Planck Constraints on General Primordial Isocurvature Perturbations and Curvaton Model

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on behalf of the Planck collaboration

Based on Section 10 of arXiv:1303.5082

Planck 2013 results. XXII. Constraints on inflation

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(Affiliations can be found after the references)

Preprint online version: March 22, 2013

Motivation: Why to study isocurvature in the *Planck* Inflation paper?

1. An important test of inflationary models.
   - Single field inflation (with one degree of freedom) can produce only the primordial curvature perturbation, i.e., adiabatic primordial perturbations, since exciting isocurvature perturbations requires additional degrees of freedom.
   - Therefore a detection of primordial isocurvature perturbations would point to more complicated models of inflation, such as **multi-field** inflationary scenarios which can produce a (possibly correlated) mixture of curvature and isocurvature perturbations.

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3. The determination of the “standard” ΛCDM model parameters, $\Omega_b h^2$, $\Omega_c h^2$, τ, θ, A_s, n_s, (H_0, Ω_Λ) could be significantly affected by an undetected isocurvature contribution.
    - Need to check how allowing for general initial conditions for perturbations affects the basic results.

General phenomenological models studied

Flat ΛCDM model with power law primordial spectra for the adiabatic mode, for **one** isocurvature mode at a time, and for their correlation,

$$\mathcal{P}(k) = \begin{pmatrix} \mathcal{P}_{\mathcal{R}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}}(k) \\ \mathcal{P}_{\mathcal{I}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}\mathcal{I}}(k) \end{pmatrix},$$

where $\mathcal{I}$ can be any of the non-singular, i.e., non-decaying isocurvature modes:

- **CDI** (cold dark mater density isocurvature mode).
- **NDI** (neutrino density isocurvature mode).
- **NVI** (neutrino velocity isocurvature mode).
- BDI (There can be also baryon density isocurvature mode, which is indistinguishable from CDI by the CMB observations. Above, the CDI mode can be regarded to include also baryons as: $\mathcal{I}_{\mathrm{CDI}}^{\mathrm{effective}} = \mathcal{I}_{\mathrm{CDI}} + (\Omega_{\mathrm{b}}/\Omega_{\mathrm{c}})\mathcal{I}_{\mathrm{BDI}})$

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$$\mathcal{P}(k) = \begin{pmatrix} \mathcal{P}_{\mathcal{RR}}(k) & \mathcal{P}_{\mathcal{RI}}(k) \\ \mathcal{P}_{\mathcal{IR}}(k) & \mathcal{P}_{\mathcal{II}}(k) \end{pmatrix},$$

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In the general models we have:

- 4 background params (as in the adiabatic ΛCDM model): $\Omega_b h^2$, $\Omega_c h^2$, τ, θ.
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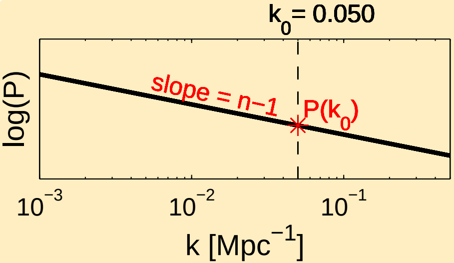
Theoretically motivated special cases with only 1 extra param

Curvaton, axion.

How to parametrize power law primordial spectra?



For each spectrum specify 2 parameters:

– amplitude at the pivot scale k_0, $\mathcal{P}(k_0)$

– spectral index $n = \mathrm{d}\ln\mathcal{P} \,/\, \mathrm{d}\ln k + 1$

ALARM! Cannot be used in MCMC, if $n_{\rm iso}$ or $n_{\rm cor}$ (or n_t) are free.

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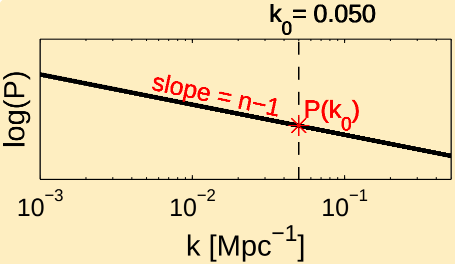

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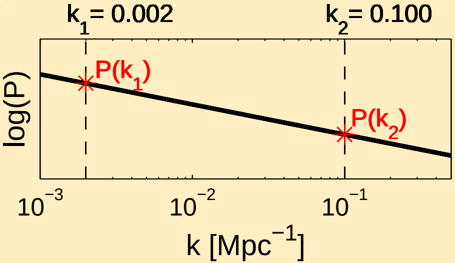


