Non-Gaussianity in CMB map seen through Needlets

WMAP 5-year Temperature Data Analysis

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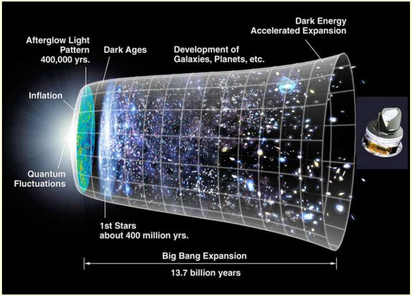
Outline

ΛCDM - The Cosmological Concordance Model



- One field inflation: nearly scale invariant perturbations;
- Dark Matter: perturbation growth and structure formation;
- Cosmological constant: late time acceleration of the Universe;
- Basic 6 parameters ΛCDM model.
- CMB thermal relic of the Big Bang
- Current constraints from CMB surveys (WMAP,BOOMERanG,CBI,ACBAR), Large Scale Surveys (2dF,NVSS,SDSS), SNe, HST
- Future: Planck, CMBpol, BOSS...

Cosmological Parameters

Beyond the Simplest Cosmological Model

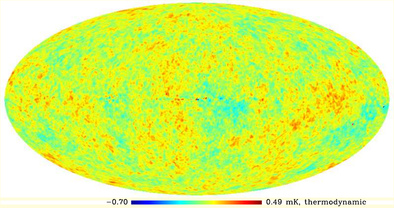
- Signature of non-standard inflation models (multifield inflation, ekpyrotic or cyclic scenarios...):
  - Deviation from Gaussian perturbations: large f_{NL},
  - Gravitational waves,
  - Polarization B-modes;
- Dark energy as a possible explanation of the late time evolution of the Universe:
  - Evolving scalar field;
  - Equation of state parameter;
  - Speed of sound.

- Technique: Spherical Needlets
- Foregrounds subtraction: needlets ILC (Fay et al. 2008), point sources, polarization

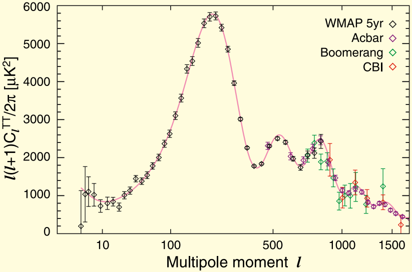
Spherical Needlets

Marinucci et al. MNRAS **838** (2008) 539-545

Pixel space: temperature map



Harmonic space: angular power spectrum



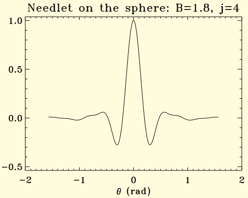
Dealing with masks, foregrounds and noise

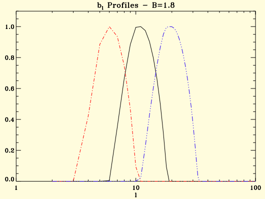
$$T(\gamma) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\gamma) \qquad \gamma \longleftrightarrow \mathrm{k-pixel}$$

Cosmological parameter estimation

Spherical Needlets

Marinucci et al. MNRAS **838** (2008) 539-545





Needlets in pixel space.

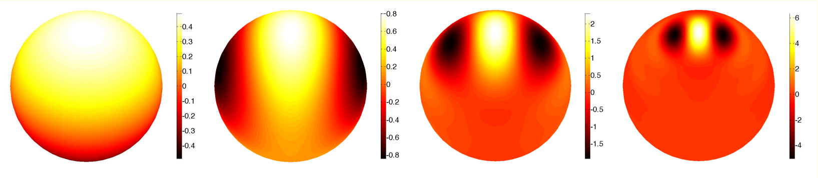
- Peculiar combination of spherical harmonics: $T(\hat{\gamma}) = \sum_{j,k} \beta_{jk} \psi_{jk}(\hat{\gamma})$
- Expansion coefficients: $\beta_{jk} = \sqrt{\lambda_{jk}} \sum_\ell b\left(\frac{\ell}{B^j}\right) \sum_m a_{\ell m} Y_{\ell m}(\xi_{jk})$
- $\sum_j \beta_j = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell$; $\beta_j = \langle \sum_k \beta_{jk}^2 \rangle$

$b(\ell/B^j)$ filter function in multipole domain. $B = 1.8, j = 3, 4, 5.$

- Small overlap between filters in ℓ-space;
- Easy to encode (Healpix based).

