Dark energy with non-adiabatic sound speed

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COSMO/Cospa 2010. Tokyo

Overview

1. Introduction
2. The sound speed
3. Initial conditions
    - Radiation era
    - Matter era
4. Prospects for detection
5. Conclusions

arXiv:1004.5509

G. Ballesteros and J.Lesgourgues

Accelerated expansion of the universe

- Cosmological constant
- Dark energy fluid $(w < -1/3)$
- Quintessence
- Modifed gravity
- other possibilities...

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

Perturbations can help.

The sound speed of dark energy

Perfect fluids: adiabatic sound speed: ${c_a}^2 = \dot{p}/\dot{\rho}$ (gauge independent)

Non–interacting fluids: $\dot{w} = 3(1+w)\left(w - {c_a}^2\right)\mathcal{H}$

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

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

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

(exponential growth of δ) $0 \leq \hat{c_s}^2 \leq 1$ (superluminal propagation)

Adiabatic initial conditions

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

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

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

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

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

Fastest growing mode

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

Synchronous gauge (with $\theta_c = 0$)

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

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

Conformal Newtonian gauge

$$\delta_c^{(c)} = \delta_b^{(c)} = \frac{3}{4}\delta_\nu^{(c)} = \frac{3}{4}\delta_\gamma^{(c)} = \text{constant} = \frac{\delta_x}{(1+w)}$$

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

Initial conditions. Matter era. $\delta_\gamma = \delta_\nu = 0$

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

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

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

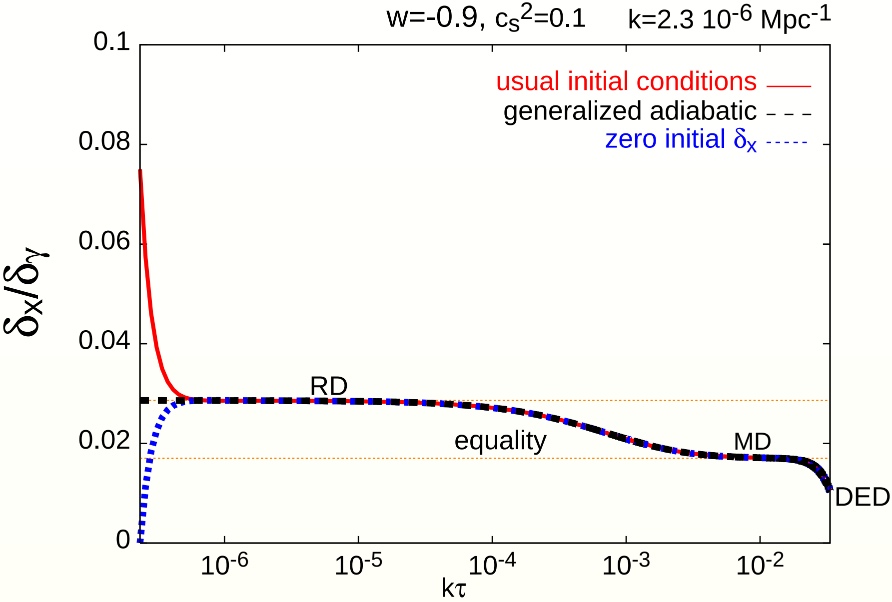
$$\delta_x = (1+w)\frac{1-2\hat{c_s}^2}{1-3w+\hat{c_s}^2}\delta_c\,, \qquad \hat{c_s}^{-1}\mathcal{H} \gg k \gg \mathcal{H}$$

Conformal Newtonian gauge

$$\delta_c^{(c)} = \left(1+3\frac{\mathcal{H}^2}{k^2}\right)\delta_c\,,$$

$$\delta_x^{(c)} = \delta_x + 3(1+w)\frac{\mathcal{H}^2}{k^2}\delta_c$$

Attractors (Synchronous gauge)



Detectability of $\hat{c}_s$ (dark energy perturbations)

Current CMB, LSS, SN not sensitive
Effect on the CMB through late ISW at $\hat{c_s}^{-1}\mathcal{H} \gg k \gg \mathcal{H}$
CMB alone is limited by cosmic variance

- Lensing extraction
- Cross correlation with LSS

Forecasts

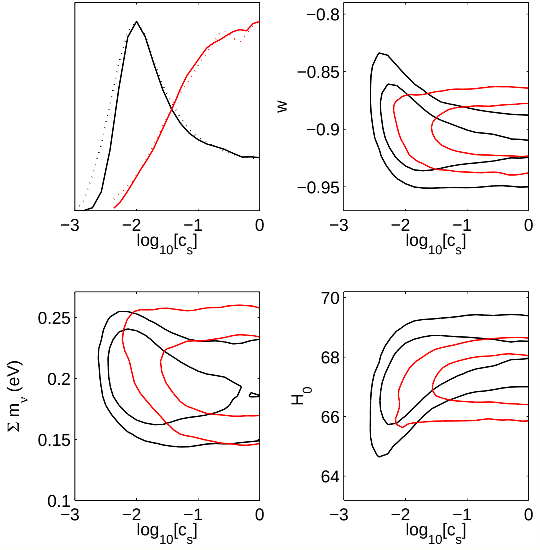
- Fisher matrix analysis: (See talk of D. Sapone)
  See also e.g.: `(Hu and Scranton. 2004) and (Takada. 2006)`

Linear level approximation needs improvement.

- MCMC analysis and FULL LIKELIHOOD MARGINALIZATION. Planck + LSST.

Disentangle degeneracies. $\hat{c_s}^2, m_\nu, w, H_0$

Detectability



Conclusions

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

- Planck + LSST $\rightarrow$ Lower bound on $\hat{c}_s$

- Generalization of the usual adiabatic initial conditions for radiation and matter epochs
- Existence of attractors