For each spectrum specify
2 parameters:

– amplitude at scale k_1, $\mathcal{P}(k_1)$

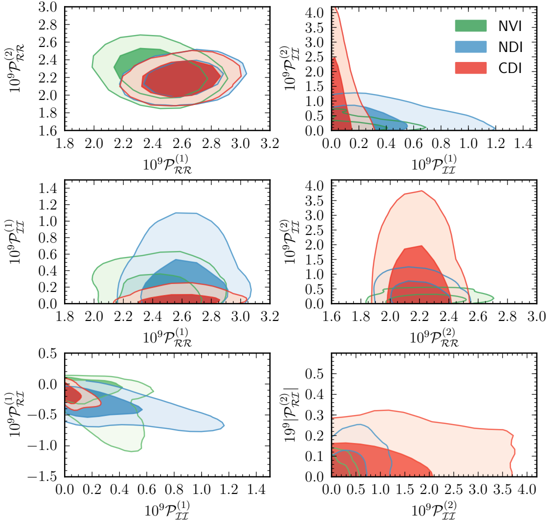
– amplitude at scale k_2, $\mathcal{P}(k_2)$

From these the spectral index n and amplitude $\mathcal{P}(k_0)$ can be calculated as **derived** parameters.

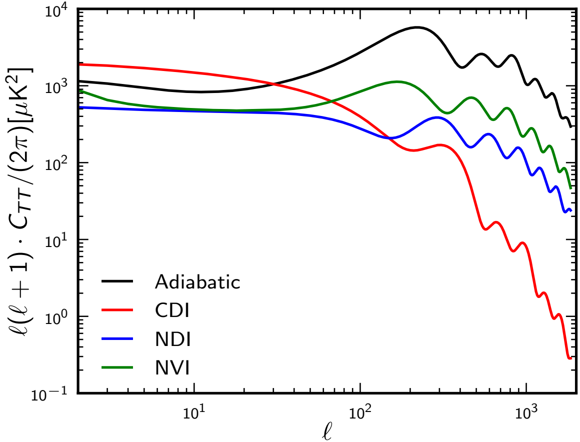
Idea presented in 2004 in H. Kurki-Suonio, V. Muhonen, and J. Valiviita, Phys. Rev. D **71**, 063005, and used ever since in most of isocurvature studies.

68% & 95% C.L. constraints on primord. powers at two scales

For perturbations, our primary MCMC parameters with uniform priors are the powers at
$k_1 = 0.002\,\mathrm{Mpc}^{-1}$, i.e., $\mathcal{P}^{(1)}_{\mathcal{RR}}$, $\mathcal{P}^{(1)}_{\mathcal{II}}$, $\mathcal{P}^{(1)}_{\mathcal{RI}}$ and at
$k_2 = 0.100\,\mathrm{Mpc}^{-1}$, i.e., $\mathcal{P}^{(2)}_{\mathcal{RR}}$, $\mathcal{P}^{(2)}_{\mathcal{II}}$, $|\mathcal{P}^{(2)}_{\mathcal{RI}}|$.



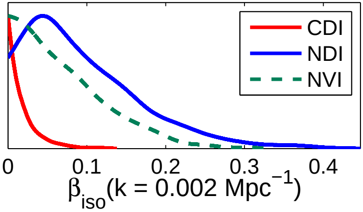
C_ℓ from scale-invariant spectra with equal primordial amplitude

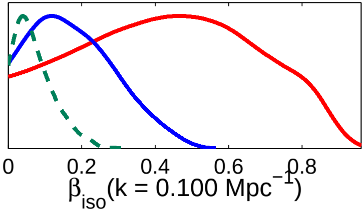


Note the $(k/k_{\rm eq})^{-2}$, i.e., ℓ^{-2} damping of CDI compared to the other modes, in particular compared to the adiabatic mode.
$\Rightarrow$ With CMB C_ℓ^{TT}, the CDI spectral index can never be constrained to much less than $n_{\rm iso} \simeq n_{\rm ad} + 2 \simeq 3$, if the data are almost "adiabatic".

