Università degli Studi
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Future CMB constraints on
Early, Cold or Stressed Dark Energy

Calabrese et al., arxiv:1010.5612,
Accepted for publication on PRD (January 2011)

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Cosmology on the beach 2011, 10/01/2011
1. Component with negative pressure that drives the Universe in an accelerated expansion;

2. The accelerating Universe quenches gravitational collapse of large scale structures and suppresses the growth of dark matter density perturbations;

3. Dark energy comes to dominate the density of the Universe only recently ($z \leq 1$) but it could also be subdominant in the early Universe;

4. Dark energy is almost spatially smooth, its perturbations should be small.
**DARK ENERGY Models**

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} \]

Let’s cancel \( \Lambda \)!

We can consider other models of dark energy (quintessence, K-essence, Phantom models, Coupled Dark Energy...)

\[
\begin{align*}
\Omega_\Lambda &\equiv const \\
p &= -\rho \\
\delta\rho_\Lambda &= 0
\end{align*}
\]

\[
\begin{align*}
\Omega_{de} &\equiv f(a) \\
p &= w(a)\rho(a) \\
\delta\rho_{de} &\neq 0
\end{align*}
\]
Early DARK ENERGY

The dark energy contribution is assumed to be represented by a scalar field whose evolution tracks that of the dominant component of the cosmic fluid at a given time!

Ferreira and Joyce, PRD, 58, 023503 (1998)
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$$\Omega_{\text{de}}(a) = \frac{\Omega^0_{\text{de}} - \Omega_{\text{e}}(1 - a^{-3w_0})}{\Omega^0_{\text{de}} + \Omega^0_m a^{3w_0}} + \Omega_{\text{e}}(1 - a^{-3w_0})$$

$$w(a) = -\frac{1}{3[1 - \Omega_{\text{de}}(a)]} \frac{d \ln \Omega_{\text{de}}(a)}{d \ln a} + \frac{a_{\text{eq}}}{3(a + a_{\text{eq}})}$$


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\]

\[
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\[
\frac{\dot{\delta}}{1 + w} = - \left[ k^2 + 9 \left( \frac{\dot{a}}{a} \right)^2 \left( c_s^2 - w + \frac{\dot{w}}{3(1 + w)(\dot{a}/a)} \right) \right] \frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3 \frac{\dot{a}}{a} (c_s^2 - w) \frac{\delta}{1 + w} \\
\dot{\theta} = - \frac{\dot{a}}{a} (1 - 3c_s^2) \theta + \frac{\delta}{1 + w} c_s^2 k^2 - k^2 \sigma \\
\dot{\sigma} = -3 \frac{\dot{a}}{a} \left[ 1 - \frac{\dot{w}}{3w(1 + w)(\dot{a}/a)} \right] \sigma + \frac{8c_{vis}^2}{3(1 + w)} \left[ \theta + \frac{\dot{h}}{2} + 3\eta \right]
\]


• Any indication for perturbations in the dark energy fluid would falsify a scenario based on \(\Lambda\).

• However to detect them one needs some period in cosmic history when \(w\) differs substantially from \(-1\).

• Such a deviation in \(w\) is constrained at late times by the observations, so we are led to consider this at early times, along with a non-negligible early dark energy density.
CURRENT AND FUTURE CONSTRAINTS

De Putter et al., arXiv:1002.1311v1 [astro-ph.CO]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel [GHz]</th>
<th>FWHM</th>
<th>$\Delta T$ [$\mu K$]</th>
<th>$\Delta P$ [$\mu K$]</th>
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<td></td>
<td>70</td>
<td>12.0'</td>
<td>0.148</td>
<td>0.209</td>
</tr>
</tbody>
</table>


J. Bock et al. [EPIC Collaboration], arXiv:0906.1188
EDE Effects on CMB

\[
\frac{\dot{\delta}}{1+w} = -\left[ k^2 + 9 \left( \frac{\dot{a}}{a} \right)^2 \left( c_s^2 - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)} \right) \right] \frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3 \frac{\dot{a}}{a} (c_s^2 - w) \frac{\delta}{1+w}
\]

\[
\dot{\theta} = -\frac{\dot{a}}{a} (1 - 3c_s^2) \theta + \frac{\delta}{1+w} c_s^2 k^2 - k^2 \sigma
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\[
\dot{\sigma} = -3 \frac{\dot{a}}{a} \left[ 1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)} \right] \sigma + \frac{8c_{\text{vis}}^2}{3(1+w)} \left[ \theta + \frac{\dot{h}}{2} + 3\eta \right]
\]
**EDE Effects on CMB 2**

\[
\frac{\delta T^{ISW}}{T} = 2\int \dot{\phi}[r(t), t] dt
\]

\[
\nabla^2 \Phi = 4\pi G a^2 \rho \delta \quad \Rightarrow \quad \Phi \propto \frac{\delta}{a}
\]

