Planck 2014 Constraints on Primordial Isocurvature Perturbations

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on behalf of the Planck collaboration

Motivation: Why study isocurvature with *Planck*?

1. An important test of inflationary models.
   - Single field inflation (with one degree of freedom) can produce only the primordial curvature perturbation, i.e., the adiabatic perturbation, 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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2. It is important to check the robustness of the adiabaticity assumption made in most of the (other) *Planck* analysis.

3. The determination of the "standard" ΛCDM parameters, $\Omega_b h^2$, $\Omega_c h^2$, τ, θ, A_s, n_s, (H_0, Ω_Λ, σ_8), 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

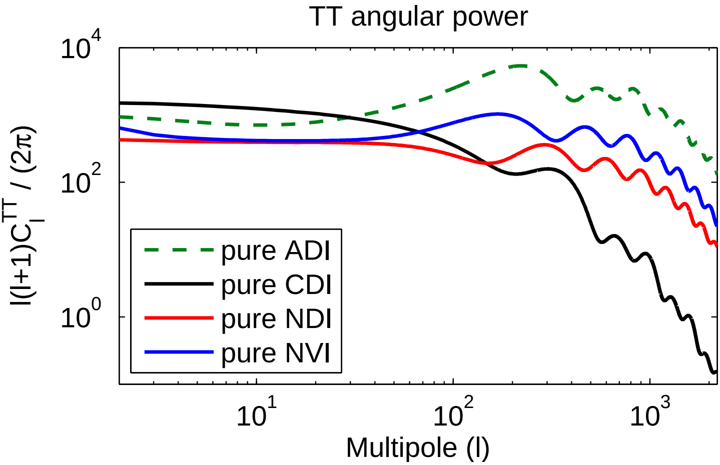
Flat ΛCDM model with power law primordial spectra for the adiabatic mode, for **one** isocurvature mode at a time, and for their correlation,

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

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 also be a baryon density isocurvature mode, which is indistinguishable from CDI by the CMB observations. Above, the CDI mode can be regarded to also include baryons as: $\mathcal{I}_{\rm CDI}^{\rm effective} = \mathcal{I}_{\rm CDI} + (\Omega_{\rm b}/\Omega_{\rm c})\mathcal{I}_{\rm BDI}$)

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" at all scales.

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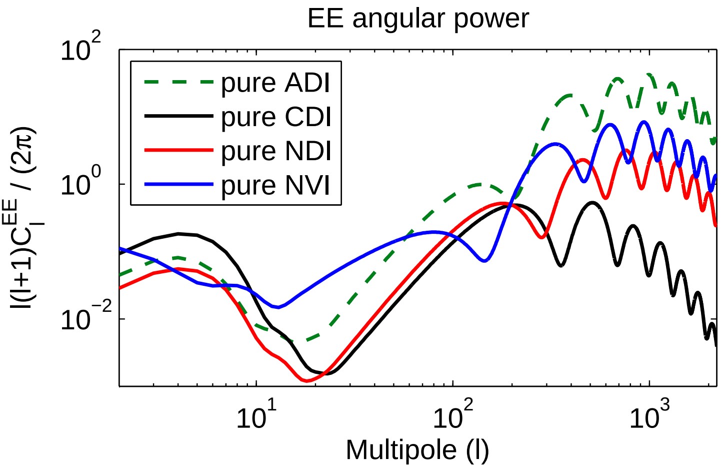
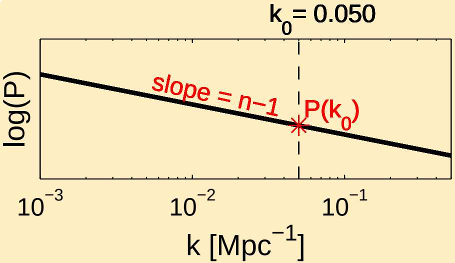


How to parametrize power law primordial spectra?



For each spectrum specify 2 parameters:

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

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

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

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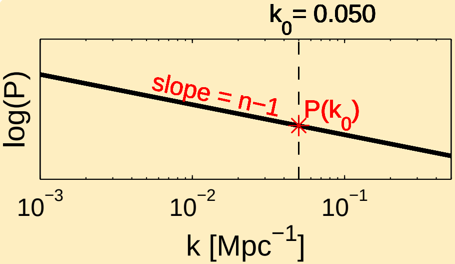

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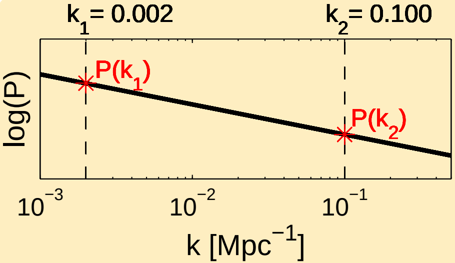

For each spectrum specify

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.

