Phantom appearances of non-phantom cosmologies

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Dark energy

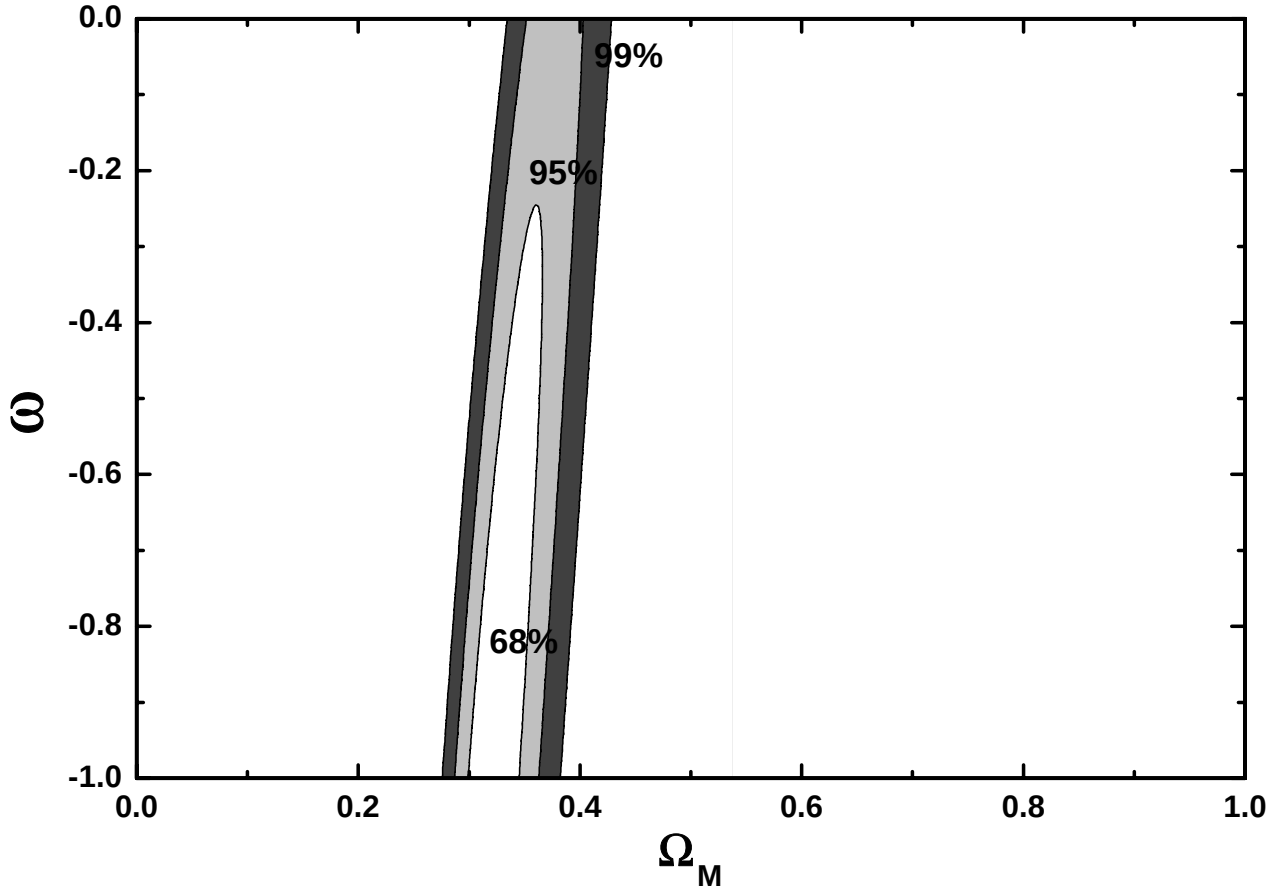
- Accelerated expansion of the universe
- Equation of state

$$p_d = w\rho_d$$

- w > -1: quintessence, Chaplygin gas ...
- w = -1: cosmological term
- w < -1: phantom energy

