Dark energy with non–adiabatic sound speed

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G. Ballesteros and J.Lesgourgues

Accelerated expansion of the universe.

Candidates:

- Cosmological constant
- Dark fluid $(w < -1/3)$
- Quintessence, K-essence, ...
- Modifed gravity

Any expansion history can be obtained from a (time varying) w,

$\Downarrow$

perturbations may help to determine the nature of the acceleration.

Assume a fluid description with two parameters: $\{w, c_s\}$

The sound speed of dark energy

Adiabatic sound speed: $\dot{p} = {c_a}^2 \dot{\rho}$

No interactions: $\dot{w} = 3(1+w)\left(w - {c_a}^2\right)\mathcal{H}$

Entropy perturbations: ${c_s}^2 = \delta p / \delta \rho$ (gauge dependent)

Fluid's rest frame $\longrightarrow$ $\hat{c_s}^2$ definite number

$${c_s}^2 \delta = \hat{c_s}^2 \delta + 3\mathcal{H}\,(1+w)\left(\hat{c_s}^2 - {c_a}^2\right)\theta / k^2$$

for $w > -1$: $0 \leq \hat{c_s}^2 \leq 1$

Adiabatic initial conditions

$$\rho_i(\tau,\vec{x}) = \bar\rho_i(\tau+\delta\tau(\vec{x})) \simeq \bar\rho_i + \dot{\bar\rho}_i\,\delta\tau(\vec{x})$$
$$p_i(\tau,\vec{x}) = \bar p_i(\tau+\delta\tau(\vec{x})) \simeq \bar p_i + \dot{\bar p}_i\,\delta\tau(\vec{x})$$

$${c_s}^2 = \delta p_i/\delta\rho_i = \dot{\bar p}_i/\dot{\bar\rho}_i = {c_a}^2$$

$$\tfrac{\delta_i}{1+w_i} = -3\mathcal{H}\delta\tau\,,\forall i$$

$$\delta_c = \delta_b = \frac{3}{4}\delta_\nu = \frac{3}{4}\delta_\gamma$$

Fastest growing mode

Initial conditions. Radiation era. $k \ll \mathcal{H} \to k\tau \ll 1$

Synchronous gauge (with $\theta_c = 0$)

$$\delta_c = \delta_b = \frac{3}{4}\delta_\nu = \frac{3}{4}\delta_\gamma \propto (k\tau)^2$$

$$\boxed{\delta_x = (1+w)\frac{4-3\hat{c_s}^2}{4-6w+3\hat{c_s}^2}\delta_c}$$

Conformal Newtonian gauge

$$\delta_c^{(c)} = \delta_b^{(c)} = \frac{3}{4}\delta_\nu^{(c)} = \frac{3}{4}\delta_\gamma^{(c)} \propto (k\tau)^0$$

$$\boxed{\delta_x^{(c)} = (1+w)\delta_c^{(c)} + \delta_x}$$

Initial conditions. Matter era.

2–fluid approximation: (CDM + baryons) and DE. $\Omega_x \to 0$

Synchronous gauge (with $\theta_c = 0$). $\delta_c \propto (k\tau)^2$

$$\begin{aligned} \delta_x &= (1+w)\frac{5-6\hat{c_s}^2}{5-15w+9\hat{c_s}^2}\delta_c\,, \qquad k \ll \mathcal{H} \\ \delta_x &= (1+w)\frac{1-2\hat{c_s}^2}{1-3w+\hat{c_s}^2}\delta_c\,, \qquad \hat{c_s}^{-1}\mathcal{H} \gg k \gg \mathcal{H} \end{aligned}$$

Conformal Newtonian gauge

$$\begin{aligned} \delta_c^{(c)} &= \left(1+3\frac{\mathcal{H}^2}{k^2}\right)\delta_c\,, \\ \delta_x^{(c)} &= \delta_x + 3(1+w)\frac{\mathcal{H}^2}{k^2}\delta_c \end{aligned}$$

Initial conditions. Matter era.

2–fluid approximation: (CDM + baryons) and DE. $\Omega_x \to 0$

Synchronous gauge (with $\theta_c = 0$). $\quad \delta_c \propto (k\tau)^2$

$$\begin{aligned}
\delta_x &= (1+w)\frac{5-6\hat{c_s}^2}{5-15w+9\hat{c_s}^2}\delta_c\,, & k \ll \mathcal{H} \\
\delta_x &= (1+w)\frac{1-2\hat{c_s}^2}{1-3w+\hat{c_s}^2}\delta_c\,, & \hat{c_s}^{-1}\mathcal{H} \gg k \gg \mathcal{H}
\end{aligned}$$

