

Hints of Isocurvature Perturbations in the Cosmic Microwave Background, [astro-ph/0611917](#) (JCAP)

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The Bottom Line, astro-ph/0611917 (JCAP)

- We use **CMB** and **LSS** data only.
 - 3-year **WMAP**, **CBI** and **Boomerang** for CMB
 - **SDSS** for LSS
- Adiabatic and isocurvature perturbations **can be correlated**.
 - 10 parameters \Rightarrow we need long MCMC chains
- For the first time, the **CMB data disfavors the pure adiabatic model** with more than 95% confidence level.
 - the best-fit model has a 4% non-adiabatic contribution
 - the best χ^2 is better by 9.7 than in the pure adiabatic model
 - in practice, **all the improvement comes from the 2nd and 3rd acoustic peak regions in the CMB data** (the peaks are too narrow to be fitted well by pure adiabatic Λ CDM model)

- We have our friend, the gauge-invariant quantity (super-Hubble scales)

$$\mathcal{R} = -\zeta = H \frac{\delta\rho}{\dot{\rho}} + \psi = -\frac{1}{3} \frac{1}{1+w} \frac{\delta\rho}{\rho} + \psi,$$

where ψ is the metric perturbation.

- the continuity eq: $\dot{\rho} = -3H(1+w)\rho$, where $w \equiv p/\rho$
- On the uniform density hypersurface $\delta\rho \equiv 0$ and we get

$$\mathcal{R} = \psi, \text{ hence the name, "curvature perturbation".}$$

- On the flat hypersurface $\psi \equiv 0$, which gives

$$\mathcal{R} = -\frac{1}{3} \frac{1}{1+w} \frac{\delta\rho}{\rho}.$$

- In the case of multiple species of particles i

$$\mathcal{R} = \sum_i \frac{\dot{\rho}_i}{\dot{\rho}} \mathcal{R}_i, \text{ where } \mathcal{R}_i = H \frac{\delta\rho_i}{\dot{\rho}_i} + \psi.$$

Adiabatic, or curvature, perturbations:

- When all the particles are decay products of a single field

$$\mathcal{R}_i = \mathcal{R}_j = \mathcal{R} \quad \text{for all } i \text{ and } j.$$

- From the definition we then have

$$\frac{1}{1+w_i} \frac{\delta\rho_i}{\rho_i} - \frac{1}{1+w_j} \frac{\delta\rho_j}{\rho_j} = 0 \quad \text{for all } i \text{ and } j.$$

Isocurvature, or entropy, perturbations:

- If the species decay from different fields, it's possible that

$$\mathcal{S} \equiv 3(\mathcal{R}_i - \mathcal{R}_j) \neq 0 \quad \text{for } i \neq j.$$

- Thus we have

$$\frac{1}{1+w_i} \frac{\delta\rho_i}{\rho_i} - \frac{1}{1+w_j} \frac{\delta\rho_j}{\rho_j} = \mathcal{S}_{ij}.$$

- We have studied the cold dark matter (CDM) isocurvature, thus from now on: $\mathcal{S} \equiv \mathcal{S}_{c\gamma} = \mathcal{R}_c - \mathcal{R}_\gamma = \delta_c - \frac{3}{4}\delta_\gamma$.
- Adiabatic perturbation is conserved on super-Hubble scales

$$\mathcal{R}(t) = \mathcal{R}(t_{\text{init}})$$
- The entropy perturbation is not a conserved quantity in itself

$$\mathcal{S}(t) = T_{SS}\mathcal{S}(t_{\text{init}})$$
 (e.g., thermalisation $\rightarrow T_{SS} = 0$)
- The entropy perturbation can seed curvature perturbation

$$\mathcal{R}(t) = \mathcal{R}(t_{\text{init}}) + T_{RS}\mathcal{S}(t_{\text{init}})$$
- All of this can be written nicely into a matrix form:

$$\begin{bmatrix} \mathcal{R}(t_{\text{pri}}, \mathbf{k}) \\ \mathcal{S}(t_{\text{pri}}, \mathbf{k}) \end{bmatrix} = \begin{bmatrix} 1 & T_{RS}(k) \\ 0 & T_{SS}(k) \end{bmatrix} \begin{bmatrix} \mathcal{R}(t_*, \mathbf{k}) \\ \mathcal{S}(t_*, \mathbf{k}) \end{bmatrix},$$

where t_* denotes the time when the mode was generated (horizon crossing during inflation) and t_{pri} some time deep in the radiation dominated era after the nucleosynthesis.