Spherical Needlets

Marinucci et al. MNRAS **838** (2008) 539-545

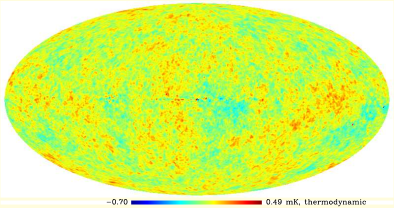


Credit:Wiaux et al. 0712.3519

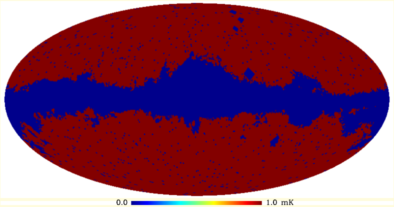
Anisotropic Features in WMAP 5-year Data

Pietrobon et al. Phys. Rev. D.**78** (2008) 103504

- Needlet analysis of CMB temperature map looking for anisotropic features: cold and hot spots
- $B = 1.8$ set applied to WMAP 5-year + Kq75 mask;



WMAP 5-year ILC temperature map.



WMAP 5-year broad mask: Kq75.

Anisotropic Features in WMAP 5-year Data

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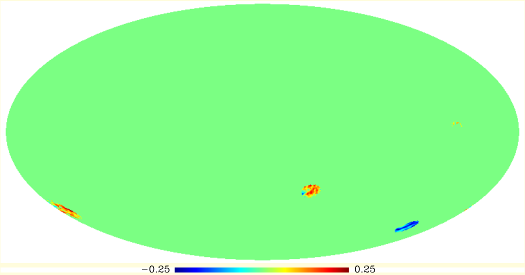
We found three significant large scale structures at ℓ 10 to 20.



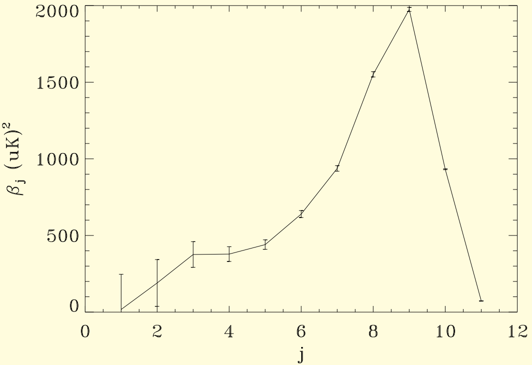
Spots detected.

- The Cold Spot (Vielva et al. 2004);
- Two hot spots.

Angular Power Spectrum estimate: N vs. S

Pietrobon et al. Phys. Rev. D.**78** (2008) 103504

CMB power spectrum in needlet space up to $\ell \sim 200$ $\beta_j = \sum_k \beta_{jk}^2 / N_{\rm pix}$



Whole sky power spectrum.

Angular Power Spectrum estimate: N vs. S

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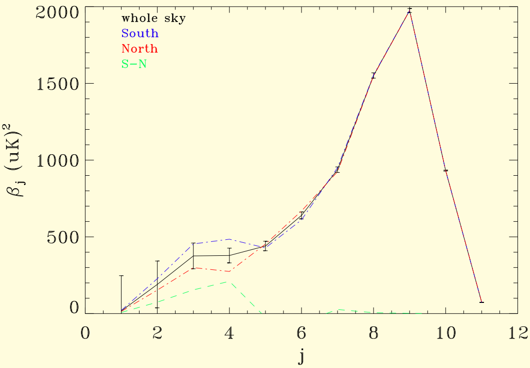

Significant difference between the power spectrum computed in the two hemispheres. (Hansen et al. (2008))