Parametrization of general phenomenological models

In the generally correlated models we have:

- 4 background parameters (as in the adiabatic ΛCDM model): $\Omega_b h^2$, $\Omega_c h^2$, τ, θ.

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- 2 adiabatic perturbation parameters for the power law spectrum $\mathcal{P}_{\mathcal{R}\mathcal{R}}(k)$:
  $\mathcal{P}^{(1)}_{\mathcal{R}\mathcal{R}} \equiv \mathcal{P}_{\mathcal{R}\mathcal{R}}(k = k_1 = 0.002\,\mathrm{Mpc}^{-1})$ and
  $\mathcal{P}^{(2)}_{\mathcal{R}\mathcal{R}} \equiv \mathcal{P}_{\mathcal{R}\mathcal{R}}(k = k_2 = 0.100\,\mathrm{Mpc}^{-1})$.

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- In addition, 2 extra perturbation parameters for the isocurvature power law spectrum $\mathcal{P}_{\mathcal{I}\mathcal{I}}(k)$: $\mathcal{P}^{(1)}_{\mathcal{I}\mathcal{I}} \equiv \mathcal{P}_{\mathcal{I}\mathcal{I}}(k = k_1 = 0.002\,\mathrm{Mpc}^{-1})$ and $\mathcal{P}^{(2)}_{\mathcal{I}\mathcal{I}} \equiv \mathcal{P}_{\mathcal{I}\mathcal{I}}(k = k_2 = 0.100\,\mathrm{Mpc}^{-1})$.

Parametrization of general phenomenological models

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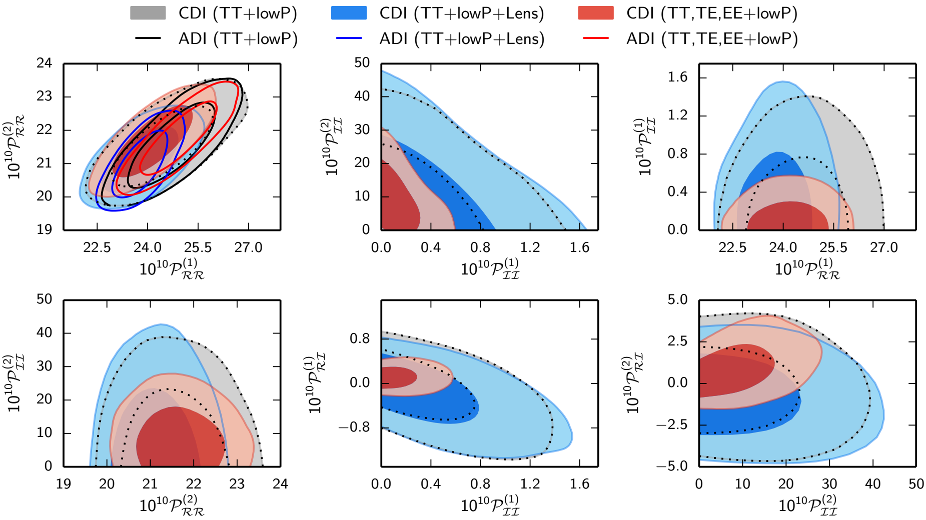
- 2 adiabatic perturbation parameters for the power law spectrum $\mathcal{P}_{\mathcal{RR}}(k)$: $\mathcal{P}^{(1)}_{\mathcal{RR}} \equiv \mathcal{P}_{\mathcal{RR}}(k = k_1 = 0.002\,\mathrm{Mpc}^{-1})$ and $\mathcal{P}^{(2)}_{\mathcal{RR}} \equiv \mathcal{P}_{\mathcal{RR}}(k = k_2 = 0.100\,\mathrm{Mpc}^{-1})$.
- In addition, 2 extra perturbation parameters for the isocurvature power law spectrum $\mathcal{P}_{\mathcal{II}}(k)$: $\mathcal{P}^{(1)}_{\mathcal{II}} \equiv \mathcal{P}_{\mathcal{II}}(k = k_1 = 0.002\,\mathrm{Mpc}^{-1})$ and $\mathcal{P}^{(2)}_{\mathcal{II}} \equiv \mathcal{P}_{\mathcal{II}}(k = k_2 = 0.100\,\mathrm{Mpc}^{-1})$.
- And 1 extra parameter for the correlation spectrum $\mathcal{P}_{\mathcal{RI}}(k) = \mathcal{P}_{\mathcal{IR}}(k)$: $\mathcal{P}^{(1)}_{\mathcal{RI}} \equiv \mathcal{P}_{\mathcal{RI}}(k = k_1 = 0.002\,\mathrm{Mpc}^{-1})$.