Primordial isocurvature fraction and spectral index

$$\beta_{\rm iso}(k) = \mathcal{P}_{\mathcal{II}}(k) \;/\; [\mathcal{P}_{\mathcal{RR}}(k) + \mathcal{P}_{\mathcal{II}}(k)]$$





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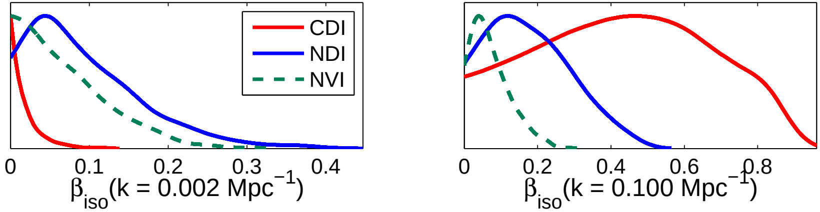
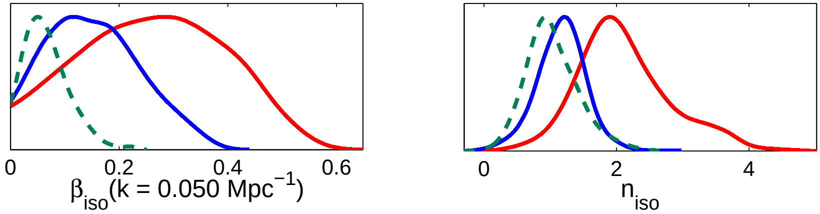
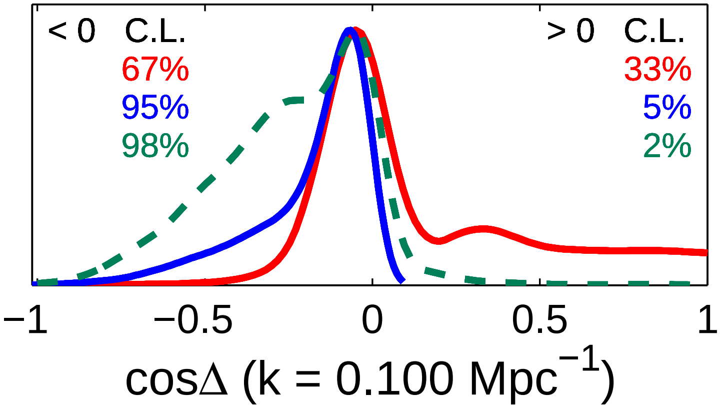


$$n_{\rm iso} \equiv n_{\mathcal{II}} = {\rm d}(\ln \mathcal{P}_{\mathcal{II}}) \,/\, {\rm d}(\ln k) + 1$$



Primordial correlation fraction

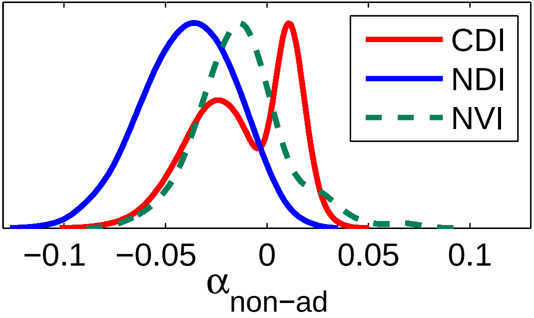
$$\cos\Delta\,(k) = \frac{\mathcal{P}_{\mathcal{RI}}(k)}{\sqrt{\mathcal{P}_{\mathcal{RR}}(k)\mathcal{P}_{\mathcal{II}}(k)}}$$



Non-adiabaticity of the CMB temperature fluctuations

The non-adiabaticity fraction in **today's** CMB $(\delta T)^2$

$$\alpha_{\rm non-ad} = \frac{\langle(\delta T_{\rm non-ad})^2\rangle}{\langle(\delta T_{\rm total})^2\rangle} = \frac{\sum_{\ell=2}^{2500}(2\ell+1)(C^{TT}_{\mathcal{II},\ell} + C^{TT}_{\mathcal{RI},\ell})}{\sum_{\ell=2}^{2500}(2\ell+1)C^{TT}_{{\rm tot},\ell}}$$



Constraints on the general isocurvature cases

95% C.L. constraints and $\Delta\chi^2_{\rm eff} = \chi^2_{\rm eff,ISO,best} - \chi^2_{\rm eff,adiabatic,best}$

