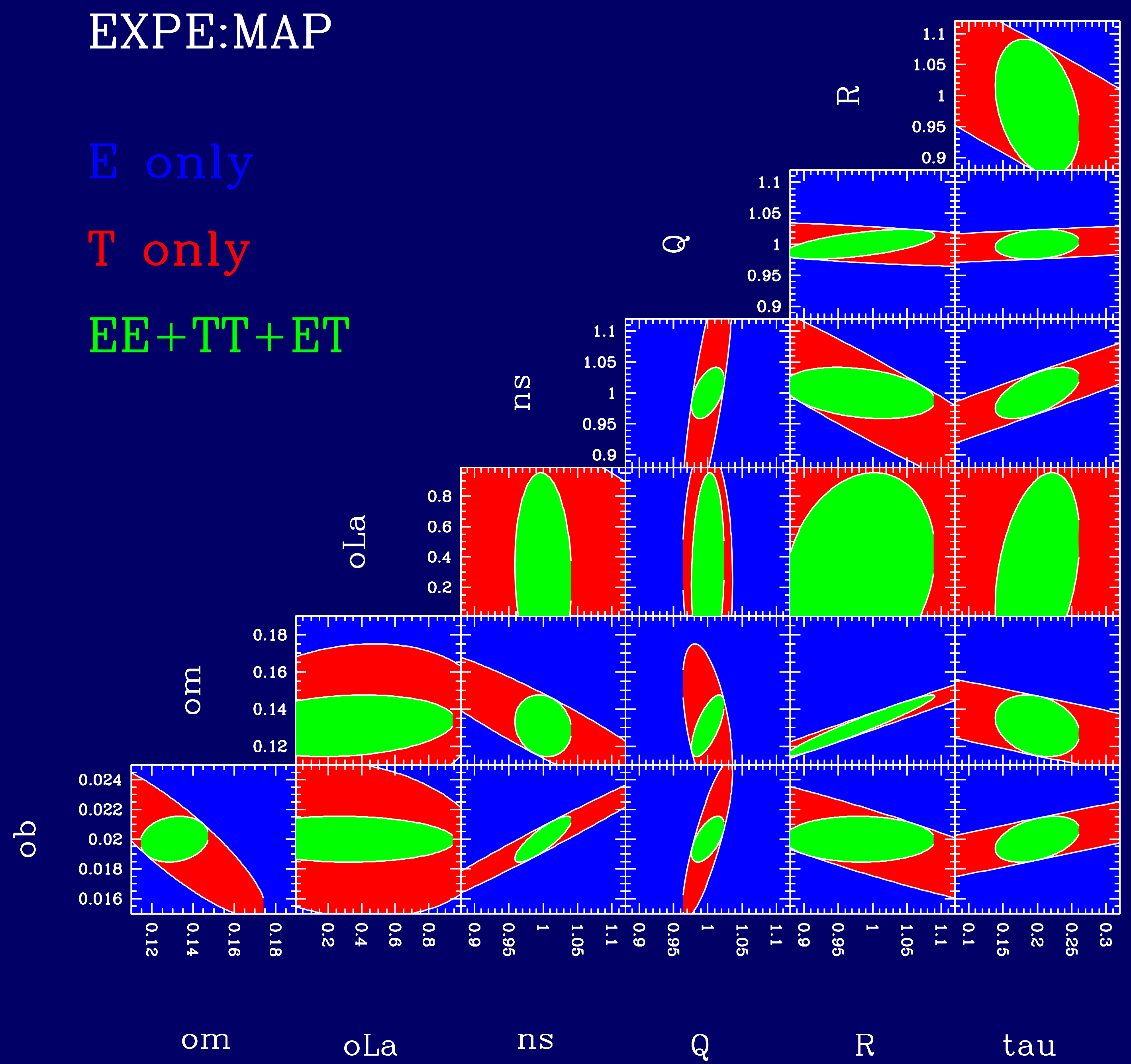
Cov^{-1} is the inverse of the covariance matrix, Θ_i are the cosmological parameters we want to estimate and X, Y stands for T (temperature),E, B (polarization modes),C (cross-correlation of the power spectra for T and E). For each l one has to invert the covariance matrix and sum over X and Y.