Note that $\mathcal{P}^{(2)}_{\mathcal{RI}} = \mathcal{P}^{(1)}_{\mathcal{RI}} \times \frac{\sqrt{\mathcal{P}^{(2)}_{\mathcal{RR}}\mathcal{P}^{(2)}_{\mathcal{II}}}}{\sqrt{\mathcal{P}^{(1)}_{\mathcal{RR}}\mathcal{P}^{(1)}_{\mathcal{II}}}}$ is a derived parameter, so that

$n_{\mathcal{RI}} = (n_{\mathcal{RR}} + n_{\mathcal{II}})/2$, and the primordial correlation fraction

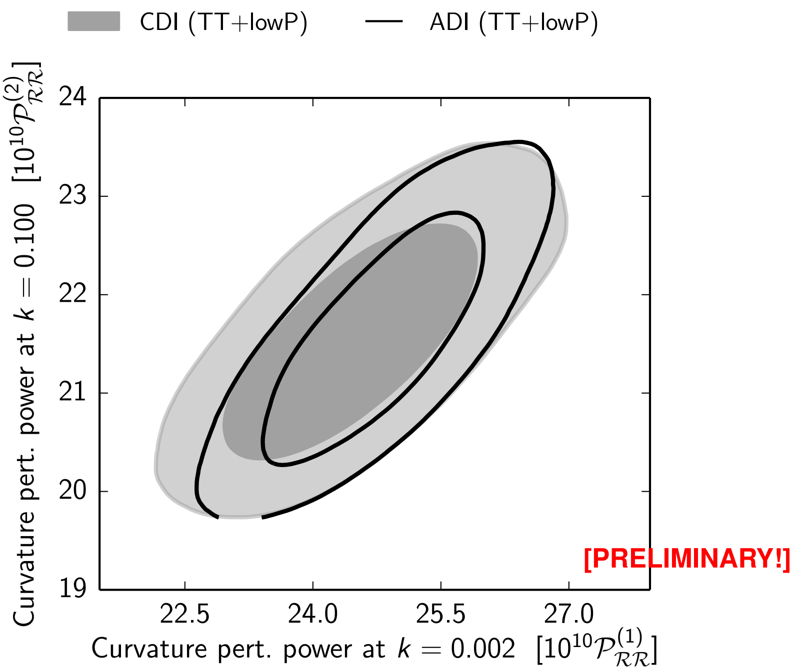
$\cos\Delta \equiv \mathcal{P}_{\mathcal{RI}}(k)/\sqrt{\mathcal{P}_{\mathcal{RR}}(k)\mathcal{P}_{\mathcal{II}}(k)}$ is **scale independent**.

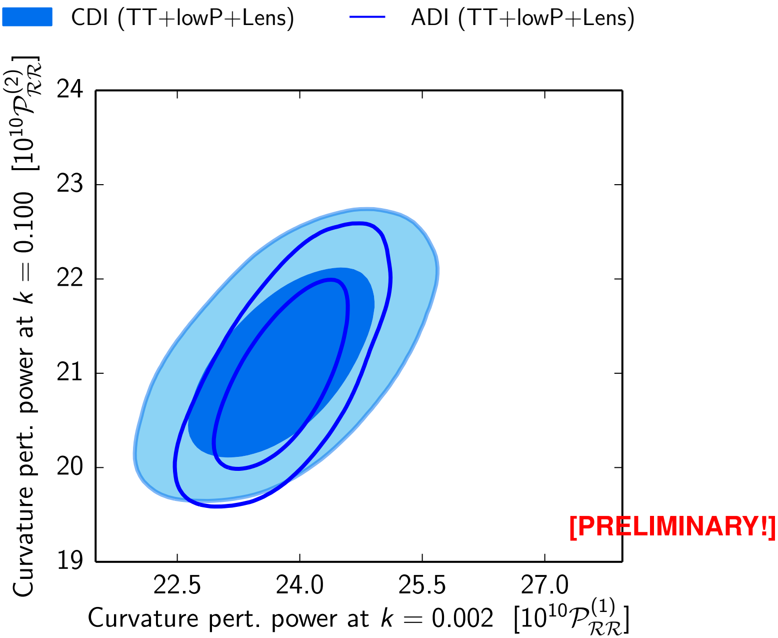
Generally correlated mixture of primordial adiabatic and Cold dark matter Density Isocurvature perturbations (**CDI**), and pure adiabatic model (ADI)



The polarization results (TT,TE,EE+lowP, red colors) reported here are very preliminary, because we do not yet have confidence that all systematic and foreground uncertainties have been properly characterized, and the results may therefore be subject to revision.