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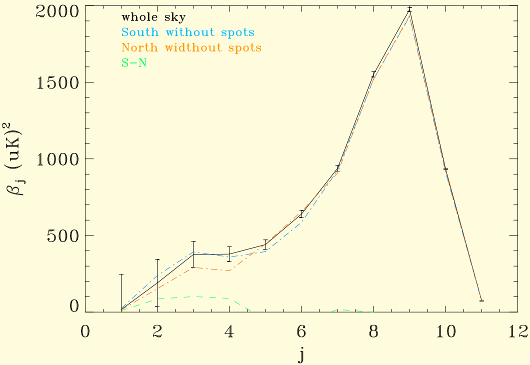

The asymmetry decreases by a factor 2 when spots are removed

Cosmological parameter implication

Pietrobon et al. Phys. Rev. D.**78** (2008) 103504

- How do the spots affect the cosmological parameter estimation?
- The effect on the whole sky angular power spectrum exceeds the cosmic variance at one/two sigma in few multipoles
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- We could expect a change of few 10^{-3} on A_s, τ, n_s
- We ran MCMC but no significant changes were found
    - Cosmic variance;
    - degeneracy among parameters.

Limits on $f_{\rm NL}$ from WMAP 5-year Data

Pietrobon et al. arXiv:astro-ph/0812.2478 (2008)

- Primordial non-Gaussianity due to second order effect:

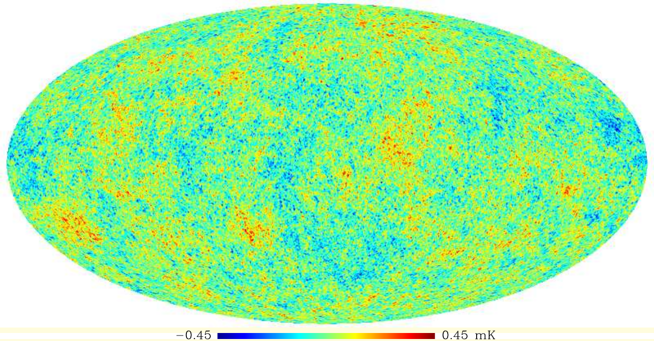
$$\Phi(\mathbf{x}) = \phi_G(\mathbf{x}) + f_{\rm NL}[\phi_G^2(\mathbf{x}) - \langle\phi_G^2\rangle]$$

- Claim of detection at 2.5 sigma level by Yadav & Wandelt in WMAP 3-year data (Phys.Rev.Lett.100:181301,2008);
  $f_{\rm NL} \sim 80 \longrightarrow$ non-standard early universe models (ekpyrotic, cyclic);
- Slightly lower confidence level in Komatsu et al. (2008) with WMAP 5-year data;

Fast cubic estimator KSW	bispectrum based	$\delta f_{\rm NL} \sim \pm 60$ at 95% c.l.
Wavelets Curto et al.	“binned” bispectrum	$\delta f_{\rm NL} \sim \pm 60$ at 95% c.l.
N-pdf Vielva & Sanz	bayesian analysis	$\delta f_{\rm NL} \sim \pm 124$ at 95% c.l.

Effect of $f_{\rm NL}$ on CMB sky

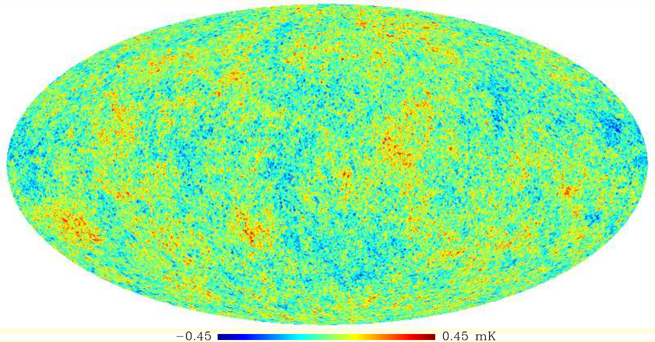
$f_{\rm NL} = 0$



Credit: M. Liguori et al.