The primordial correlators $\langle x(\mathbf{k})y^*(\mathbf{k}') \rangle = \frac{2\pi^2}{k^3} C_{xy}(k) \delta^{(3)}(\mathbf{k} - \mathbf{k}')$:

$$\mathcal{P}_{\mathcal{R}}(k) \equiv C_{\mathcal{R}\mathcal{R}}(k) = A_r^2 \hat{k}^{n_{\text{ad}1}-1} + A_s^2 \hat{k}^{n_{\text{ad}2}-1},$$

$$\mathcal{P}_S(k) \equiv C_{SS}(k) = B^2 \hat{k}^{n_{\text{iso}}-1},$$

$$C_{\mathcal{R}S}(k) = C_{S\mathcal{R}}(k) = A_s B \hat{k}^{n_{\text{cor}}-1}, \quad n_{\text{cor}} = (n_{\text{ad}2} + n_{\text{iso}})/2$$

where $\hat{k} = k/k_{\text{pivot}}$ and $k_{\text{pivot}} = 0.01 \text{Mpc}^{-1}$ (CMB multipole $\ell \sim 140$) is the pivot scale at which the amplitudes are defined.

The total C_ℓ is now a sum of **4 components**: the uncorrelated and correlated adiabatic parts, the isocurvature part, and the correlation between the last two:

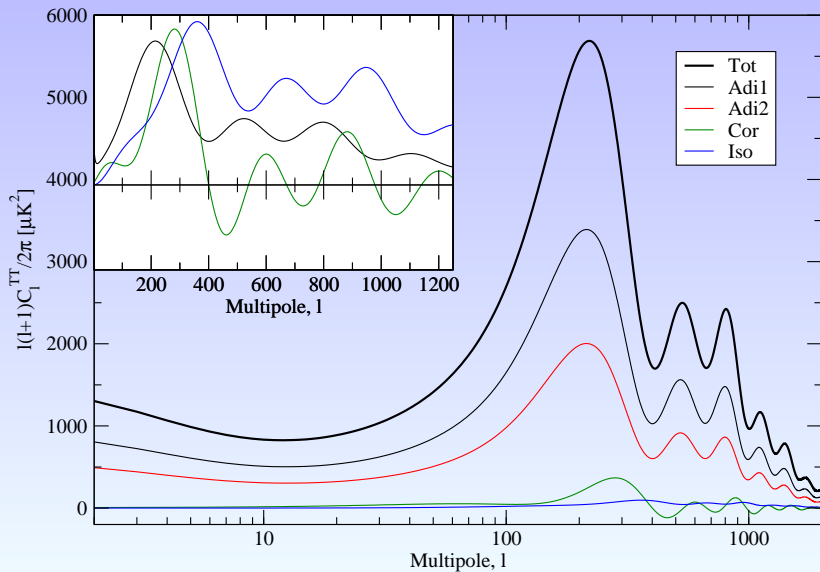
$$C_\ell \equiv C_\ell^{\text{ad}1} + C_\ell^{\text{ad}2} + C_\ell^{\text{iso}} + C_\ell^{\text{cor}} = A^2 [(1 - \alpha)(1 - |\gamma|) \hat{C}_\ell^{\text{ad}1} + (1 - \alpha)|\gamma| \hat{C}_\ell^{\text{ad}2} + \alpha \hat{C}_\ell^{\text{iso}} + \text{sign}(\gamma) \sqrt{\alpha(1 - \alpha)} |\gamma| \hat{C}_\ell^{\text{cor}}],$$

where we have defined (at the pivot scale)

$$A^2 \equiv A_r^2 + A_s^2 + B^2, \quad \alpha \equiv \frac{B^2}{A^2} \in [0, 1], \quad \gamma \equiv \text{sign}(A_s B) \frac{A_s^2}{A_r^2 + A_s^2} \in [-1, 1]$$

total amplitude isocurvature fraction correlation

\hat{C}_ℓ denote spectra obtained with unit amplitudes ($A_r = 1, A_s = 1, B = 1$)



Our model has 10 parameters (the adiabatic Λ CDM has 6).
We assign uniform, or flat, prior probabilities to them.

The 4 **background** parameters:

- physical baryon density ($\omega_b = h^2 \Omega_b$), the physical CDM density ($\omega_c = h^2 \Omega_c$), the sound horizon angle (θ) and the optical depth to reionization (τ).

