BBN Constraints on Scaling Quintessence Models and Dark Energy Surveys

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Introduction

- The universe is undergoing a period of accelerated expansion driven by an unknown component (dark energy)
- A time-independent cosmological constant is consistent with all observations, but it is important to look for alternatives
- Consider models where a scalar field scales with the background fluid during the radiation and matter eras, and dominates the energy density of the universe at late times
- Big bang nucleosynthesis (BBN) gives a strong constraint on the energy density of dark energy during the radiation era
- Investigate whether it is possible to distinguish between scaling models and a cosmological constant with observations

Scaling models

Wetterich, 1988

- Exponential potential

$$V(\phi) = M^4 e^{-\lambda\kappa\phi} \qquad \kappa^2 = 8\pi G$$

- $\lambda^2 > 3(1 + w_b)$: scales with the background fluid

$$w_\phi = p_\phi/\rho_\phi = w_b \qquad \Omega_\phi = 3(1 + w_b)/\lambda^2$$

- $\lambda^2 < 3(1 + w_b)$: dominant component of the universe

$$w_\phi = -1 + \lambda^2/3 \qquad \Omega_\phi = 1$$

$$\Omega_\phi = \rho_\phi/\rho_c \qquad \rho_c = 3H^2/8\pi G$$

Constraints from BBN

- The presence of a scalar field changes the expansion rate of the universe at a given temperature
- Affects the abundance of light elements at the time of nucleosynthesis
- Constraint on Ω_ϕ during the radiation dominated era
  Bean, Hansen and Melchiorri, 2001

$$\Omega_\phi(T \sim 1MeV) < 0.045$$

- Constraint on the value of λ (in the scaling regime)

$$\lambda^2 > \frac{4}{0.045} \quad \Rightarrow \quad \lambda \gtrsim 9.43$$

Polynomial $w(z)$ parametrization

- Scaling until z_t and $w(z) = w_0 + w_1 z + w_2 z^2$ in the region $0 \leq z < z_t$
- Assume $w(z_t) = w_m = 0$ and $w(0) = -1$

$$w(z) = -1 + w_1 z + \left(\frac{1}{z_t^2} - \frac{w_1}{z_t} \right) z^2$$

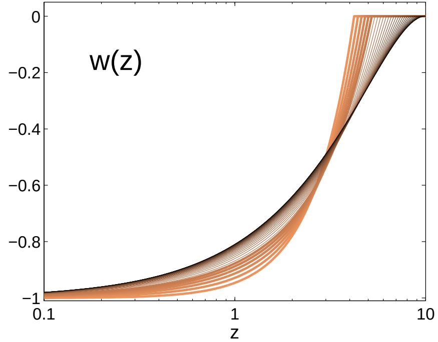
$$\Omega_{DE}(z_t) = \frac{\Omega_{DE}^{(0)} f(z_t)}{\Omega_{DE}^{(0)} f(z_t) + \Omega_m^{(0)} (1+z_t)^3} = 0.045$$

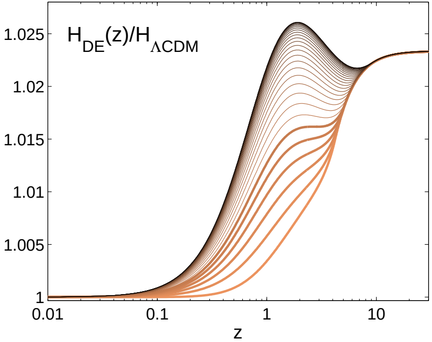
$$f(z) = \exp\left(3 \int_0^z \frac{1 + w(z')}{1 + z'} dz' \right)$$