Effect of $f_{\rm NL}$ on CMB sky

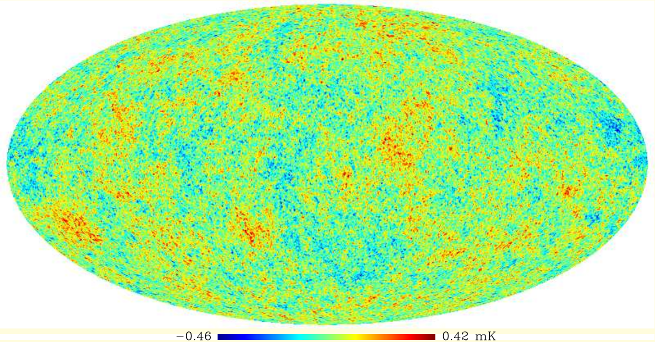
$f_{\rm NL} = 10$



Credit: M. Liguori et al.

Effect of $f_{\rm NL}$ on CMB sky

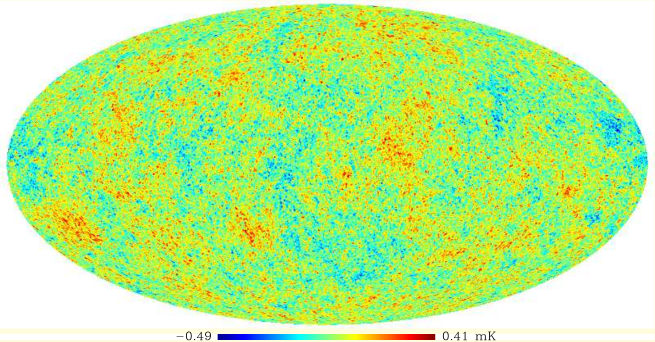
$f_{\rm NL} = 100$



Credit: M. Liguori et al.

Effect of f_{NL} on CMB sky

$f_{NL} = 500$



Credit: M. Liguori et al.

Procedure Applied to the Data

Pietrobon et al. arXiv:astro-ph/0812.2478 (2008)

- Noise weighted combination of all channels: Q, V and W foregrounds reduced
- Extract needlet coefficients β_{jk}
- Compute the skewness

$$S_j = \frac{1}{\tilde{N}_p} \sum_{k'} \frac{(\beta_{jk'} - \langle \beta_{jk'} \rangle)^3}{\sigma_j^3}$$

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- Apply the same procedure to:
  - non-Gaussian simulations in order to find the best fit for $f_{\rm NL}$
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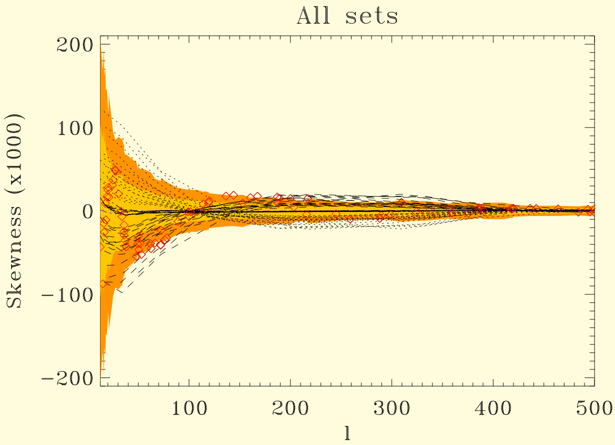
- Apply the same procedure to:
  - non-Gaussian simulations in order to find the best fit for f_{NL}
  - Gaussian simulations to estimate covariance matrix (valid for small f_{NL})
- We combined several sets of needlets in order to span as homogeneously as possible the multipole range.

Constraints on f_{NL}

Pietrobon et al. arXiv:astro-ph/0812.2478 (2008)

Skewness of the needlet coefficients



- Lines for positive (dashed) and negative (dotted) f_{NL};
- Red diamonds: WMAP5 measurement.