Conformal Newtonian gauge

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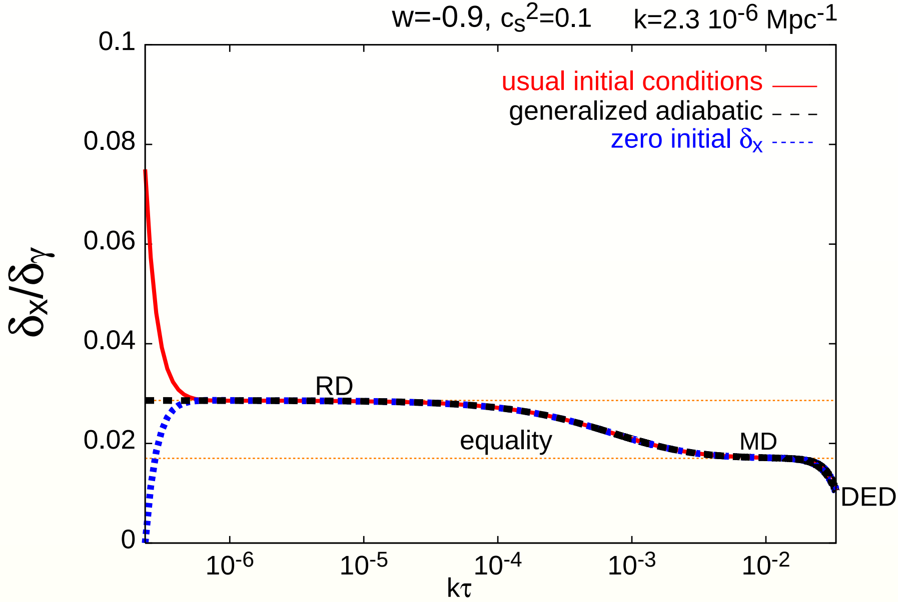
\delta_x^{(c)} &= (1+w)\delta_c^{(c)}\,, & k \ll \mathcal{H} \\
\delta_x^{(c)} &= (1+w)\frac{1-2\hat{c_s}^2}{1-3w+\hat{c_s}^2}\delta_c^{(c)}\,, & \hat{c_s}^{-1}\mathcal{H} \gg k \gg \mathcal{H}
\end{aligned}$$

Attractors (Synchronous gauge)



Detectability of $\hat{c}_s$

1. Large scale structure
2. Cosmic microwave backround

Change on the growth of $\delta_c \Rightarrow$ CMB affected through late ISW at $\mathcal{H}_s \gg k \gg \mathcal{H}$

Today's CMB, LSS, SN data not sensitive. *De putter, Huterer & Linder '10*

Fisher matrix approaches for future data prospects:

- Matter tracers. *Takada '06*
- Cross correlation of CMB and LSS. *Hu & Scranton '04*

Conclusion: Future surveys able to discriminate between quintessence like $({c_s}^2 \sim 1)$ and clustering DE $({c_s}^2 \sim 0)$

Fisher matrix needs improvement. Disentangle degeneracies bewteen $\hat{c_s}^2, m_\nu, w, H_0$ and get better accuracy.

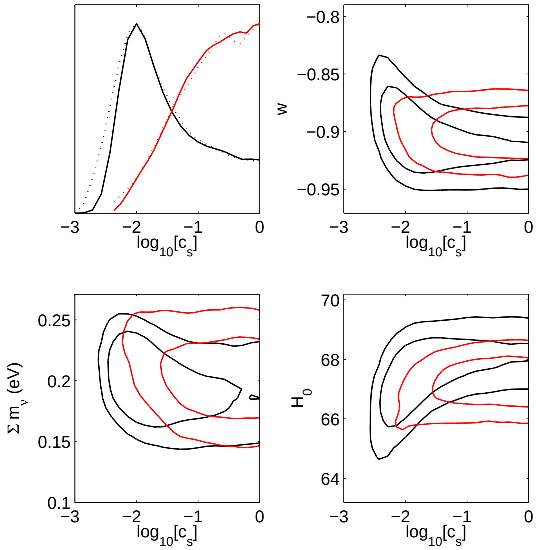
Detectability of $\hat{c}_s$

MCMC analysis and full likelihood marginalization

- **Planck with lensing extraction**: insensitive to $\hat{c}_s$
  Cross-correlates the lensing and temperature maps
- **Planck** $\times$ **LSS**:
  - determines the order of magnitude of $\hat{c}_s$
  - sets a lower bound on $\hat{c}_s$

- more stringent bounds than previous works
- parameter degeneracies are small (in particular: neutrino free streaming is a less sharp effect)
- future data will be able to exclude models with maximum clustering $\hat{c}_s \to 0$

Detectability of $\hat{c}_s$



Conclusions

For an extra fluid with constant w and $\hat{c}_s$:

- Generalized adiabatic (growing mode) initial conditions for radiation and matter epochs (are gauge and scale dependent)
- Existence of attractors (all that matters is δ of matter)

- CMB from Planck alone unable to detect $\hat{c}_s$
- **Planck + LSST $\rightarrow$ Lower bound on $\hat{\mathbf{c}}_{\mathbf{s}}$**