[PRELIMINARY!]


CDI (TT+lowP)
ADI (TT+lowP)
Curvature pert. power at $k = 0.100$ $[10^{10}\mathcal{P}^{(2)}_{\mathcal{RR}}]$
Curvature pert. power at $k = 0.002$ $[10^{10}\mathcal{P}^{(1)}_{\mathcal{RR}}]$
24
23
22
21
20
19
22.5
24.0
25.5
27.0
[PRELIMINARY!]


CDI (TT+lowP+Lens)
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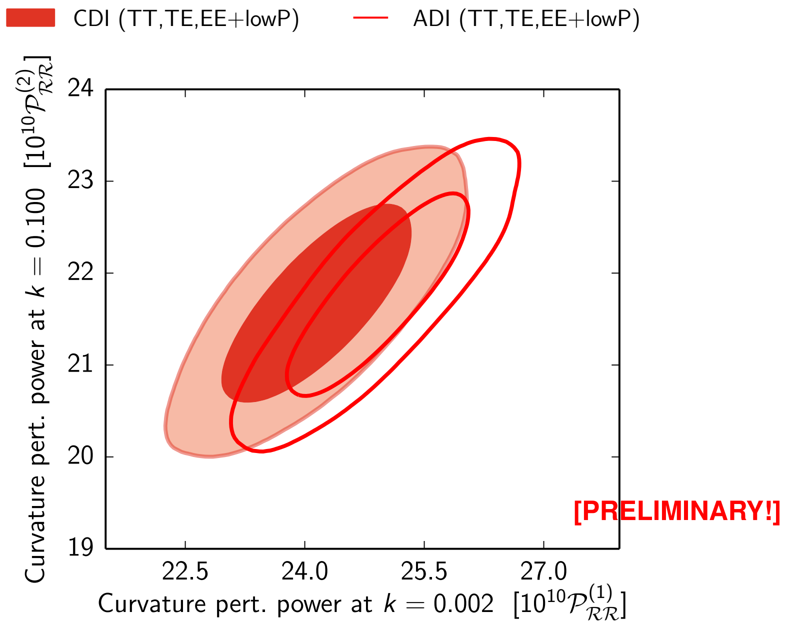
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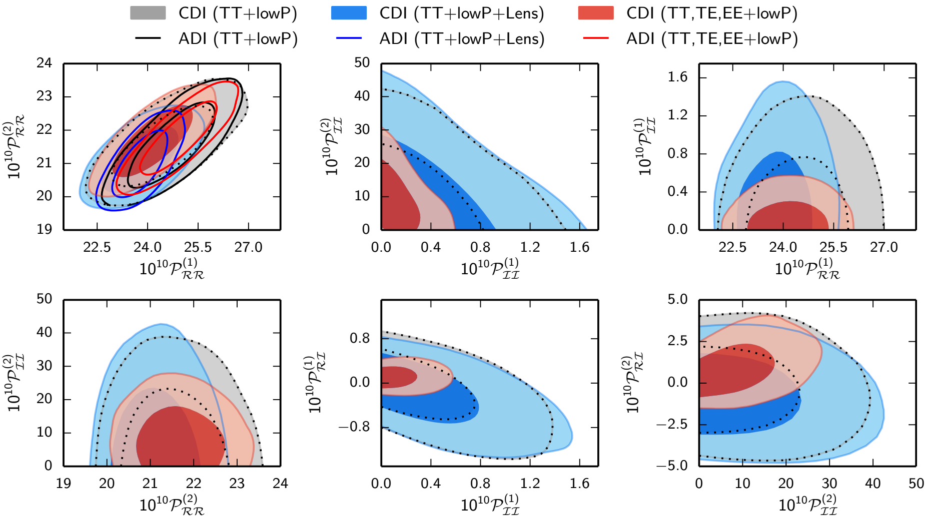
Generally correlated mixture of primordial adiabatic and Cold dark matter Density Isocurvature perturbations (**CDI**), and pure adiabatic model (ADI)



