# Hints of Isocurvature Perturbations in the Cosmic Microwave Background, JCAP09(2007)008

R. Keskitalo[1,2], H. Kurki-Suonio[1], *V. Muhonen*[1,2], J. Väliviita[3]

[1]Department of Physical Sciences
University of Helsinki

[2]Helsinki Institute of Physics (HIP)
University of Helsinki

[3]Institute of Cosmology and Gravitation (ICG)
University of Portsmouth

UniverseNET Annual School, Lesvos, Greece

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- We use CMB and LSS data only.
  - 3-year WMAP, CBI and Boomerang for CMB
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- 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 ⇒ we need long MCMC chains
- For the first time, the **CMB data disfavours the pure adiabatic model** with more than 95% confidence level.
  - the best-fit model has a 4% non-adiabatic contribution
  - the best $\chi^2$ is better by 9.7 than in the pure adiabatic model
  - in practice, all the improvement comes from the $2^{nd}$ and $3^{rd}$ acoustic peak regions in the CMB data (the peaks are too narrow to be fitted well by pure adiabatic $\Lambda$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 $\psi$ is the metric perturbation.

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where $\psi$ 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

$\mathcal{R} = \psi$, 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

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

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## Isocurvature, or entropy, perturbations:

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

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

- 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: $\mathcal{S} \equiv \mathcal{S}_{c\gamma} = \mathcal{R}_c - \mathcal{R}_\gamma = \delta_c - \frac{3}{4}\delta_\gamma$.

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- Adiabatic perturbation is conserved on super-Hubble scales
  $\mathcal{R}(t) = \mathcal{R}(t_{\rm init})$
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- The entropy perturbation can seed curvature perturbation
  $\mathcal{R}(t) = \mathcal{R}(t_{\rm init}) + T_{\mathcal{RS}}\mathcal{S}(t_{\rm init})$
- All of this can be written nicely into a matrix form:

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

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

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

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$$\mathcal{P}_\mathcal{R}(k) \equiv \mathcal{C}_{\mathcal{R}\mathcal{R}}(k) = A_r^2 \hat{k}^{n_{\mathrm{ad1}}-1}$$

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

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The total $C_\ell$ is now a sum of 4 components: the uncorrelated and correlated adiabatic parts, the isocurvature part, and the correlation between the last two:

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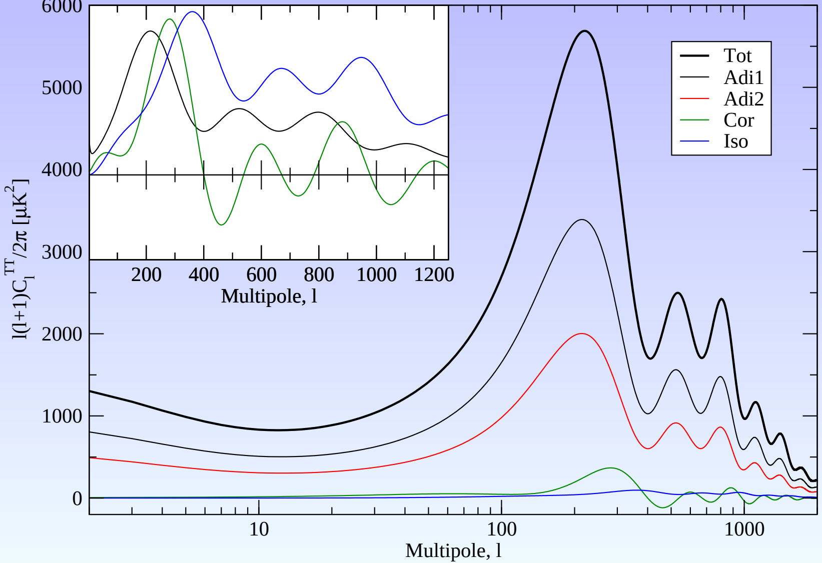
$$C_\ell \equiv C_\ell^{\rm ad1} + C_\ell^{\rm ad2} + C_\ell^{\rm iso} + C_\ell^{\rm cor} = A^2 \Big[ (1-\alpha)(1-|\gamma|) \hat{C}_\ell^{\rm ad1} + (1-\alpha)|\gamma| \hat{C}_\ell^{\rm ad2} + \alpha \hat{C}_\ell^{\rm iso} + \mathrm{sign}(\gamma) \sqrt{\alpha(1-\alpha)|\gamma|}\, \hat{C}_\ell^{\rm cor} \Big],$$

where we have defined (at the pivot scale)

