Why Dark Energy?

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Quintessence

Scalar-tensor DE models

Modified gravity models

Chameleon models

Growth function, growth index

Observations

Outlook

Dark Energy

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David Polarski

Université Montpellier 2

June 8, 2010

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- Dark energy paradigm started with observations: Luminosity distances from SNIa

$$\mathcal{F} = \frac{L}{4\pi d_L^2} \qquad\qquad m - M = 5 \log d_L + 25$$

$$d_L(z) = c\,(1+z)\,H_0^{-1}\,|\Omega_{k,0}|^{-\frac{1}{2}}\,\mathcal{S}\left(|\Omega_{k,0}|^{\frac{1}{2}}\int_0^z \frac{dz'}{h(z')}\right)$$

- Universe expansion does not look like in (old) textbooks

$$\ddot{a} < 0 \rightarrow \ddot{a} > 0 \qquad \text{at } z \sim 0.5$$

- What is the origin of the accelerated expansion?

- We are not really unhappy...

$$\Omega_{m,0} \approx 0.3, \qquad \Omega_{DE,0} \approx 0.7, \qquad \Omega_{k,0} \approx 0$$

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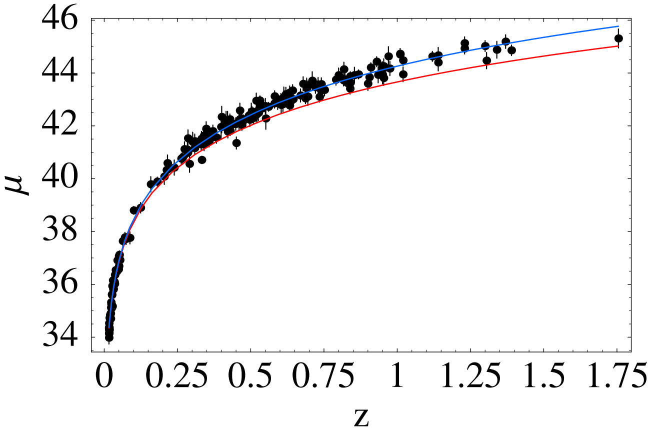

$\Lambda CDM \quad \Omega_{m,0} = 0.3 \quad \Omega_{k,0} = 0$

EdS

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- $\Omega_i = \frac{\rho_i}{\rho_{cr}}$ $\quad H^2 = \frac{8\pi G}{3}\,\rho_{cr}$ $\quad w_i \equiv \frac{p_i}{\rho_i}$

  $\Omega_k = -\frac{k}{a^2 H^2}$ $\quad k = 0, \pm 1$

- $\left(\frac{\dot a}{a}\right)^2 \equiv H^2 = H^2\left(\sum_i \Omega_i + \Omega_k\right)$

  $q \equiv -\frac{\ddot a}{aH^2} = \frac{1}{2}\sum_i \Omega_i(1 + 3w_i)$

- At late times for flat universe

  $q \simeq \frac{1}{2}(1 + 3w_{DE}\Omega_{DE})$

- $w_{DE} < -\frac{1}{3}\,\Omega_{DE}^{-1}$ $\quad q < 0$ $\quad$ acc. exp.

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  "...My greatest blunder..." A. Einstein
- Conceptual problem: $\Lambda \sim 10^{-122} l_{Pl}^{-2}$
- Some observational problems:

  Dark matter halo density profile (no cusp seen)
  Large scale peculiar flows
  Unexpected brightness of SNIa data at $z > 1$
  Observed emptiness of voids
- Achilles' heel: $w_\Lambda = -1$ and ρ_Λ strictly constant
- Prominent contenders have dynamical $w_{DE}(z)$!!

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- Quintessence: (minimally coupled) scalar field $\phi(t)$, so successful in inflationary models

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{\dot{\phi}^2 - 2V}{\dot{\phi}^2 + 2V}$$

$$-1 \le w_\phi \le 1 \Leftrightarrow \rho_\phi + p_\phi \ge 0$$

No phantom!

