The promises of Dark Energy

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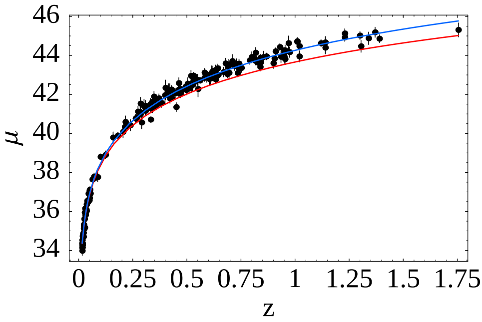
Dark Energy paradigm comes from observations: SNIa Luminosity-distances

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



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

Expansion different from standard cosmology

$$\ddot{a} < 0 \rightarrow \ddot{a} > 0 \qquad @ \quad z \sim 0.5$$

Dark Energy puzzle:
What is the origin of this accelerated expansion ?

We are not really unhappy...

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

A consistent vision has emerged supported by many observations: SNIa, CMB, BAO,...

“Old” simple solution: cosmological constant Λ

“...My greatest blunder...” A. Einstein

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho_m + \frac{\Lambda}{3}$$

Conceptual problem : $\Lambda \sim 10^{-122} l_{Pl}^{-2}$

Consistent with *all* observations ?

Many contenders: Scalar field models, modified gravity,...

But ΛCDM remains the model to beat!

Pending questions:

Is ρ_{DE} constant / Is $w_{DE} = -1$? $w_{DE}(z)$?

$\Omega_{DE} \to 0$ for $z \gg 1$?
Is DE related to Inflation?

Coupling in the dark sector ?

Smooth component ?

Is DE connected to dark matter ?

Is DE a perfect fluid ?

Is gravity described by GR ?

Is our universe homogeneous ?
Higher dimensions ?

- Modified gravity DE models
  Maybe gravity differs from GR on large scales ?
  Accelerated expansion without DE component ?

  We keep the RW metric

$$ds^2 = dt^2 - a^2(t)\, d\ell^2$$

  We get modified Friedmann equations
  They can be often recast in an “Einsteinian” way

  The growth of perturbations gets modified as well!
  Crucial probe of modified gravity models

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

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

Another choice

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

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

-

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

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

- $G_{\mathrm{eff},0} \simeq G_{N,0} \simeq G$

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- Modified background equations

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

Define ρ_{DE} and p_{DE}:

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

- $\frac{dh^2}{dz} < 3\,\Omega_{m,0}\,(1+z)^2 + 2\,\Omega_{k,0}\,(1+z) \iff$ phantom

Possible in scalar-tensor models

$$8\pi\, G_* \left(\rho_{DE} + p_{DE} \right) = \dot{\Phi}^2 + \ddot{F} - H\dot{F} + 2(F - F_0)\,\dot{H}$$

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Possible in scalar-tensor models

$8\pi\, G_*\,(\rho_{DE} + p_{DE}) = \dot\Phi^2 + \ddot F - H\dot F + 2(F - F_0)\,\dot H$

$$L = \frac{1}{2}\Big(F(\Phi)\, R - Z\,\partial_\mu\Phi\partial^\mu\Phi - 2U(\Phi)\Big)$$

$$ZF = -\frac{1}{6}\Phi^2 + \kappa^{-2}$$

$$ZU = \frac{\Lambda}{\kappa^2} - c\Phi^4 \qquad \Lambda,\ c > 0$$

$$3H^2 = \Lambda + \kappa^2\frac{A}{a^4},$$

$$\frac{1}{2}\left(\frac{d\chi}{d\eta}\right)^2 - c\chi^4 = A \qquad \chi \equiv a\Phi$$

$$a_B = \left(\frac{-A\kappa^2}{\Lambda}\right)^{\frac{1}{4}} \qquad A < 0$$

Family of non-degenerate spatially flat integrable bouncing solutions

In EF (Quintessence!):

integrable solutions with inverted double-well potential

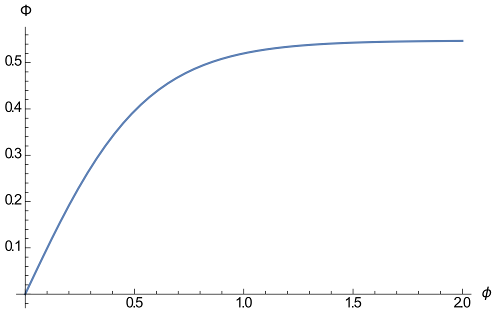


Figure: It is seen that Φ is a monotonically growing function of ϕ. The limit $\Phi \to \frac{\sqrt{6}}{\kappa} \equiv \Phi_{max}$ corresponds to $\phi \to \infty$. The interval $0 < \phi < \infty$ covers the physically viable interval $0 < \Phi < \Phi_{max}$ for which $F > 0$ in the JF .

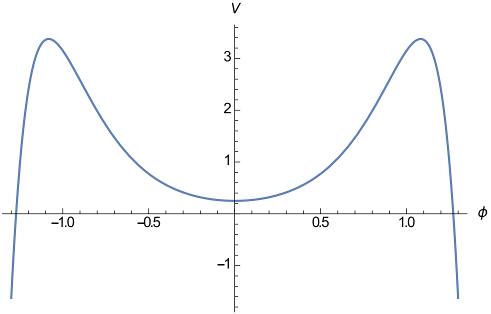


Figure: The EF potential V is shown in the case $Z = 1$ for the same parameters. The value $\phi = \infty$ corresponds to $\Phi = \frac{\sqrt{6}}{\kappa} \equiv \Phi_{max}$, the unphysical limit where F vanishes and for which either a Big Bang or a Big Crunch takes place in the EF.