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 $\rightarrow$ 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.


EXPE:MAP
E only
T only
EE+TT+ET
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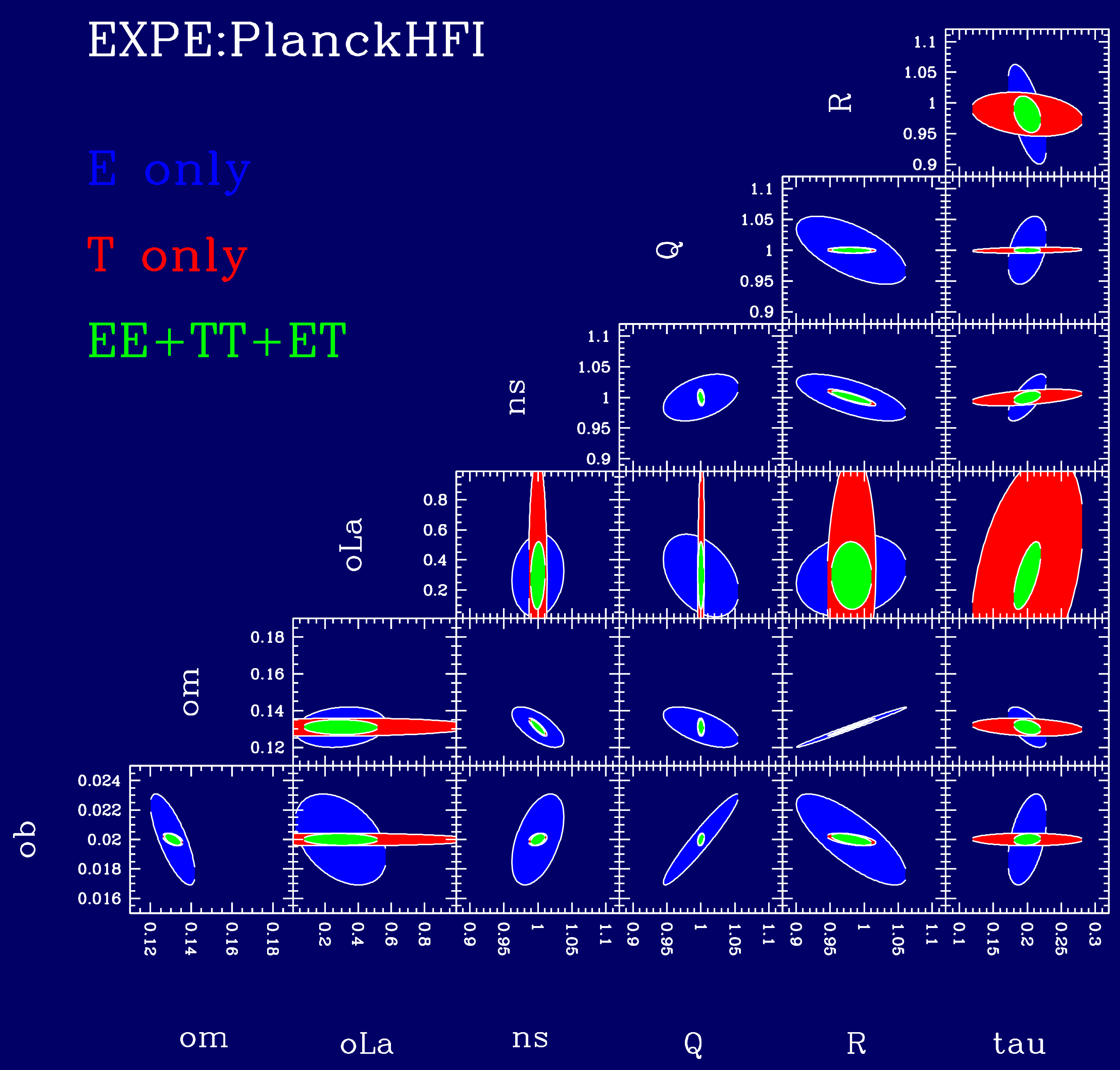
EXPE:PlanckHFI
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T only
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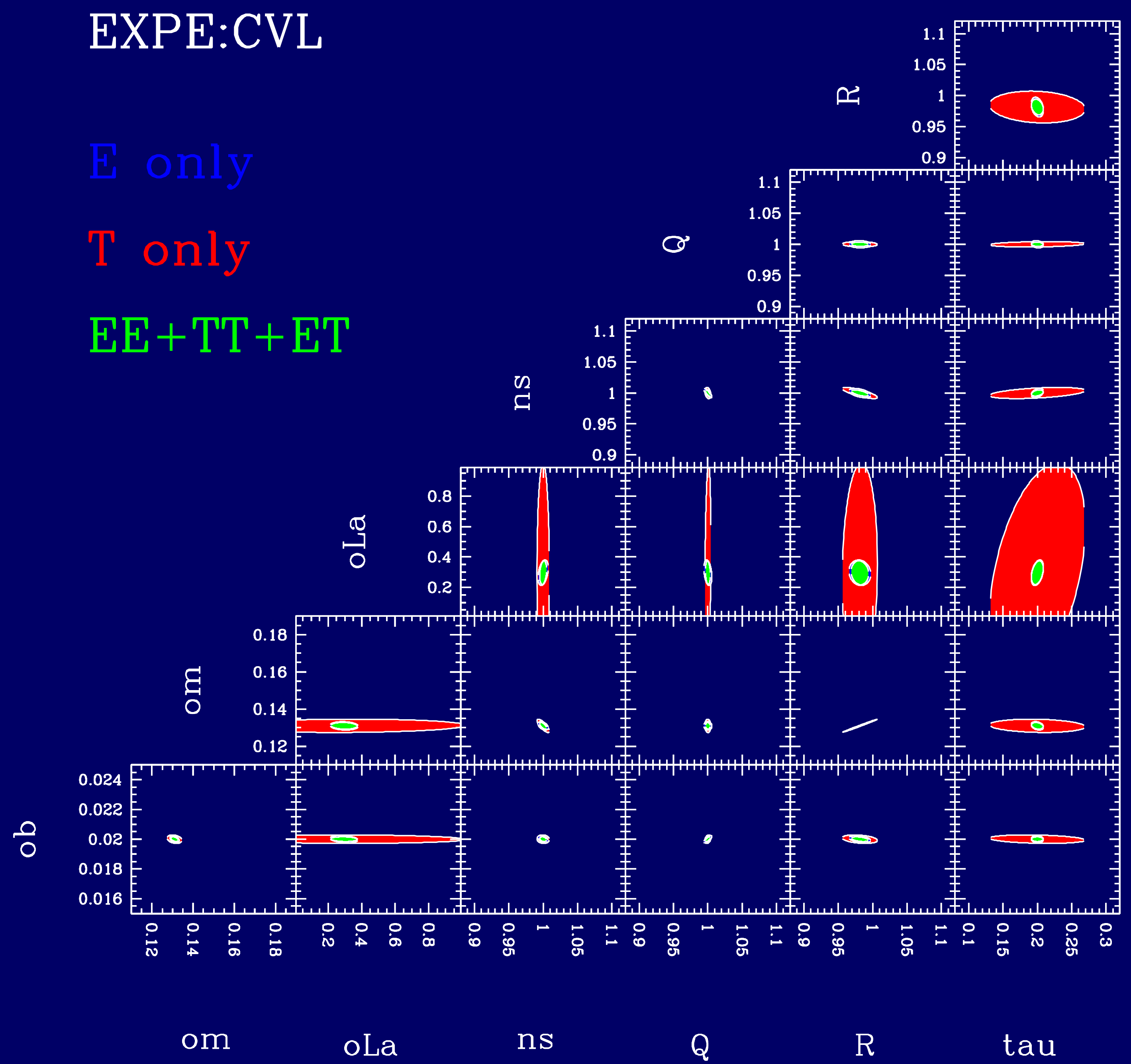