	Primordial isoc. fraction $\beta_{\rm iso}$ (k=0.002	0.050	0.100)	Isoc. frac. in **CMB** $\alpha_{\rm non-ad}$	$\Delta\chi^2_{\rm eff}$	$*$) low-ℓ TT	$**$) high-ℓ TT
CDI	<0.08	<0.39	<0.60	-7% ... +2%	**-4.6**	-4.7	-0.2
NDI	<0.27	<0.27	<0.32	-9% ... +1%	**-4.2**	-3.8	-0.8
NVI	<0.18	<0.14	<0.17	-5% ... +4%	**-2.5**	-2.2	+0.1

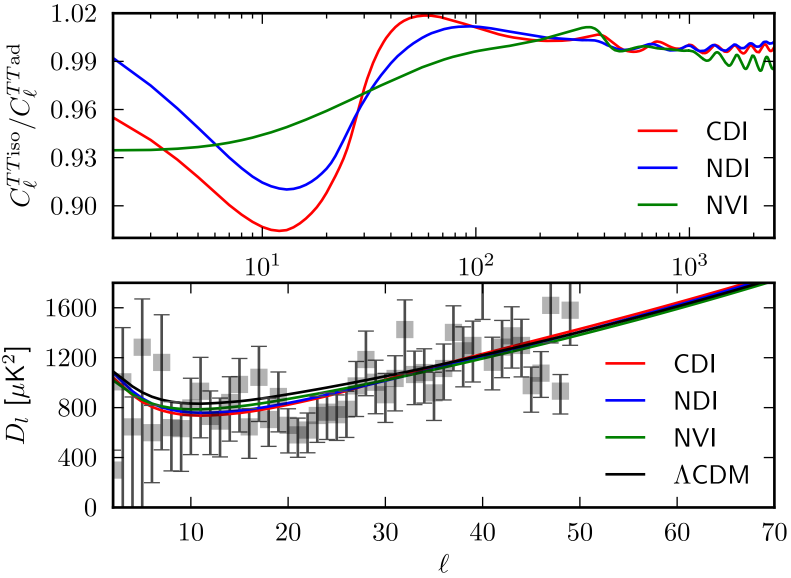
These models have 4 extra parameters compared to the pure adiabatic model.

$*$) Low-ℓ TT = *Planck* TT likelihood at $\ell = 2 — 49$ (commander_v4.1_lm49.clik)

$**$) High-ℓ TT = *Planck* TT likelihood at $\ell = 50 — 2500$ (CAMspec_v6.2TN_2013_02_26.clik)

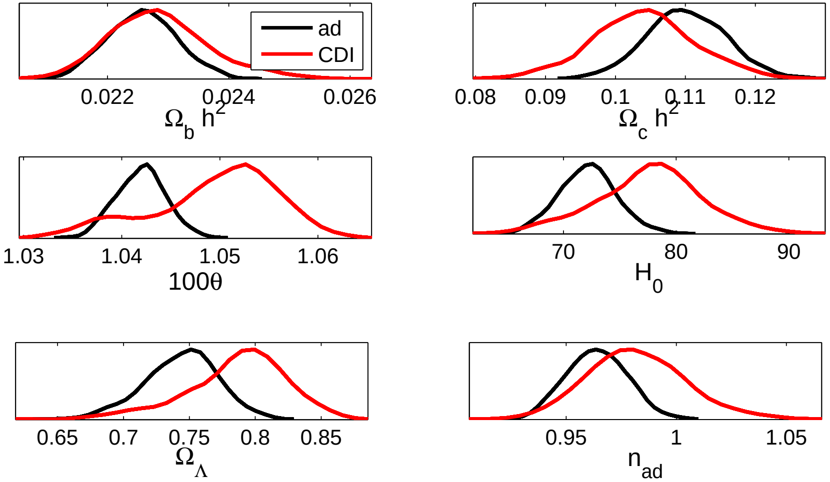
$***$) The rest (NOT IN THE TABLE) = WMAP-9 TE and EE (lowlike_v222.clik)