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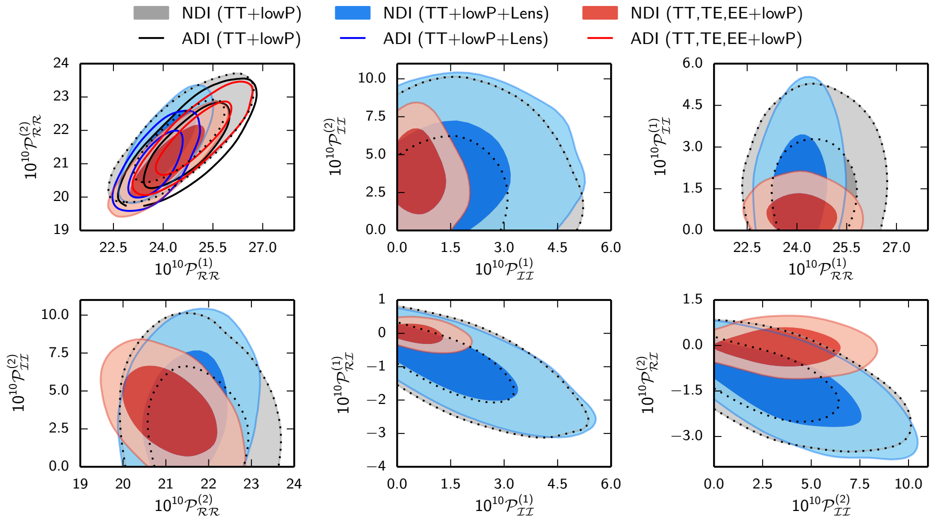
Generally correlated mixture of primordial adiabatic and Neutrino Density Isocurvature perturbations (**NDI**), and pure adiabatic model (ADI)



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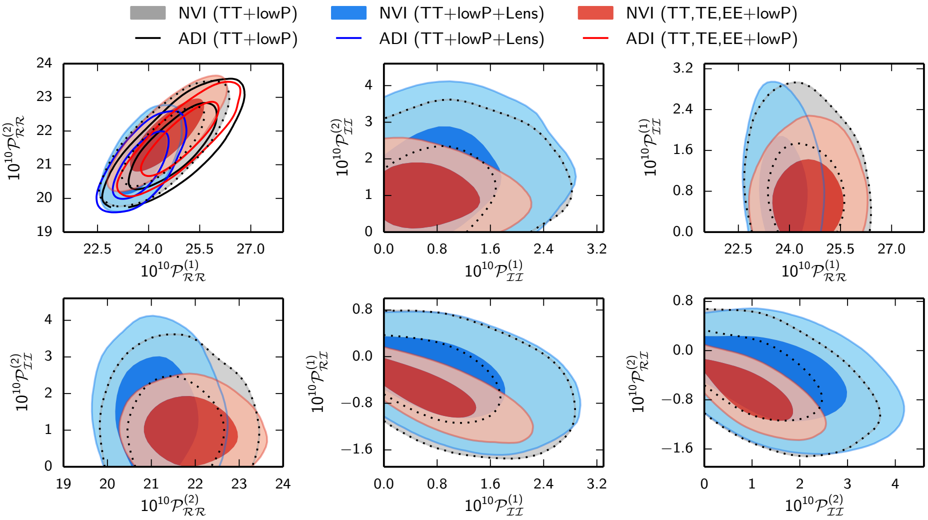
[PRELIMINARY!]

Generally correlated mixture of primordial adiabatic and Neutrino Velocity Isocurvature perturbations (**NVI**), and pure adiabatic model (ADI)



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[PRELIMINARY!]

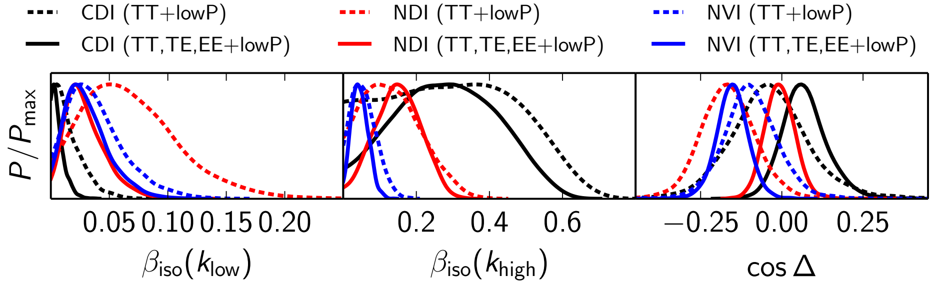
Primordial isocurvature and correlation fraction

Primordial isocurvature fraction

$$\beta_{\rm iso}(k) = \frac{\mathcal{P}_{\mathcal{II}}(k)}{\mathcal{P}_{\mathcal{RR}}(k)+\mathcal{P}_{\mathcal{II}}(k)}$$