- no effect in matter dominated epoch: \( \delta_m \propto a \Rightarrow \dot{\Phi} = 0 \)
- early ISW in transition from radiation epoch
- late ISW in transition to curvature or DE epoch

While variations on large scales are negligible compared to cosmic variance errors, perturbations introduce signal via the early ISW term that is more significant. \( \Rightarrow \) in the EDE scenario perturbations can play a more significant role than in a standard late dark energy scenario!

\[ \Omega_e \uparrow \]

\( \text{lISW}(l<30) \) and \( \text{eISW} (l < 200) \)

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**Graphs:**

- Graph 1: \( C_{TT-ISW}(l+1)/(2\pi) \) for different values of \( c_s^2 \) and \( c_{vis}^2 \) with \( \Omega_e = 0 \).
- Graph 2: \( C_{TT-ISW}(l+1)/(2\pi) \) for different values of \( c_s^2 \) and \( c_{vis}^2 \) with \( \Omega_e = 0.03 \).
Suppressing perturbations by taking \( c_{\text{vis}}^2 = 1 \) or \( c_s^2 = 1 \) (or both) are nearly equivalent.

Only when perturbations are more allowed, through \( c_{\text{vis}}^2 = 0 \) and \( c_s^2 = 0 \) together, the lensing power is significantly enhanced.

In this case, early dark energy plays the major role, yielding an enhancement by a factor 30%, while the model with no early dark energy only sees a 6% boost relative to its no-perturbation case.

We expect that the lensing signal can predominantly improve the constraints when combined with observations of the primary CMB signal.
At the four-point function level (or considering its harmonic anologue, the trispectrum), the weak lensing effect contributes to the correlation function due to its non-linear mode-coupling nature, generating a correlation between different CMB multipoles that otherwise would be fully uncorrelated.

\[
C_{\ell}^{dd} = \ell(\ell + 1)C_{\ell}^{\phi \phi}
\]

\[
\langle a_{\ell}^m b_{\ell'}^{m'} \rangle = (-1)^m \delta_{m}^{m'} \delta_{\ell}^{\ell'} C_{\ell}^{ab} + \sum_{LM} \Xi_{\ell \ell'}^{MM} \phi_{LM}^{M} \quad \text{with } a, b \text{ running over } T, E, \text{ and } B \text{ modes}
\]

**Inversion defining a quadratic estimator**

\[
\langle d(a,b)_{L}^{M} d(a',b')_{L'}^{M'} \rangle \equiv \delta_{L}^{L'} \delta_{M}^{M'} (C_{L}^{dd} + N_{L}^{ab ab'})
\]

\[
C_{\ell}^{dd}, N_{\ell}^{dd} = \frac{1}{\sum_{ab'bb'} (N_{\ell}^{ab ab'})^{-1}}
\]

FUTURE CONSTRAINTS

EDE parameters

\[ F_{ij} \equiv \left\langle -\frac{\partial^2 \ln L}{\partial p_i \partial p_j} \right\rangle_{p_0} \]

\[ F_{ij}^{\text{CMB}} = \sum_{l=2}^{l_{\text{max}}} \sum_{\alpha, \beta} \frac{\partial C_l^\alpha}{\partial p_i} (\text{Cov}_l)^{-1}_{\alpha \beta} \frac{\partial C_l^\beta}{\partial p_i} , \]

\[ \sigma_{p_i} \geq \sqrt{\left( F^{-1} \right)_{ii}} \]

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The constraint on $c_s^2$ can be affected. Assuming a value of $c_{vis}^2$ lower than the truth is like assuming more perturbations, so $c_s^2$ must be biased high to compensate and reduce the perturbations. The resulting best fit value is 1sigma away from the fiducial value for Planck, and about 2sigma away for CMBPol.

The other parameters are only mildly biased.

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FUTURE CONSTRAINTS

Neutrino mass degeneracy

\[ \sum m_\nu = 94\Omega_\nu h^2 \text{eV} \]

The anticorrelation between the early dark energy density and the sum of neutrinos masses means that future CMB bounds on the neutrino mass can be affected by the presence of EDE!

In particular, we studied the impact of one component on the other. As we can see from the Table the presence of early dark energy and massive neutrinos almost doubles the uncertainty on both of these parameters.

Calabrese et al., arxiv:1010.5612
CONCLUSIONS

✓ Early, Cold and Stressed Dark Energy model

✓ Upper limit of about 6% of EDE density in current cosmological data

✓ Future experiments offer strong constraints on this EDE model that has to be well parametrized to not affect estimates of other cosmological parameters.