Temperature C_ℓ spectra of the best-fit models



Effect on the estimation of “standard” parameters

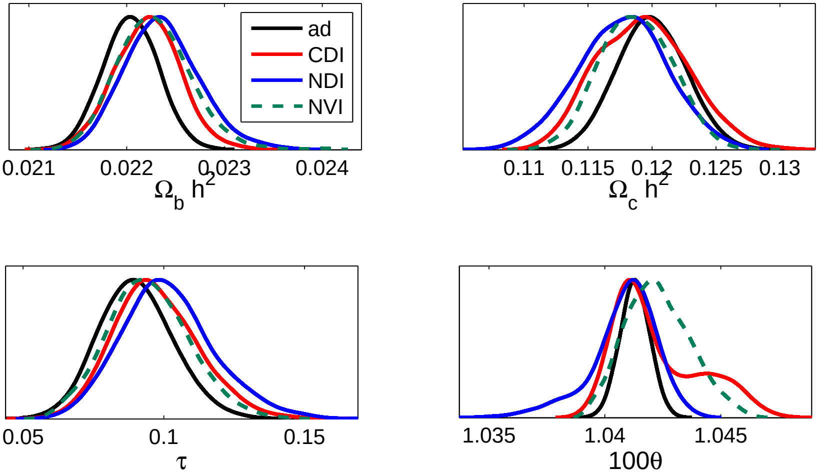
State-of-art in 2009 (with **WMAP5 and ACBAR**)



From: Jussi Valiviita and Tommaso Giannantonio, Phys. Rev. D **80**, 123516 (2009) [arXiv:0909.5190 [astro-ph.CO]].

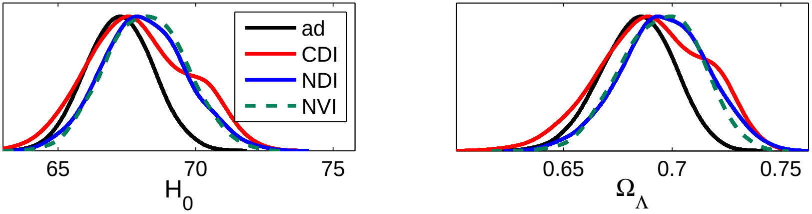
Effect on the estimation of background parameters

In March 2013 with *Planck*+WP data



..effect on the derived bg params & adiabatic spectrum

Larger values of H_0 and Ω_Λ are acceptable than in the pure adiabatic model



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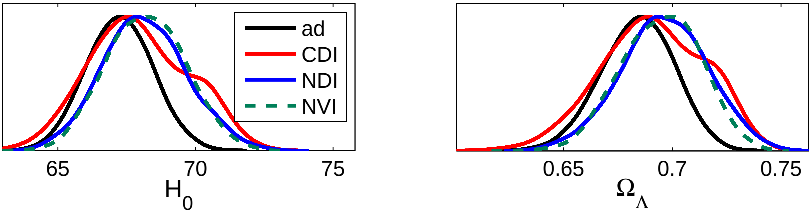
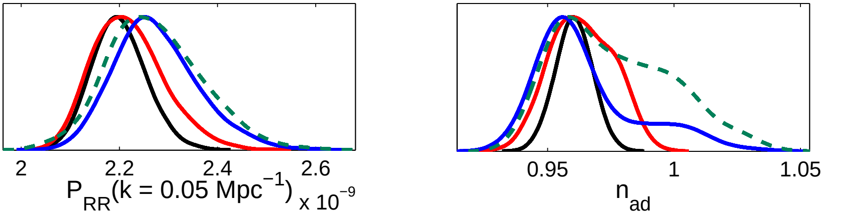


$$n_{\rm ad} \equiv n_{\mathcal{RR}} = \frac{{\rm d}(\ln \mathcal{P}_{\mathcal{RR}})}{{\rm d}(\ln k)} + 1$$



A theoretically motivated special case: **curvaton**

The Planck collaboration studied the curvaton scenario with assumptions:

(1) The average curvaton field value, χ_*, is sufficiently below the Planck mass at the time when cosmologically interesting scales exit the horizon during inflation.
(2) The curvature perturbation from inflaton is negligible compared to the curvaton perturbation at horizon exit during inflation.
(3) The same is true for any inflaton decay products after reheating. This means that after reheating the Universe is homogeneous, except for the spatially varying entropy (i.e., isocurvature perturbation) due to the curvaton field perturbations.
(4) Later, CDM is created from the curvaton decay.

This curvaton scenario leads to fully correlated primordial curvature and isocurvature perturbations with the same shape of their power spectra:

$$\mathcal{P}_{\mathcal{RI}} = +\sqrt{\mathcal{P}_{\mathcal{RR}}\mathcal{P}_{\mathcal{II}}}, \qquad n_{\mathrm{iso}} = n_{\mathrm{ad}}.$$

Hence only one extra parameter compared to the adiabatic model.