EXPE:CVL
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T only
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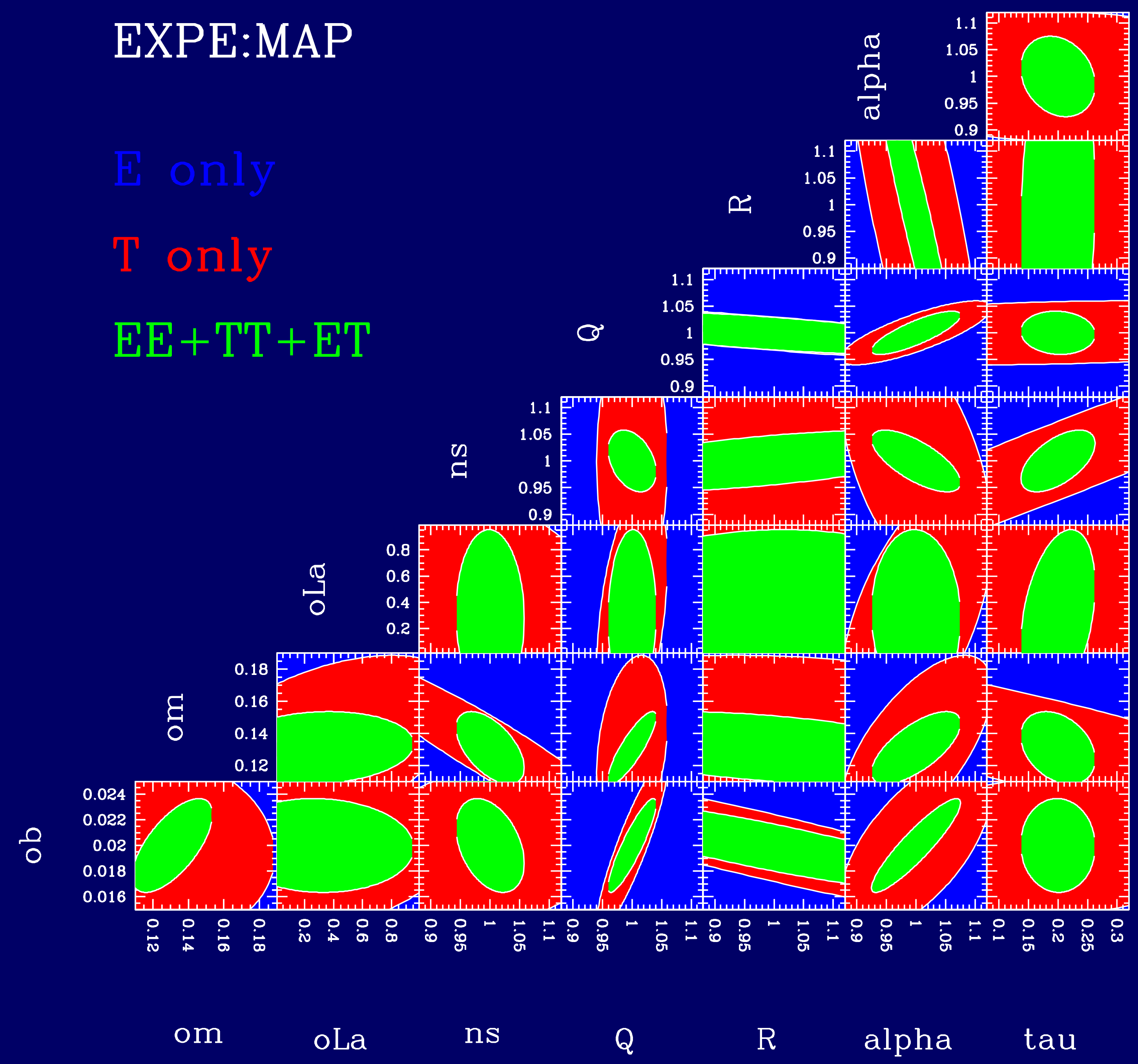
EXPE:MAP
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