R.R. Caldwell, Phys. Lett. B545 (2002) 23

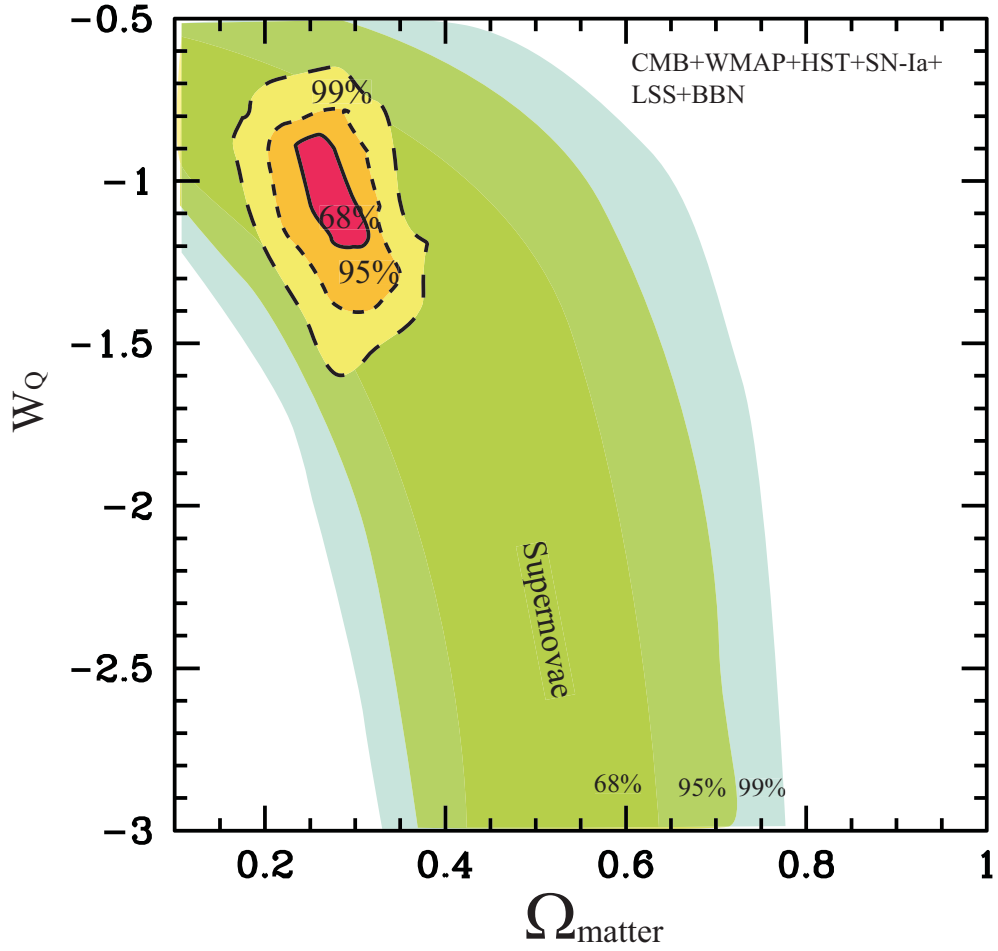
Cosmological observations



Luminosity of galactic clusters in X ray region
+
baryonic mass density measurments
+
HST

