$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_B g_{\mu\nu} = \kappa T_{\mu\nu} \tag{1}$$

$\kappa = (8\pi G)/c^4$

Λ_B

$$T_{\mu\nu}$$

$$T_{\mu\nu}^{\mathrm{vac}} \propto \rho_{\mathrm{vac}} g_{\mu\nu}$$

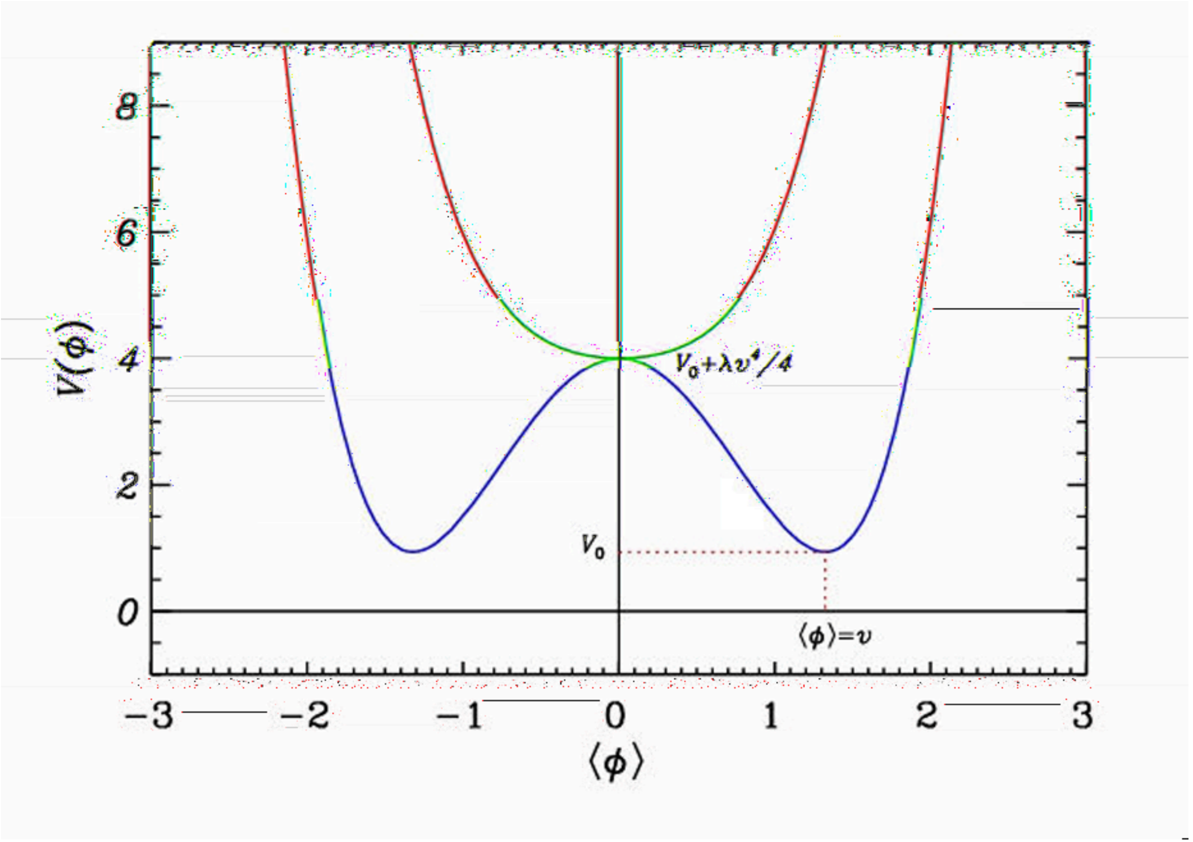
$$\Lambda_{\text{eff}} = \Lambda_B + \kappa\rho_{\text{vac}} \tag{2}$$

Λ

Λ_B

$\kappa\rho_{\text{vac}}$

$$\langle 0|T_{\mu\nu}|0\rangle = \frac{\kappa}{(2\pi)^3}\int \mathrm{d}^3k \cdot \frac{1}{2}\omega(k) \tag{3}$$