Technical details

$$ds^2 = (1+2\phi)dt^2 - a^2\,(1-2\psi)d\mathbf{x}^2$$

$$\phi = \psi - \frac{\delta F}{F}$$

In quasi static limit

Perturbed dilaton equation of motion:

$$\delta\Phi = (\phi - 2\psi)\,\frac{dF}{d\Phi} = -\phi\,\sqrt{F}\,\frac{\sqrt{\omega_{BD}}}{2+\omega_{BD}}$$

Combination of the perturbed Einstein equations:

$$\frac{k^2}{a^2}\,\phi = 4\pi G_{\rm eff}\,\rho_m\,\delta_m$$

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

$$L = \frac{R}{16\pi G_*} - \frac{1}{2} g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V(\phi) + L_m\left[\Psi_m; A^2(\phi)\, g_{\mu\nu}\right]$$

Interacting dark sector

$f(R)$ modified gravity DE models: $R \to f(R)$

e.g. $R - \lambda R_c \left(1 - \left(1 + \frac{R^2}{R_c^2}\right)^{-n}\right)$, $n, \lambda > 0 \ \ (n \geq 2)$

$$G_{\rm eff}(z,k) = \frac{G_*}{F}\left(1 + \frac{1}{3}\,\frac{\frac{k^2}{a^2 m^2}}{1 + \frac{k^2}{a^2 m^2}}\right) \qquad \frac{F}{F'} \equiv 3\, m^2$$

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

Chameleon mechanism

Horndeski model

Galileon model

modified Friedmann eqs with “effective” $\rho_{DE}(\phi, \dot{\phi})$

$w_{DE,0} = -1, w_{DE}$ can be < -1

$G_{\rm eff}(z) \Rightarrow$ signature in the perturbation growth

Laboratory and solar system constraints: Vainshtein mechanism

Massive gravity

Mimetic matter

Various theoretical frameworks and approaches:

PPF (Parametrized Post-Friedmannian)

EFT (Effective Field Theory)

Cosmographic approach, Reconstruction

Phenomenological tools:

EoS parametrizations, null-tests, growth index,...

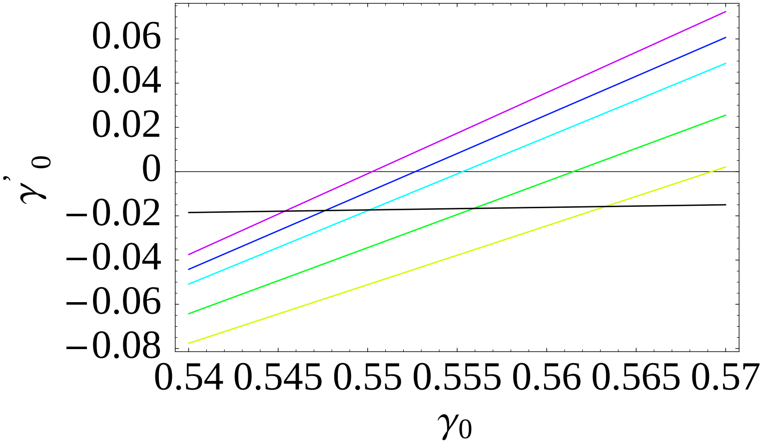
Matter perturbations can be characterized by the "growth function" $f = \frac{d \ln \delta}{d \ln a} \equiv \frac{d \ln \delta}{dx}$

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

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!



$\Omega_{m,0} = 0.3$ and various values of $w_{DE,0}$
We have from top to bottom:
$w_{DE,0} = -1.4,\ -1.3,\ -1.2,\ -1,\ -0.8.$
The black line gives the **true** value of γ_0 realized: same non vanishing $\gamma'_0 \approx -0.02$.

BAO

Acoustic scale at various $z \Rightarrow D_A(z)$ and $H(z)$

BAO forecasts for a Full-Sky survey

$z_{\rm min}$	$z_{\rm max}$	Vol	% Err $D_A(z)$	% Err $H(z)$	Ω_Λ	σ_w
0.00	0.15	0.33	2.8	4.9	0.708	0.64
0.15	0.32	2.62	0.95	1.7	0.616	0.088
0.32	0.51	7.89	0.53	0.96	0.515	0.036
0.51	0.73	16.5	0.35	0.63	0.413	0.021
0.73	0.99	28.4	0.26	0.46	0.318	0.015
0.99	1.28	42.9	0.21	0.36	0.236	0.013
1.28	1.62	59.0	0.17	0.28	0.170	0.012
1.62	2.00	75.8	0.14	0.24	0.119	0.013
2.00	2.44	92.3	0.13	0.21	0.082	0.014
2.44	2.95	108	0.12	0.18	0.056	0.016
2.95	3.53	121	0.11	0.17	0.038	0.020
3.53	4.20	133	0.10	0.15	0.025	0.025
4.20	4.96	142	0.10	0.15	0.017	0.033

The art of inducing accelerated expansion:
Large variety of models and approaches

Phenomenology $\approx \Lambda$CDM

The promise of DE is not clear yet...