- $L = \frac{1}{16\pi G_*}\left(F(\Phi)\, R - Z\partial_\mu\Phi\partial^\mu\Phi - 2U(\Phi)\right) + L_m(g_{\mu\nu})$
- Brans-Dicke parametrization

$$F(\Phi) = \Phi \qquad Z(\Phi) = \frac{\omega_{BD}(\Phi)}{\Phi}$$

Another choice

$$F(\Phi) = \text{arbitrary} \qquad Z = 1 \Leftrightarrow \omega_{BD} > 0$$

$$\omega_{BD} = \frac{F}{(dF/d\Phi)^2} > -\frac{3}{2} \qquad \omega_{BD,0} > 4 \times 10^4$$

- $$V = -G_{\text{eff}}\,\frac{M_1\; M_2}{r} \qquad \text{massless}\;\;\Phi\;\;\text{field}$$

$$G_{\text{eff}} = G_N\left(1 + \frac{1}{2\omega_{BD} + 3}\right) \qquad G_N = \frac{G_*}{F}$$

- $G_{\text{eff},0} \simeq G_{N,0}$

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- $$3FH^2 = 8\pi G_* \, \rho_m + \frac{\dot{\Phi}^2}{2} + U - 3H\dot{F}$$

$$-2F\dot{H} = 8\pi G_* \, \rho_m + \dot{\Phi}^2 + \ddot{F} - H\dot{F}$$

Define ρ_{DE} and p_{DE}:

$$3\left(H^2 + \frac{k}{a^2}\right) = 8\pi G_{N,0} \left(\rho_m + \rho_{DE}\right)$$
$$-2\left(\dot{H} - \frac{k}{a^2}\right) = 8\pi G_{N,0} \left(\rho_m + \rho_{DE} + p_{DE}\right)$$

- $$h^2(z) = \Omega_{m,0} \, (1+z)^3 + \Omega_{DE,0} \, f(z) + \Omega_{k,0} \, (1+z)^2$$

$$f(z) = \exp\left[3 \int_0^z dz' \, \frac{1 + w_{DE}(z')}{1 + z'}\right]$$

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Growth of matter perturbations is modified:

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\rm eff}\, \rho_m\, \delta_m = 0$$

$$h^2\, \delta_m'' + \left(\frac{(h^2)'}{2} - \frac{h^2}{1+z} \right) \delta_m' = \frac{3}{2}(1+z)\frac{G_{\rm eff}}{G}\, \Omega_{m,0}\, \delta_m$$

Perturbations $\delta_m(z)$ must be consistent with background expansion ($h(z) \equiv \frac{H(z)}{H_0}$)!

- No new component (DE), just change gravity!
  $\Leftrightarrow$ Modified gravity DE models

- $f(R)$ modified gravity DE models: $R \to f(R)$
  Most popular models $(R + \frac{\mu^2}{R})$ lead to unviable cosmic expansion with $a \sim t^{\frac{2}{3}} \to a \sim t^{\frac{1}{2}}$

- Some interesting viable $f(R)$ models still remain:
  $f(R) = R - \lambda R_c \, f_1(x) \qquad x \equiv R/R_c$
  e.g. $R - \lambda R_c \left(1 - \left(1 + \frac{R^2}{R_c^2}\right)^{-n}\right), \; n, \lambda > 0 (n \geq 2)$

- In $f(R)$ models ($F \equiv \frac{df(R)}{dr}$):

$$G_{\rm eff} = G_{\rm eff}(z, k) \Leftrightarrow V(r) = -\frac{G_*}{F} \frac{M_1 \, M_2}{r} \left(1 + \frac{1}{3} \, e^{-mr}\right)$$

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- $A^2 = e^{2\beta\phi/M_{PL}}$ $\qquad$ $V = M^4 \, e^{\left(\frac{M}{\phi}\right)^n}$

  $M \ll \phi \ll M_{PL} \rightarrow V$ is like Λ!

- $G_{\text{eff}}(z, k) \Leftrightarrow V(r) = -G_* \frac{M_1 M_2}{r} \left(1 + 2\,\beta^2 \, e^{-m_\phi r}\right)$

  m_ϕ is too large, no influence on cosmological scales!

- Coupling to dark matter only?

  $A_b = 0$ $\qquad$ $A_{dm} \neq 0$

  Interacting dark sector

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- Matter perturbations can be characterized by the "growth function" $f = \frac{d \ln \delta}{d \ln a} \equiv \frac{d \ln \delta}{dx}$

$$\frac{df}{dx} + f^2 + \frac{1}{2}(1 - 3\, w_{\text{eff}})\, f = \frac{3}{2}\frac{G_{\text{eff}}}{G}\Omega_m$$

- A convenient "parameterization" $f = \Omega_m^{\gamma}$.
  Actually

$$\delta_m(z, k) \Leftrightarrow \gamma = \gamma(z, k)$$

- In ΛCDM: $\gamma \simeq 0.55$
  It can be very different in modified gravity models!