8
6
4
2
0
$V(\phi)$
$V_0+\lambda v^4/4$
V_0
$\langle\phi\rangle=v$
−3
−2
−1
0
1
2
3
$\langle\phi\rangle$

$$\Lambda_B$$

$\Phi(t)$

$V(\Phi)$

$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi) \tag{4}$$

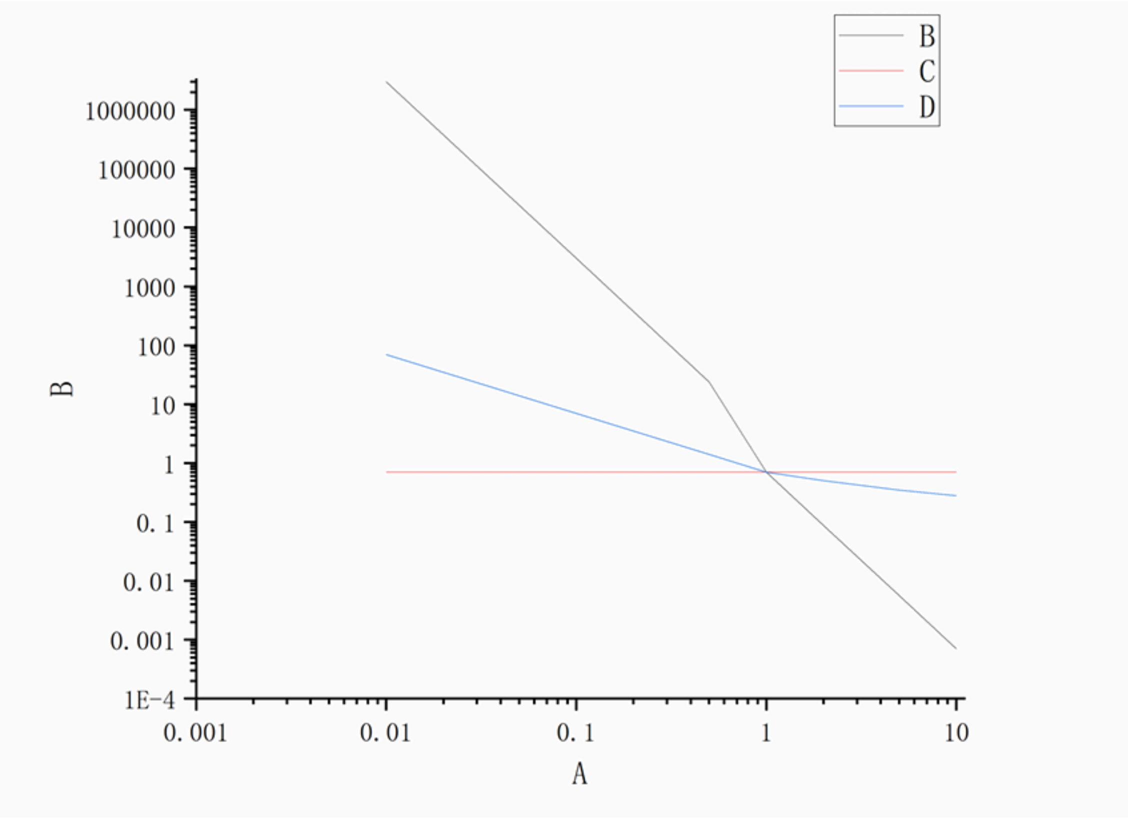
$$\ddot{\Phi} + 3H\dot{\Phi} + V(\Phi)' = 0 \tag{5}$$

Φ_0

$$V(\Phi) = M^{4+\alpha}\Phi^{-\alpha} \tag{6}$$

$\alpha = 2$

$\Lambda\mathrm{CDM}$


B
C
D
1000000
100000
10000
1000
100
10
1
0. 1
0. 01
0. 001
1E-4
B
0. 001
0. 01
0. 1
1
10
A

$\alpha = 2$

M

$$m_\Phi \sim 10^{-33} eV$$

$$\rho_V < \frac{500\rho_R\delta_R^3}{729} \tag{7}$$

ρ_R, δ_R $z = 1100$

$$5\% \sim 12\%$$

ΛCDM

$f(R)$

$f(R)$

R $f(R)$

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2\kappa} f(R) + \mathcal{L}_m \right) \tag{8}$$

$f(R)$

$f(R)$

$f(R) = R$

$f(R) = R - \alpha R^{-n}$ $f(R) =$

$R + \alpha R^2$

$f(R)$

$$f(R) = R - \alpha R^{-n}$$

$$G_{\mu\nu} = 8\pi G_{\text{eff}} T_{\mu\nu} + 8\pi G T^{\text{eff}}_{\mu\nu} \tag{9}$$

$$T^{\text{eff}}_{\mu\nu} = \frac{1}{8\pi G} \frac{1}{f'(R)} \Big[\frac{1}{2}(f(R) - R f'(R)) g_{\mu\nu} \\ -(g_{\mu\nu}\Box - \nabla_\mu \nabla_\nu) f'(R) \Big] \tag{10}$$