J.A.S. Lima, J.V. Cunha, J.S. Alcaniz, Phys. Rev. D68 (2003) 023510

Cosmological observations

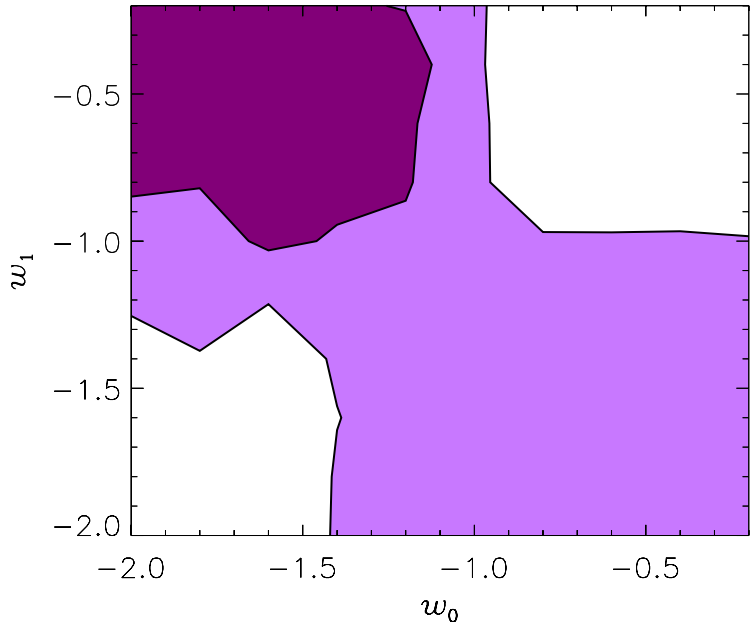


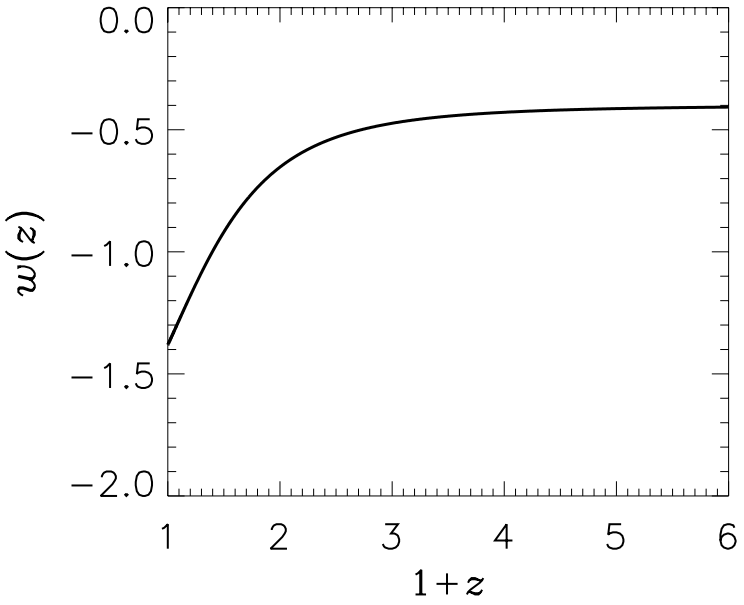
A. Melchiorri, L. Mersini, C.J. Ödman, M. Trodden, Phys. Rev. D68 (2003) 043509

w variable with redshift

S. Hannestad and E. Mortsell, astro-ph/0407259

SNIa+ CMB+LSS





$w(a)=w_0\, w_1(a^q + a_s^q)/(a^q\, w_1+a_s^q\, w_0)$

Phantom energy

- Phantom energy density grows in time
- Singularity reached in finite time – “Big Rip”
- $w = -1-\kappa_0 = \text{const}$

$$H(t) = \frac{H(t_0)}{1 - \frac{3}{2}H(t_0)\kappa_0(t - t_0)}$$

$$a(t) = a(t_0)\left(1 - \frac{3}{2}H(t_0)\kappa_0(t - t_0)\right)^{-\frac{2}{3\kappa_0}}$$

Phantom energy – “Big Rip”

- Decomposition of all bound systems in the universe
- Gravitationally bound systems

$$G(\rho_d + 3p_d)R^3 \quad \text{vs.} \quad GM$$

- Nongravitationally bound systems

$$G(\rho_d + 3p_d)R^3$$

R.R. Caldwell, M. Kamionkowski, N.N. Weinberg, Phys. Rev. Lett. 91 (2003) 071301

Phantom energy - controversies

- Violation of energy conditions
- Problematic microscopic formulation - negative kinetic terms
  - strong phenomenological constraints

S.M. Carroll, M. Hoffman, M. Trodden, Phys. Rev. D68 (2003) 023509

J.M. Cline, S. Jeon, G.D. Moore, hep-ph/0311312

HOWEVER!!