Primordial correlation fraction

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

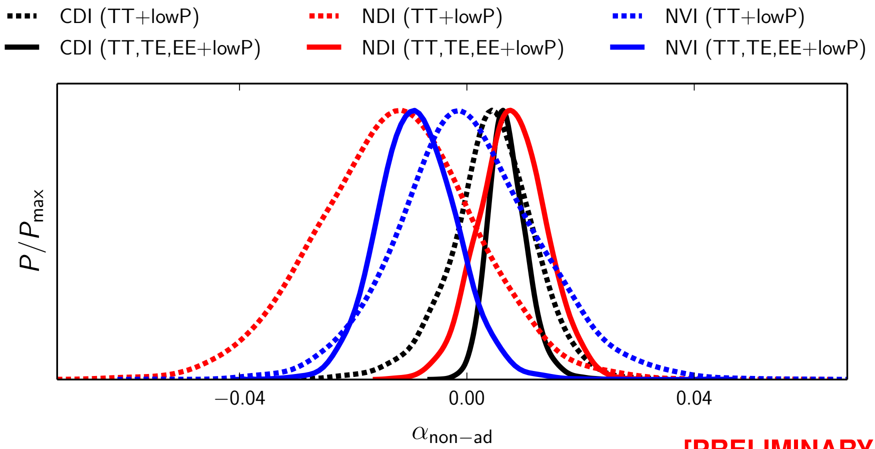


The polarization results (TT,TE,EE+lowP, solid line styles) reported here are very preliminary, because we do not yet have confidence that all systematic and foreground uncertainties have been properly characterized, and the results may therefore be subject to revision.

[PRELIMINARY!]

The non-adiabaticity fraction in the observed CMB temperature variance

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



The polarization results (TT,TE,EE+lowP, solid line styles) not to be taken too literally yet.

[PRELIMINARY!]

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Planck temperature (and prelim. pol.) angular power spectra are consistent with pure adiabatic primordial perturbations (within the flat ΛCDM model).

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Are any of them affected by the assumed initial conditions of perturbations?

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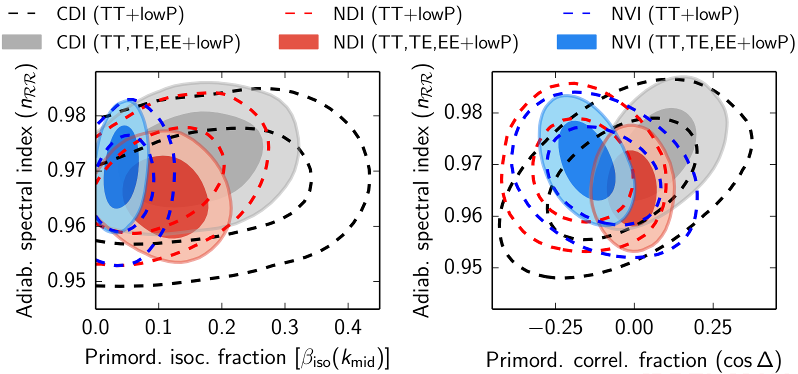
Adiabatic spectral index used to be highly degenerate with isocurvature, but not much anymore:

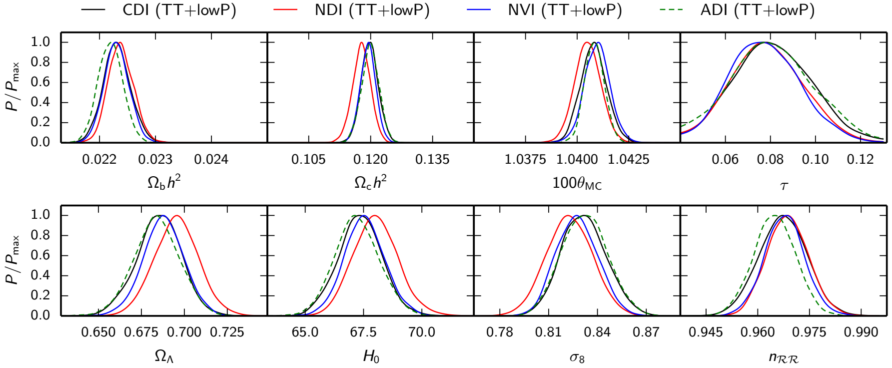


The results with high-ℓ polarization data (TT,TE,EE+lowP) are not to be taken too literally yet.

[PRELIMINARY!]

Robustness of the determination of standard params.