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

total amplitude — isocurvature fraction — correlation

$\hat{C}_\ell$ denote spectra obtained with unit amplitudes ($A_r = 1, A_s = 1, B = 1$)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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 ($\theta$) and the optical depth to reionization ($\tau$).

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- **The amplitude parametrisation** (at k/h = 0.002 and k/h = 0.05) $\ln(A_{0.002})$, $\alpha_{0.002}$, $\gamma_{0.002}$, $\ln(A_{0.05})$, $\alpha_{0.05}$, $\gamma_{0.05}$.

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

# Main results

- We define:

$$\alpha_T \equiv \frac{\sum(2\ell+1)(C_\ell^{\rm iso}+C_\ell^{\rm cor})}{\sum(2\ell+1)C_\ell},$$

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

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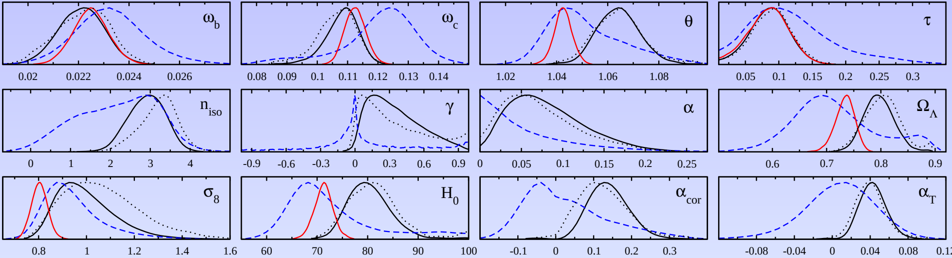
- This is **positive at 95% C.L.** ($0.017 < \alpha_T < 0.073$).
- Thus the CMB data favors a $\sim 4\%$ non-adiabatic contribution.
- $\boldsymbol{\Delta\chi^2} \equiv \chi^2(\text{best correlated model}) - \chi^2(\text{best adiabatic model})$ $= \mathbf{-9.7}$.

# Marginalised 1d likelihoods

Keskitalo, Kurki-Suonio, Muhonen & Väliviita, **astro-ph/0611917 (JCAP)**.




— 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 $\Lambda$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), $\Omega_m \approx 0.263 \pm 0.074$.

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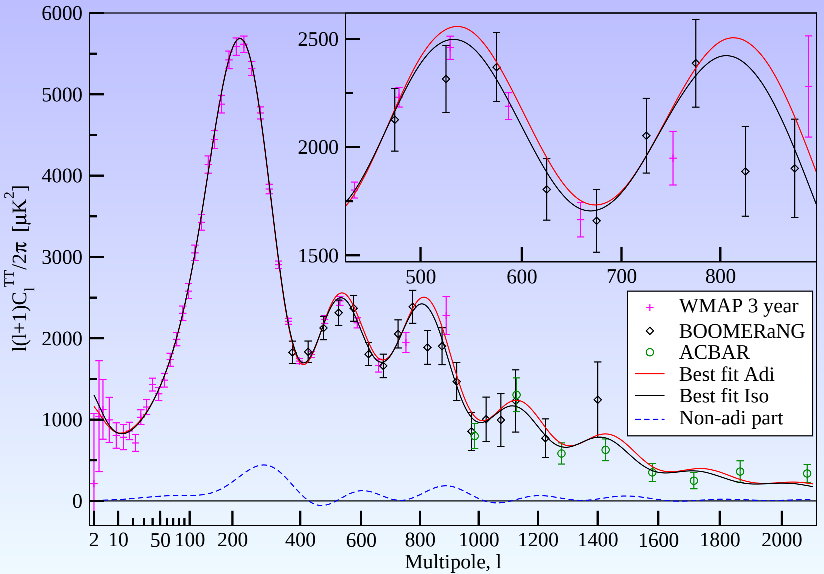
**More "adiabatic-like" 1d likelihoods if we apply:**