$f(R)$

$$
\begin{aligned}
3H^2 &= 8\pi G(\rho_m + \rho_{\text{eff}}), \\
2\dot{H}^2 + 3H^2 &= -8\pi G(P_m + P_{\text{eff}})
\end{aligned} \tag{11}
$$

$$
\begin{aligned}
\rho_{\text{eff}} &= \frac{1}{8\pi G}\frac{1}{f'(R)}\left[\frac{1}{2}(f(R) - Rf'(R)) + 3H\dot{R}f''(R)\right] \\
P_{\text{eff}} &= \frac{1}{8\pi G}\frac{1}{f'(R)}\left[\frac{1}{2}(Rf'(R) - f(R)) - \left(\dot{R}f''(R) + \ddot{R}f'''(R)\right)\right]
\end{aligned} \tag{12}
$$

$f(R)$

R $f(R) = R - \alpha R^{-n}$ $\alpha > 0,\ n > 0$

n $R \to 0$ $w_{\text{eff}} = \frac{P_{\text{eff}}}{\rho_{\text{eff}}} < -\frac{1}{3}$

$f(R)$

$S =$

$\int d^4x \sqrt{-g}\left(\frac{1}{2\kappa}R + \frac{1}{2\lambda}R^2\right)$ λ

R R^2 R^2

R

$f(R)$

$f(R)$

$f(R)$

$f(R)$

$f(R)$

$f(R)$

$f(R)$

$f(R)$

$$f(R)$$

$$S = -\frac{1}{2\mu^2}\int d^5x\sqrt{-\hat{g}}\hat{R} - \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}(R+\mathcal{L}) \tag{13}$$

$\mu, \hat{g}, \hat{R}$ κ, g, R

$$r_c = \frac{G_5}{2G_4}$$

r_c

r_c

r_c

$$H^2 \pm \frac{1}{r_c}H = \frac{8\pi G_4}{3}\rho_m \tag{14}$$

$$H^2 - \frac{1}{r_c}H = \frac{8\pi G_4}{3}\rho_m$$

$\frac{1}{r_c}H$

$$\rho_{\text{eff}} = \frac{3}{8\pi G_4 r_c}H \quad 3H^2 = 8\pi G_4(\rho_m + \rho_{\text{eff}})$$

$$w_{\text{eff}} = \frac{P_{\text{eff}}}{\rho_{\text{eff}}}$$

$$\rho \to 0$$

$$H \to \frac{1}{r_c} \quad w_{\text{eff}} \to -1$$

ΛCDM

c_s

$$
\frac{H^2(z)}{H_0^2} = \Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\mathrm{r},0}(1+z)^4 + \left(1 - \Omega_{\mathrm{m},0} - \Omega_{\mathrm{r},0}\right) f_{\mathrm{DE}}(z) \tag{15}
$$

$\Omega_{\mathrm{m},0}$ $\Omega_{\mathrm{r},0}$ $f_{\mathrm{DE}}(z)$

$$w(z) = -1 + \frac{1}{3}\frac{\mathrm{d}\ln f_{\mathrm{DE}}(z)}{\mathrm{d}\ln(1+z)} \tag{16}$$

$w(z)$

$$1 + w(a) = (1 + w_0)a^3 \left(\frac{3}{1 + 2a^3} \right)^{2/3} \tag{17}$$

$$f_{\mathrm{DE}}(z) = \frac{1 - \tanh\left(\Delta \times \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{1 + \tanh(\Delta \times \log_{10}(1 + z_t))} \tag{18}$$

Δ z_t

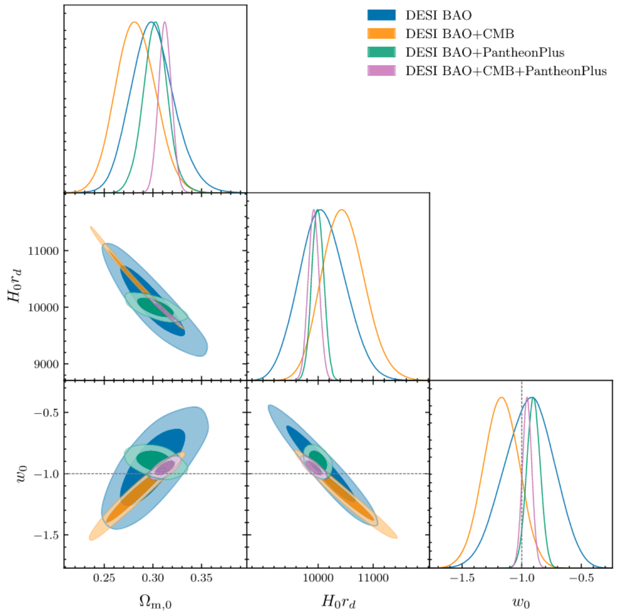
$w(z)$

$$w(z) = -1 - \frac{\Delta}{3\ln(10)}\left[1 + \tanh\left(\Delta \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)\right] \qquad (19)$$