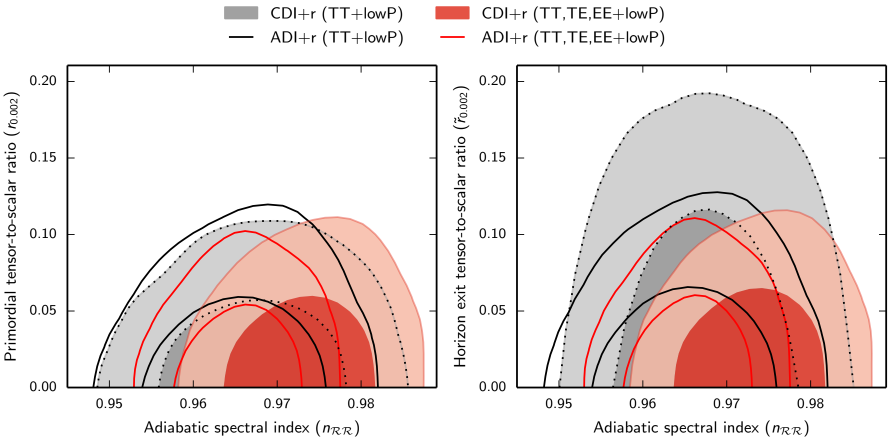
The results with *Planck* high-ℓ temperature data and low-ℓ temperature+polarization data:



Only in the generally correlated mixed adiabatic and NDI model the posteriors shift a bit, $\lesssim 0.2\sigma$, w.r.t. the pure adiabatic model (ADI, green dashed).

[PRELIMINARY!]

How about the determination of tensor-to-scalar ratio?



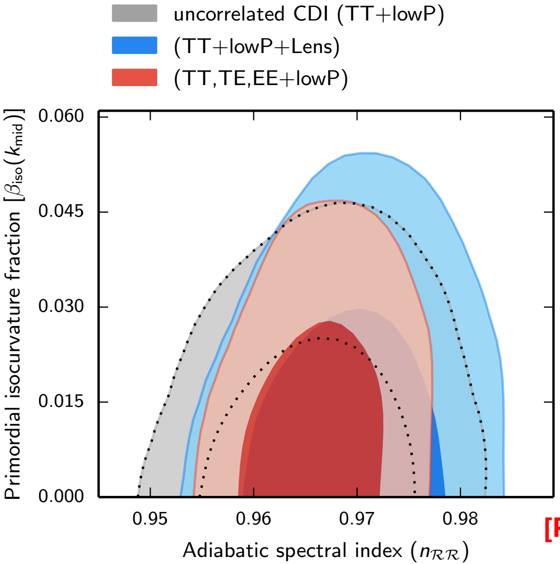
The determination of primordial tensor-to-scalar (indeed tensor-to-curvature perturbation power) ratio, $r = \mathcal{P}_{\rm tensor}/\mathcal{P}_{\mathcal{RR}}$, is surprisingly robust against allowing for a generally correlated CDI mode.

Note: the horizon exit tensor-to-curvature perturbation ratio is $\tilde{r} \approx r/(1 - \cos^2\Delta)$, see, .e.g., Byrnes & Wands (2006).

[PRELIMINARY!]

Special CDI cases with only one extra parameter w.r.t the adiabatic model

Uncorrelated adiabatic and CDI mode ($\cos\Delta = 0$), with $n_{\mathcal{II}} = 1$, “axion”:



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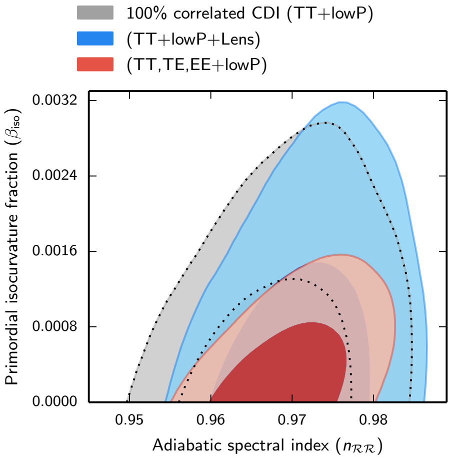
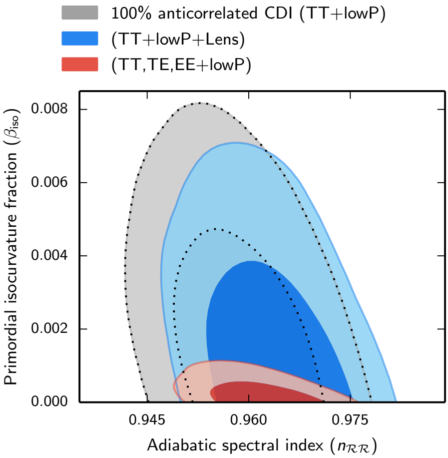
Special CDI cases with only one extra parameter w.r.t the adiabatic model

100% correlated adiab. and CDI mode ($\cos\Delta = +1$), with $n_{\mathcal{II}} = n_{\mathcal{RR}}$, "curvaton":



100% anticorrelated adiab. and CDI ($\cos\Delta = -1$), with $n_{\mathcal{II}} = n_{\mathcal{RR}}$:



[PRELIMINARY!]