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- Matter perturbations can be characterized by the "growth function" $f = \frac{d \ln \delta}{d \ln a} \equiv \frac{d \ln \delta}{dx}$

$$\frac{df}{dx} + f^2 + \frac{1}{2}(1 - 3\, w_{\rm eff})\, f = \frac{3}{2}\frac{G_{\rm eff}}{G}\Omega_m$$

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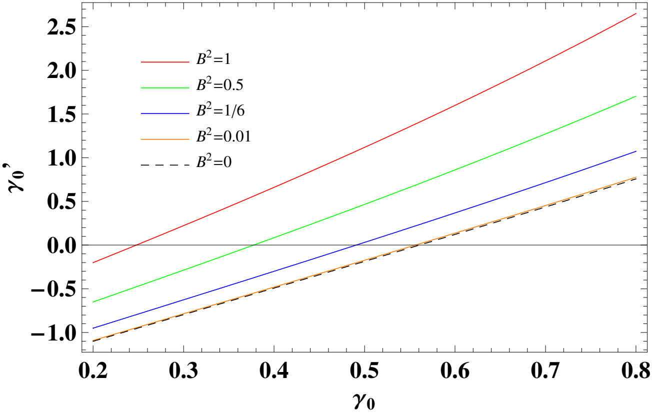
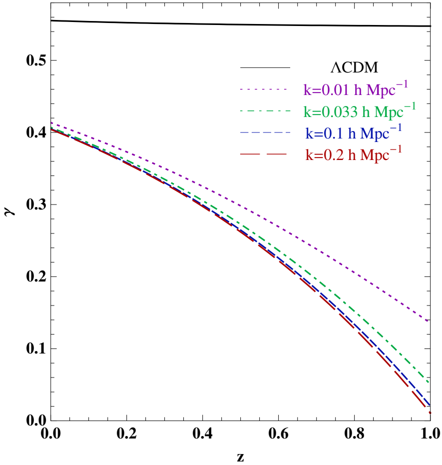
$$C\left(\gamma_0(k),\ \gamma_0'(k),\ \Omega_{m,0},\ w_{\text{eff},0},\ \frac{G_{\text{eff},0}(k)}{G} \equiv 1 + 2B^2\right) = 0$$



$$\Omega_{m,0} = 0.29 \qquad w_{DE,0} = -1$$

$$f(R) = R - \lambda R_c \frac{x^{2n}}{x^{2n}+1} \qquad x \equiv \frac{R}{R_c}$$



$$n = 1, \quad \lambda = 1.55$$

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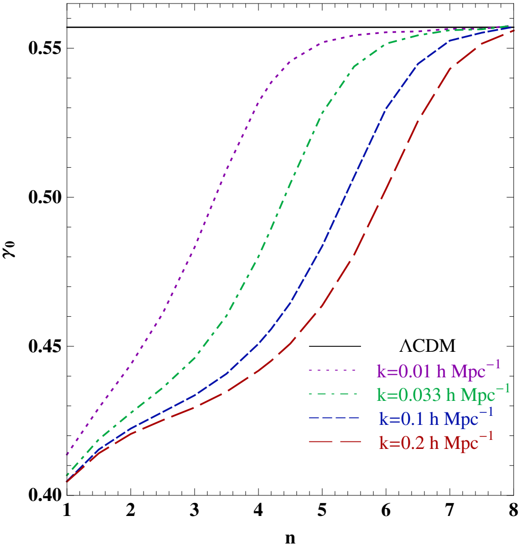

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- We need complementary probes:

  Supernovae

  Clusters

  Weak lensing

  Baryon Acoustic Oscillations

  Cosmic Microwave Background

  Gamma Ray Bursts?

  Gravitational waves?

- DE paradigm: something accelerates the expansion rate and fills the universe
- Λ or not Λ ?
- What is $w(z)$ and the underlying model?
- General Relativity or beyond ?
- When we have very precise data, which model from each family will survive?

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