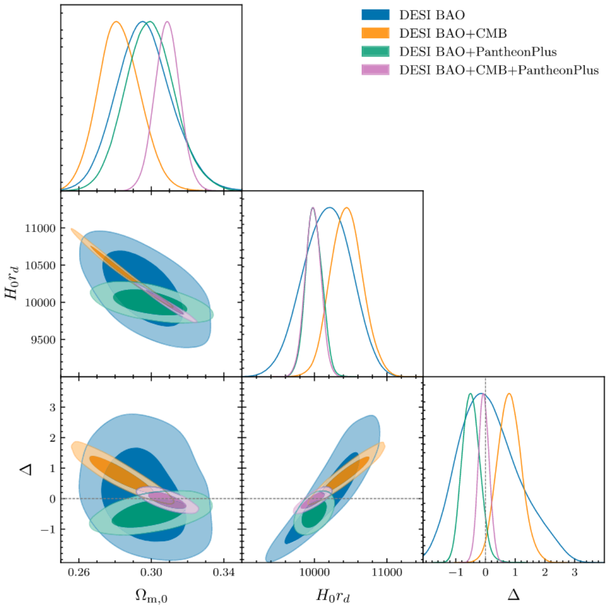
$a \approx 0.7$ w

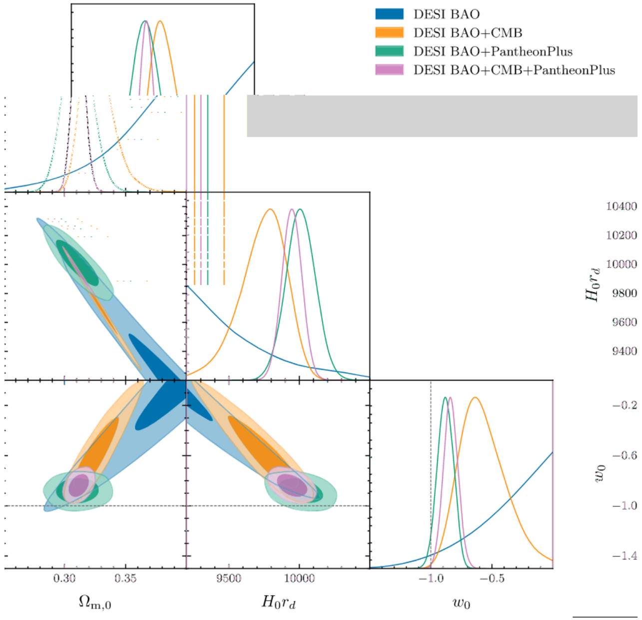
$$w_a = -3.66(1 + w_0) \tag{20}$$

ΛCDM



DESI BAO
DESI BAO+CMB
DESI BAO+PantheonPlus
DESI BAO+CMB+PantheonPlus
$H_0 r_d$
11000
10000
9000
w_0
−0.5
−1.0
−1.5
0.25
0.30
0.35
$\Omega_{\mathrm{m},0}$
10000
11000
$H_0 r_d$
−1.5
−1.0
−0.5
w_0


DESI BAO
DESI BAO+CMB
DESI BAO+PantheonPlus
DESI BAO+CMB+PantheonPlus
$H_0 r_d$
11000
10500
10000
9500
Δ
3
2
1
0
−1
0.26
0.30
0.34
$\Omega_{\mathrm{m},0}$
10000
11000
$H_0 r_d$
−1
0
1
2
3
Δ


DESI BAO
DESI BAO+CMB
DESI BAO+PantheonPlus
DESI BAO+CMB+PantheonPlus
10400
10200
10000
9800
9600
9400
$H_0 r_d$
−0.2
−0.6
−1.0
−1.4
w_0
0.30
0.35
$\Omega_{\mathrm{m},0}$
9500
10000
$H_0 r_d$
−1.0
−0.5
w_0

$$w_0 + \frac{w_{a(1-a)}}{a^2+(1-a)^2}$$

$$(w_0 - w_a) + w_a \exp(1-a)$$

$$w_0 - w_a \ln a$$

$$w_0 + w_a a(1-a)$$

$$w_0 + w_{a(1-a)}$$

Param.	Functional Form	$\Delta\chi^2$
BA	$w_0 + w_a \frac{1-a}{a^2+(1-a)^2}$	-17.3
EXP	$(w_0 - w_a) + w_a \exp(1-a)$	-17.5
LOG	$w_0 - w_a \ln a$	-17.6
JBP	$w_0 + w_a\, a(1-a)$	-13.6
CPL	$w_0 + w_a(1-a)$	-17.4