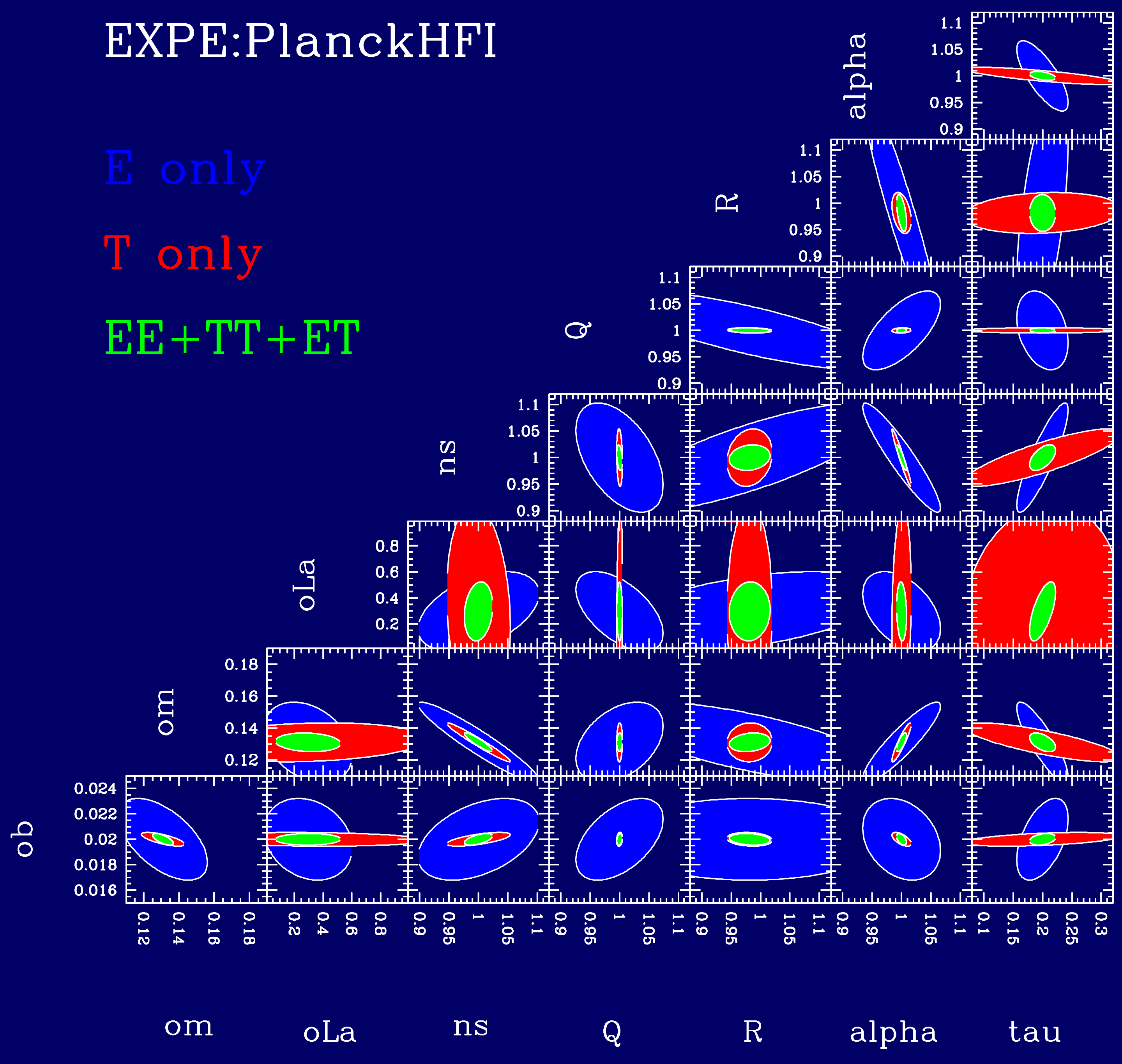
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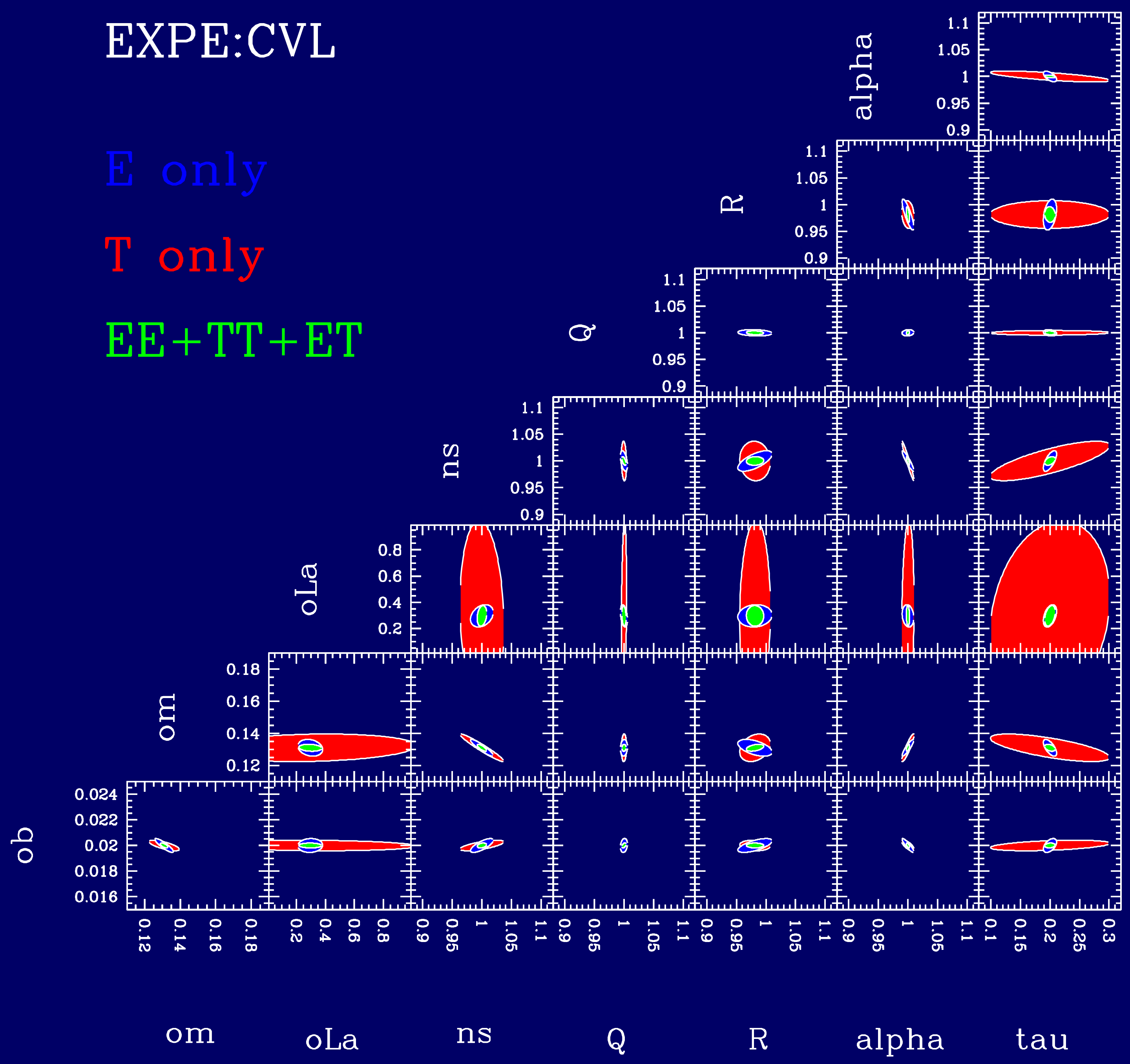
EXPE:CVL
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Conclusion $\longrightarrow$ Planck is essentially cosmic variance limited for temperature but there will still be considerable room for improvement in polarization .

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.