- Solve w_1 as a function of z_t
- Use BBN bound to maximise deviations from Λ

Polynomial $w(z)$ parametrization

- Need the constraint $w(z) > -1$ for all z to describe a canonical scalar field

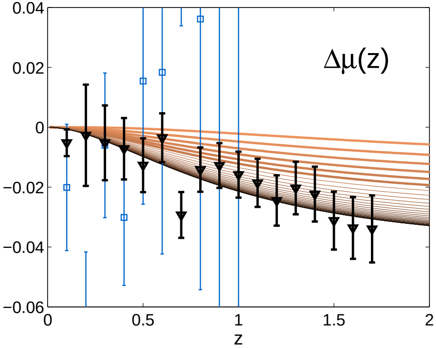




- $\lesssim 2.7\%$ deviations of $H(z)$ from ΛCDM
- Largest deviation occurs at $z \sim 2$

Polynomial $w(z)$ parametrization

- $\Delta\mu(z) = 5\log_{10}\left(\frac{d_L^{DE}(z)}{d_L^{\Lambda CDM}(z)}\right) \qquad d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$



- Predicted errors in the DETF report for Stage III (blue) and Stage IV (black) surveys

  Albrecht et al, 2006

Double exponential potential

- Potential with two exponential terms
  Barreiro, Copeland and Nunes, 2000

$$V(\phi) = M_1^4 e^{-\lambda\kappa\phi} + M_2^4 e^{-\mu\kappa\phi}$$

- Scales during the radiation and matter epochs and dominates at late times
- Need $\mu^2 < 2$ to have acceleration and M_2 such that $\Omega_\phi^{(0)} \sim 0.7$ and $\Omega_m^{(0)} \sim 0.3$
- Evolution equations

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

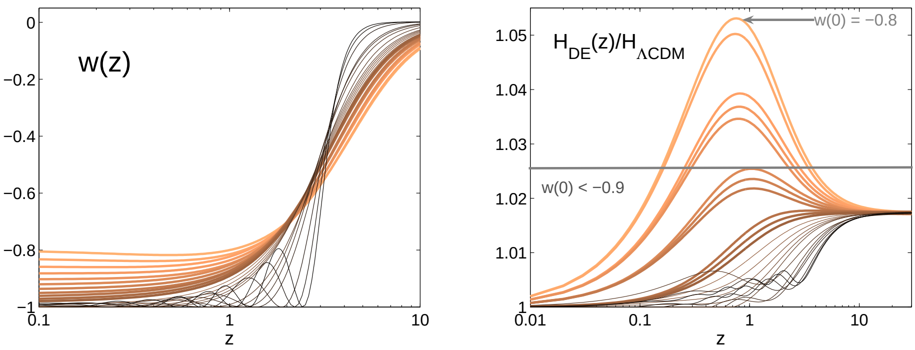
$$\dot{\rho}_m + 3H\rho_m = 0$$

$$\dot{\rho}_r + 4H\rho_r = 0$$

$$H^2 = \frac{\kappa^2}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_m + \rho_r\right]$$

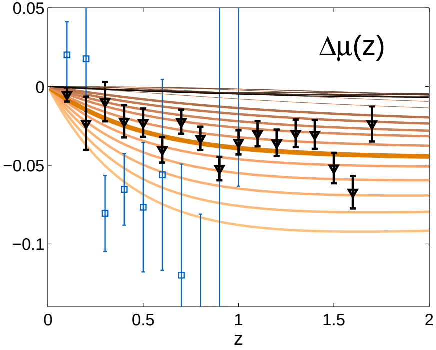
Double exponential potential

- $V(\phi) = M_1^4 e^{-\lambda\kappa\phi} + M_2^4 e^{-\mu\kappa\phi}$



- $w_\phi(0) \lesssim -0.9$ implies $\lesssim 2.7\%$ deviations of $H(z)$ from ΛCDM
- Largest deviation occurs at $z \sim 1$

Double exponential potential



- Predicted errors in the DETF report for Stage III (blue) and Stage IV (black) surveys

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Conclusions

- Constraints on the energy density of the scalar field at the time of BBN strongly limit scaling quintessence models
- Tracking quintessence dynamics may be effectively invisible until the unveiling of Stage-IV dark energy experiments (JDEM, LSST, SKA)
- Tracking scalar field models are well motivated alternatives to the cosmological constant as the source of cosmic acceleration today
- Dark energy may well be dynamical even if we do not detect such dynamics in the next decade