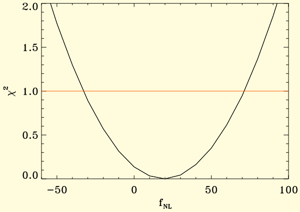
Constraints on $f_{\rm NL}$

Pietrobon et al. arXiv:astro-ph/0812.2478 (2008)

- χ^2 statistics

$$\chi^2(f_{NL}) = (X^d - \langle X(f_{NL})\rangle)^T \mathrm{C}^{-1} (X^d - \langle X(f_{NL})\rangle)$$

$f_{\rm NL} = 30$
$-50 < f_{\rm NL} < 110$ at 95% c.l.



WMAP 5-year measured χ^2.

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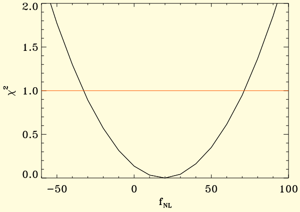


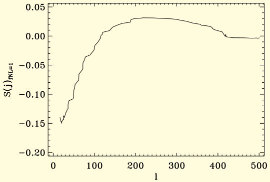
WMAP 5-year measured χ^2.

- $f_{\rm NL}$ skewness based estimator

$$S_j^{\rm obs} = f_{\rm NL} S_j^{\rm th}|_{f_{\rm NL}=1}$$

$$f_{\rm NL} = \frac{\sum_{jj'} S_j^{\rm obs} \mathrm{C}_{jj'}^{-1} S_{j'}^{\rm th}}{\sum_{jj'} S_j^{\rm th} \mathrm{C}_{jj'}^{-1} S_{j'}^{\rm th}}$$

$f_{\rm NL} = 32 \pm 90$ at 95% c.l.



Skewness template for $f_{\rm NL} = 1$.

Conclusions

- Non-Gaussian signature in the WMAP 5-year temperature map:
  - identified anomalous large scale features;
  - masking them reduces the North-South by a factor 2;
  - cosmological parameters are unchanged;
- constraints on the $f_{\rm NL}$ parameter:
  - promising limits: $-50 < f_{\rm NL} < 110$ at 95% CL;
  - χ^2-statistics and $f_{\rm NL}$ skewness estimator applied.
- Application of needlets to the Planck reference sky.
- Is there any foregrounds contamination? arXiv:astro-ph/0901.2572 $-4 < f_{\rm NL} < 80$ 95% c.l.

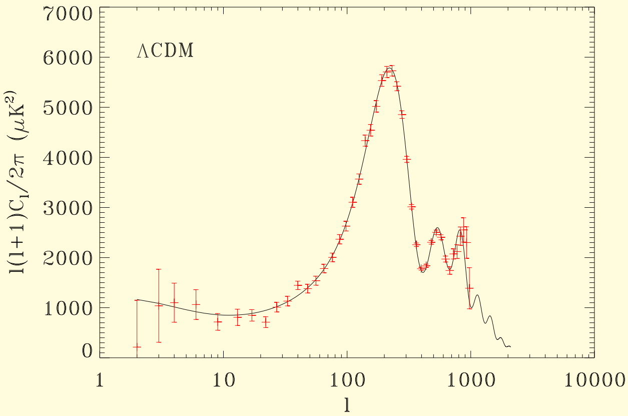
Minimal Concordance Cosmological Model Parameters

WMAP5 + SNe + BAO

$$
\begin{aligned}
\Omega_b h^2 &= 0.02267 \pm 0.00059 \\
\Omega_c h^2 &= 0.1131 \pm 0.0034 \\
\Omega_\Lambda &= 0.726 \pm 0.015 \\
n_s &= 0.960 \pm 0.013 \\
\Delta^2_{\mathcal{R}} &= (2.445 \pm 0.096) \times 10^{-9} \\
\tau &= 0.084 \pm 0.016 \\
\hline
H_0 & \quad 70.5 \pm 1.3\, km\ s^{-1} \\
\Omega_b & \quad 0.0456 \pm 0.0015 \\
\Omega_c & \quad 0.228 \pm 0.013
\end{aligned}
$$