95% C.L. upper bounds/intervals

Model (and data)	$100\beta_{\rm iso}(k_1)$	$100\beta_{\rm iso}(k_2)$	$100\cos\Delta$	$100\alpha^{(2,2500)}_{\mathcal{RR}}$	Δn	$\Delta\chi^2$
General models:						
CDI (TT+lowP)	$<$4.1	$<$57.5	[-27 : 23]	[98.1 : 101.2]	3	-2.9
CDI (TT+lowP+Lens)	$<$4.7	$<$60.4	[-28 : 16]	[98.1 : 101.3]	3	-1.3
NDI (TT+lowP)	$<$14.5	$<$27.5	[-33 : 0.5]	[98.6 : 104.0]	3	-2.3
NDI (TT+lowP+Lens)	$<$15.2	$<$28.9	[-32 : -0.1]	[98.7 : 104.1]	3	-2.7
NVI (TT+lowP)	$<$8.6	$<$11.8	[-26 : 7.7]	[97.3 : 102.4]	3	-2.6
NVI (TT+lowP+Lens)	$<$9.0	$<$13.5	[-25 : 7.5]	[97.1 : 102.2]	3	-2.9
General models + r:						
CDI+r=0.1 (TT+lowP)	$<$3.2	$<$64.6	[-32 : 24]	[98.1 : 101.4]	3	-5.3*)
CDI+r (TT+lowP)	$<$4.2	$<$57.7	[-34 : 20]	[98.0 : 101.7]	3	-3.3
Special CDI cases:						
uncorrelated (TT+lowP)	$<$3.2	$<$3.6	0	[98.6 : 100.0]	1	-0.1
(TT+lowP+Lens)	$<$3.9	$<$4.3	0	[98.2 : 100.0]	1	0
correlated (TT+lowP)	$<$0.21	$<$0.21	100	[97.3 : 100.0]	1	0
(TT+lowP+Lens)	$<$0.23	$<$0.23	100	[97.3 : 99.9]	1	0
anticorr. (TT+lowP)	$<$0.64	$<$0.64	-100	[100 : 105.1]	1	-1.2
(TT+lowP+Lens)	$<$0.56	$<$0.56	-100	[100 : 104.6]	1	-0.7

*) = Note that $\chi^2_{\rm ADI+r=0.1} - \chi^2_{\rm ADI} = +4.7$, i.e., $\chi^2_{\rm CDI+r=0.1} - \chi^2_{\rm ADI}$ is only -0.6.

$k_1 = 0.002\,{\rm Mpc}^{-1}$, $k_2 = 0.100\,{\rm Mpc}^{-1}$

$\Delta n =$ number of extra parameters compared to the adiabatic ΛCDM model.

$\Delta\chi^2 = \chi^2_{\rm best-fit} - \chi^2_{\rm best-fit\ corresponding\ adiabatic\ model}$.

$\alpha^{(2,2500)}_{\mathcal{RR}} = 1 - \alpha_{\rm non-ad}$.

[PRELIMINARY!]

Conclusions **[PRELIMINARY!]**

We have studied 3-parameter extensions to the adiabatic ΛCDM model by allowing for a (correlated) mixture of adiabatic and one isocurvature mode at a time (either CDI, NDI, or NVI):

- **No evidence of isocurvature** in the *Planck* high-ℓ temperature and low-ℓ temperature and polarization data within *Planck*'s accuracy.
- Adding **the high-ℓ polarization data** leads to much stronger constraints.
  - High-ℓ TE/EE data pull CDI and NDI toward (slightly) positive correlation, while (high-ℓ) TT allow for a larger negative correlation.
    But keep in mind: The polarization results reported here are very preliminary, because we do not yet have confidence that all systematic and foreground uncertainties have been properly characterized, and the results may therefore be subject to revision.
- **Determination of the standard cosmological parameters is robust** against the more general initial conditions.
- In addition, **the determination of the primordial tensor-to-scalar ratio** from the *Planck* data alone **is robust** against allowing for CDI.

We have studied 1-parameter extensions to the adiabatic ΛCDM model. These correspond to axion or curvaton motivated models:

- With *Planck* TT+lowP, generally stronger constraints than in 2013.
- High-ℓ polarization data strengthen the constraints significantly, except in the axion case.

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DTU Space
National Space Institute

INAF Istituto Nazionale di Astrofisica

Science & Technology Facilities Council

CSIC
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National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

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