… curvaton

The isocurvature fraction in this curvaton model will be

$$\beta_{\rm iso} = \frac{9(1-r_D)^2}{r_D^2 + 9(1-r_D)^2}, \qquad \text{where} \qquad r_D = \frac{3\rho_{\rm curvaton}}{3\rho_{\rm curvaton} + 4\rho_{\rm radiation}},$$

and the non-linearity parameter (assuming sudden decay of curvaton and quadratic potential) will be $f_{\rm NL}^{\rm local} = \frac{5}{4r_D} - \frac{5}{3} - \frac{5r_D}{6}$.

If the curvaton totally dominates the energy density at curvaton's decay time, then $r_D = 1$, $f_{\rm NL}^{\rm local} = -5/4$, and the curvaton perturbations are converted to pure adiabatic ones with no residual isocurvature.

... curvaton

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With *Planck*+WP data we find $\beta_{\rm iso} < \mathbf{0.0025}$ at 95% C.L.

5 times tighter than the WMAP9 constraint, 3 times tighter than WMAP9+ACT+SPT!

- This corresponds to $0.98 < r_D < 1$ and $-1.25 < f_{\rm NL}^{\rm local} < -1.21$.
- Fits within 1σ *Planck* constraint $f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$.

Summary on the general & special isoc. cases

95% C.L. constraints and $\Delta\chi^2_{\rm eff} = \chi^2_{\rm eff,ISO,best} - \chi^2_{\rm eff,adiabatic,best}$

	Primordial isoc. fraction $\beta_{\rm iso}$ (k=0.002	0.050	0.100)	Isoc. frac. in **CMB** $\alpha_{\rm non-ad}$	$\Delta\chi^2_{\rm eff}$
CDI	$<$0.08	$<$0.39	$<$0.60	-7% ... +2%	-4.6
NDI	$<$0.27	$<$0.27	$<$0.32	-9% ... +1%	-4.2
NVI	$<$0.18	$<$0.14	$<$0.17	-5% ... +4%	-2.5
Special CDI cases					
"axion"	$<$0.0360	$<$0.0390	$<$0.0400	$<$2%	0
"curvaton"	$<$**0.0025**	$<$0.0025	$<$0.0025	0% ... +3%	0
anti-corr.	$<$0.0087	$<$0.0087	$<$0.0087	-6% ... 0%	-1.3

The general cases IN COLOR have 4 extra parameters.
The special cases have **1 extra parameter** compared to the adiabatic model.

"axion" = no correlation ($\mathcal{P}_{\mathcal{RI}} = 0$), $n_{\rm iso} = 1$.
"curvaton" = +100% correlation ($\mathcal{P}_{\mathcal{RI}} = +\sqrt{\mathcal{P}_{\mathcal{RR}}\mathcal{P}_{\mathcal{II}}}$), $n_{\rm iso} = n_{\rm ad}$.
anti-corr. = -100% correlation ($\mathcal{P}_{\mathcal{RI}} = -\sqrt{\mathcal{P}_{\mathcal{RR}}\mathcal{P}_{\mathcal{II}}}$), $n_{\rm iso} = n_{\rm ad}$.

Conclusions (NOTE: Next year the polarization data may shed light to these questions.)

The Planck collaboration studied in **a general phenomenological set-up** all non-singular primordial isocurvature modes, CDI (and BDI), NDI, NVI, one at a time, possibly correlated with adiabatic perturbations:

- Acoustic peak structure in the *Planck* data is "adiabatic" to high precision.
- The power of *Planck* low-ℓ spectrum is about 10% below the prediction of the best-fit adiabatic ΛCDM model.
  - A negatively correlated isocurvature component improves the fit to low-ℓ data ($\Delta\chi^2_{\rm eff} \approx -4.5$), without affecting too much the high-ℓ spectrum.
  - This $\ell \sim 10...30$ "anomaly" leads to relatively large isocurvature fractions (-5% — -9%) to be allowed in the CMB temperature variance.
- Determination of standard cosmological parameters is only mildly affected by allowing for an isocurvature contribution! A great improvement over WMAP.

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In addition, the Planck collaboration studied **theoretically motivated models**:

- Both **curvaton** and **axion** models worsen the fit to the *Planck* data, since they increase the power at low-ℓ.
    - This leads to the stringent constraints on these models: primord. isoc. frac. $\beta_{\rm iso} < 0.25\%$ (curvaton) and $\beta_{\rm iso} < 3.9\%$ (axion).
- A model similar to curvaton, but with 100% anticorrelation improves the fit moderately ($\Delta\chi^2_{\rm eff} \approx -1.3$), and leads to $\beta_{\rm iso} < 8.7\%$.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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