CMB Spectra

Parameters and CMB Power Spectrum



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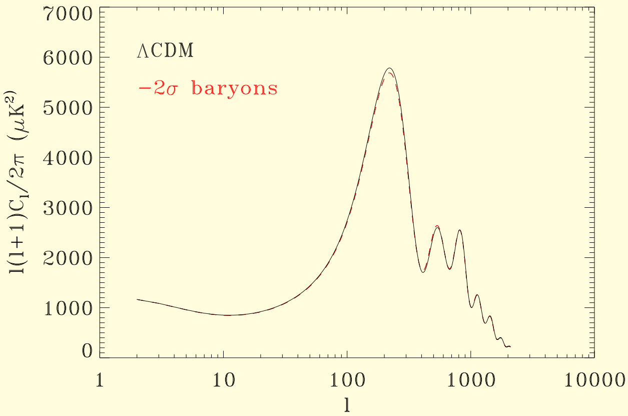
Parameters and CMB Power Spectrum



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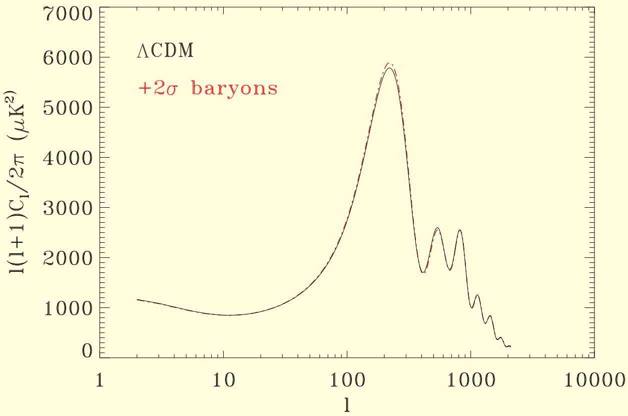

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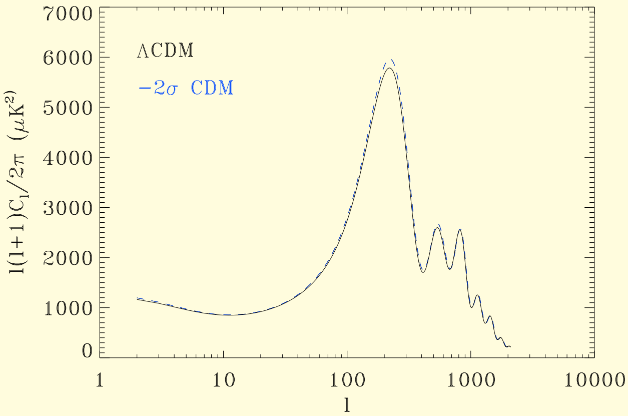

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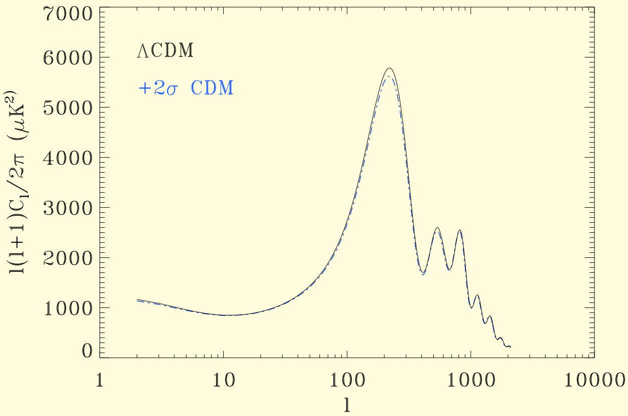