The 6 **perturbation** parameters: (in two different parametrisations)

- **The spectral index parametrisation** (at scale $k/h = 0.01$)
 $\ln(A)$, α , γ , $n_{\text{ad}1}$, $n_{\text{ad}2}$, n_{iso} .
- **The amplitude parametrisation** (at $k/h = 0.002$ and $k/h = 0.05$)
 $\ln(A_{0.002})$, $\alpha_{0.002}$, $\gamma_{0.002}$, $\ln(A_{0.05})$, $\alpha_{0.05}$, $\gamma_{0.05}$.

The MCMC chains with amplitude parametrisation converge significantly faster and thus we use that in our analysis.

Main results

- We define:

$$\alpha_{\mathcal{T}} \equiv \frac{\sum (2\ell + 1)(C_{\ell}^{\text{iso}} + C_{\ell}^{\text{cor}})}{\sum (2\ell + 1)C_{\ell}},$$

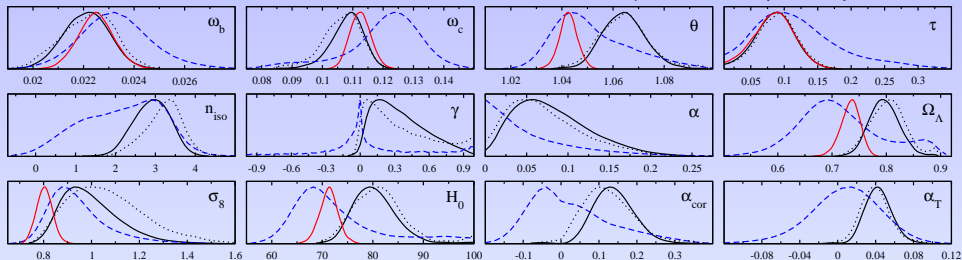
which gives the **total non-adiabatic contribution to the CMB temperature variance**.

$$\left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_{\ell}.$$

- We find **$\alpha_{\mathcal{T}} = 0.043 \pm 0.015$** .
- This is **positive at 95% C.L.** ($0.017 < \alpha_{\mathcal{T}} < 0.073$).
- Thus the CMB data favors a $\sim 4\%$ non-adiabatic contribution.
- **$\Delta\chi^2 \equiv \chi^2(\text{best correlated model}) - \chi^2(\text{best adiabatic model}) = -9.7$** .

Marginalised 1d likelihoods

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- WMAP3: Allowing for correlated adiabatic and CDM isocurvature (flat priors for the amplitudes)
- - WMAP3: Allowing for correlated adiabatic and CDM isocurvature (flat priors for the spectral indices)
- - WMAP1: Allowing for correlated adiabatic and CDM isocurvature
- WMAP3: Adiabatic Λ CDM