- SNIa from Riess et al. (2004), $\Omega_m \approx 0.30 \pm 0.04$.
- Lyman-$\alpha$ 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-$\alpha$ extends the data to "much" larger k (smaller scales).
  - is our approximation of power law spectra resonable over this extended $k$-range?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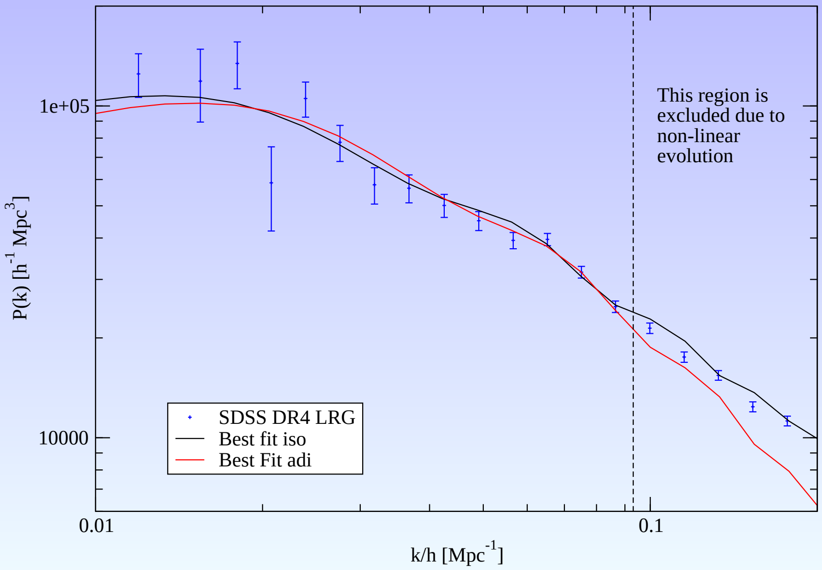
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Best fit iso
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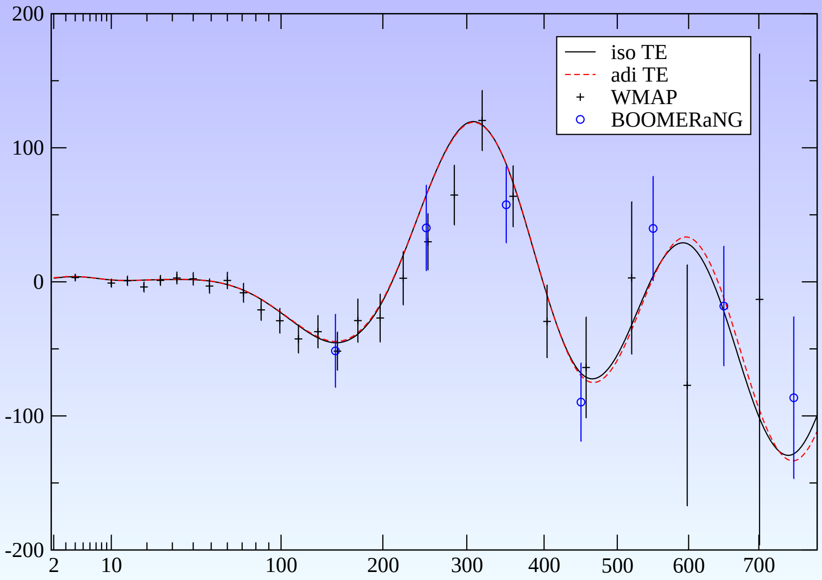
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## Conclusions (of a more technical nature)

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- 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.**

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