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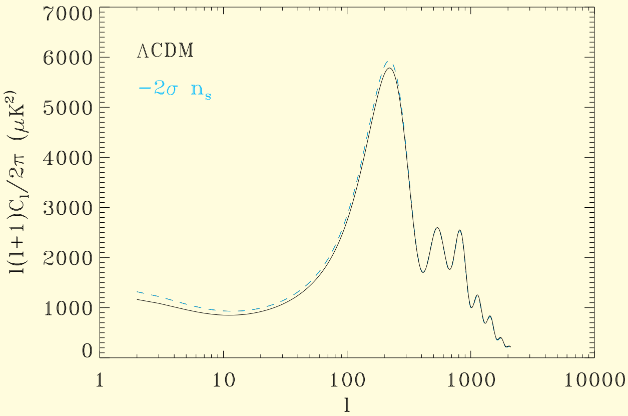

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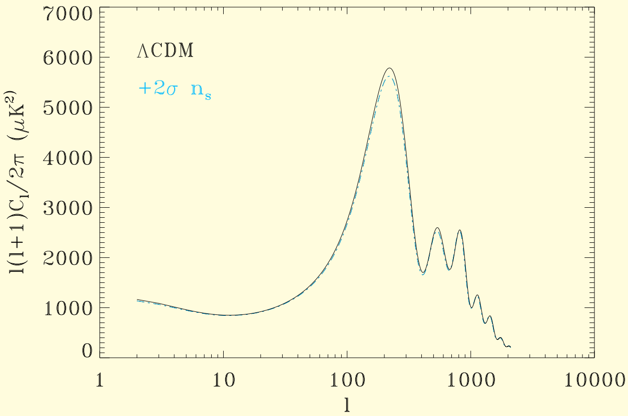

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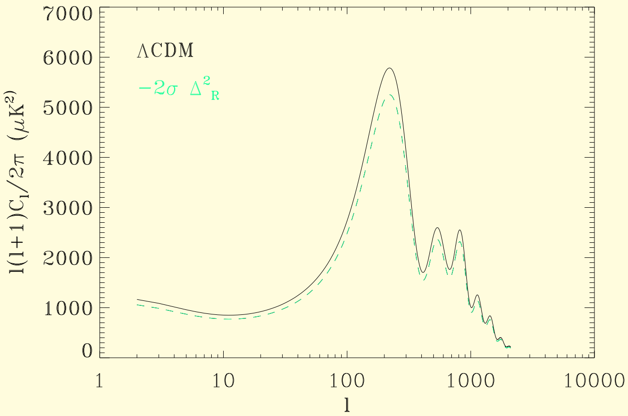

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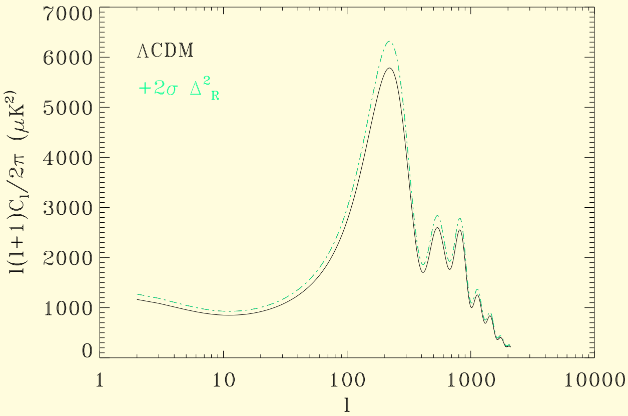

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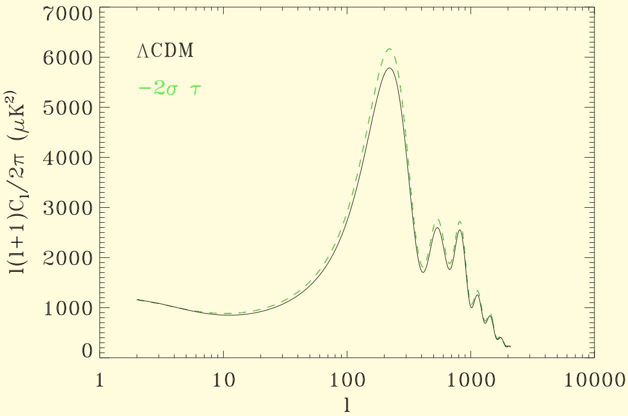

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