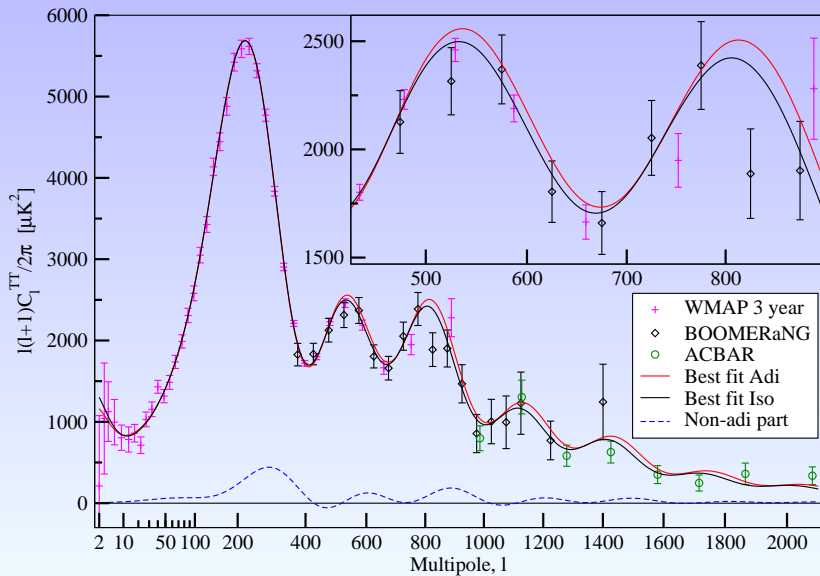
Additional data

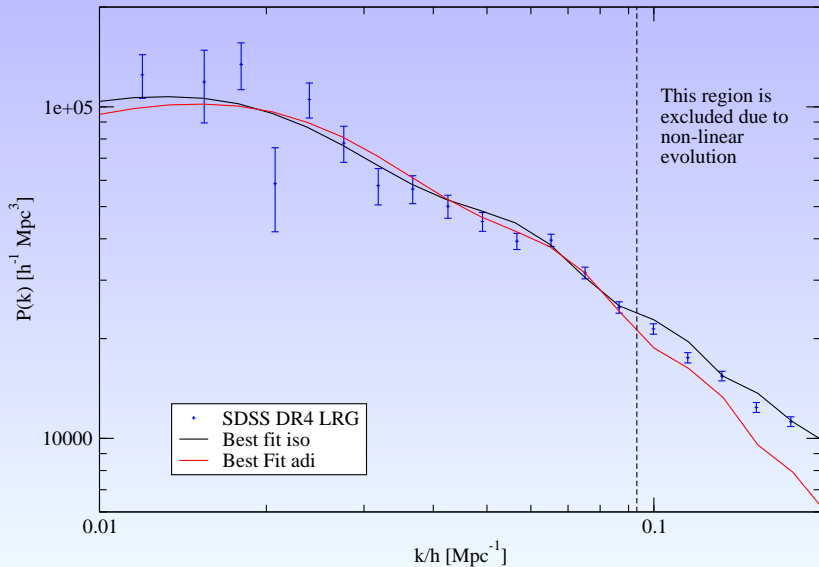
Only minor changes in the 1d likelihoods if we apply:

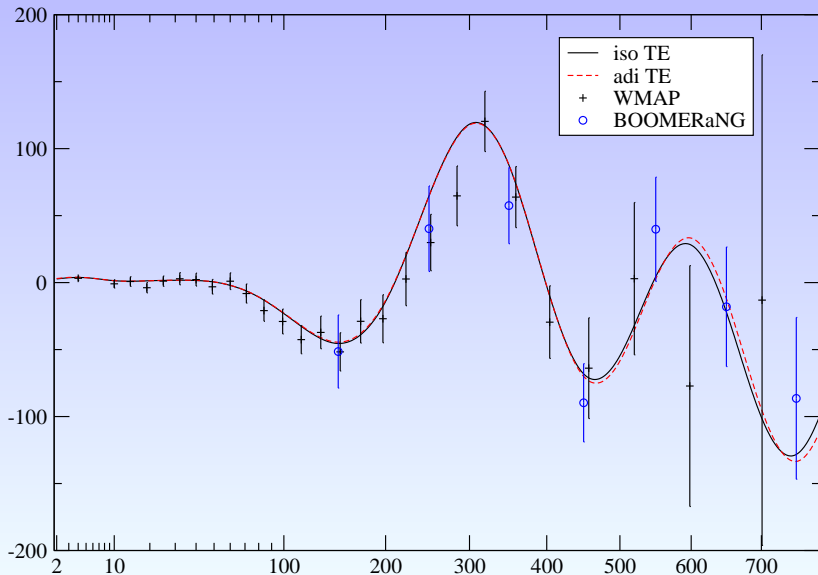
- HST prior $H_0 = 72 \pm 8$ km/s/Mpc.
- SNIa from Astier et al. (2006), $\Omega_m \approx 0.263 \pm 0.074$.

More "adiabatic-like" 1d likelihoods if we apply:

- SNIa from Riess et al. (2004), $\Omega_m \approx 0.30 \pm 0.04$.
- Lyman- α data as in Beltran, Garcia-Bellido, Lesgourgues, and Viel (2005) $\Rightarrow \alpha_T > 0$ only at 68% C.L., $\Delta\chi^2 \approx -5$.
 - Ly- α extends the data to "much" larger k (smaller scales).
 - are power law spectra a good approximation over this extended k -range?







Conclusions (of a more technical nature)

- The amplitude parametrisation in the MCMC study is significantly (about an order of magnitude) faster than the spectral index parametrisation.
- The amplitude parametrisation favours a bit larger isocurvature and correlation fractions, since it does not give artificially large weight for the adiabatic model upon marginalisation.

Conclusions (the physics part)

- **The CMB peak structure** is marginally ($\sim 3\sigma$) **inconsistent with the pure adiabatic model.**
- **No conclusive evidence** for the CDM isocurvature. This “feature” could be:
 - just a statistical fluke
 - some yet unaccounted for **systematic effect both in the Boomerang and WMAP** data
 - some other non-standard cosmological feature
 e.g., isocurvature from cosmic strings as by Bevis *et al.*, astro-ph/0702223
- Some other data complementary to CMB may (dis)favour isocurvature. Ly- α , BAO, ISW-LSS correlation?
- In any case, the future data (hopefully already by Planck) will show whether or not the feature in C_ℓ remains.
 - worth keeping an eye on, since if confirmed, it would automatically **rule out single-field inflation**