- Observational support

Mimicking phantom energy?

- Is it possible that the non-phantom components of the universe produce the expansion of the universe characteristic of cosmologies with phantom energy?

i.e.

- Is phantom energy a mirrage mimicked by the non-phantom components?

H.Š. Eur. Phys. J. C 36 (2004) 523

Model 1

Two components

Ordinary matter component $\gamma(a) \geq 0$

$$p_m = \gamma(a)\rho_m \qquad \rho_m = \rho_{m,0}\, e^{-3\int_{a_0}^{a}(1+\gamma(a'))\frac{da'}{a'}}$$

Dark energy component → Nonconserved energy-mometum tensor

$$p_d = \eta(a)\rho_d\,, \qquad \eta(a) \geq -1$$

$$(G(t)T^{\mu\nu})_{;\nu} = 0$$

Variable G

Total energy-momentum tensor

Model 1

$$d(G\rho_d) + \rho_m dG + 3G\rho_d(1+\eta(a))\frac{da}{a} = 0$$

Assumption

$$G\rho_d = G_0\rho_{d,0}\left(\frac{a}{a_0}\right)^{-3(1+w(a))} \longrightarrow G = G_0\left(1 - \frac{\rho_{d,0}}{\rho_{m,0}}\frac{\eta - w}{\gamma - w}\left[\left(\frac{a}{a_0}\right)^{-3(w-\gamma)} - 1\right]\right)$$

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi}{3}G(\rho_m + \rho_d)$$

$$G\rho_m = G_0\left(\rho_{m,0} + \rho_{d,0}\frac{\eta - w}{\gamma - w}\right)\left(\frac{a}{a_0}\right)^{-3(1+\gamma)} - G_0\rho_{d,0}\frac{\eta - w}{\gamma - w}\left(\frac{a}{a_0}\right)^{-3(1+w)}$$

$$G(\rho_m + \rho_d) = G_0\left(\rho_{m,0} + \rho_{d,0}\frac{\eta - w}{\gamma - w}\right)\left(\frac{a}{a_0}\right)^{-3(1+\gamma)} + G_0\rho_{d,0}\frac{\gamma - \eta}{\gamma - w}\left(\frac{a}{a_0}\right)^{-3(1+w)}$$

Model 2

- Two components, G nonvariable
- Dark energy

$$p_d = \eta(a)\rho_d\,, \qquad \eta \geq -1$$

- “Ordinary” matter

$$p_m = \gamma(a)\rho_m\,, \qquad \gamma \geq 0$$

- Conservation of total energy-momentum tensor

$$T^{\mu\nu} = T_m^{\mu\nu} + T_d^{\mu\nu}$$

$$d\rho_m + 3\rho_m(1+\gamma(a))\frac{da}{a} =$$

$$-d\rho_d - 3\rho_d(1+\eta(a))\frac{da}{a}$$

Model 2

Assumption $$\rho_d = \rho_{d,0} \left(\frac{a}{a_0} \right)^{-3(1+w(a))}$$

$$\rho_m = \left(\rho_{m,0} + \rho_{d,0} \frac{\eta - w}{\gamma - w} \right) \left(\frac{a}{a_0} \right)^{-3(1+\gamma)} - \rho_{d,0} \frac{\eta - w}{\gamma - w} \left(\frac{a}{a_0} \right)^{-3(1+w)}$$

$$\rho = \left(\rho_{m,0} + \rho_{d,0} \frac{\eta - w}{\gamma - w} \right) \left(\frac{a}{a_0} \right)^{-3(1+\gamma)} + \frac{\gamma - \eta}{\gamma - w} \rho_{d,0} \left(\frac{a}{a_0} \right)^{-3(1+w)}$$

Model 2 - a more detailed formulation

$$\mathcal{L} = \frac{\dot{\phi}^2}{2} + \frac{\dot{\psi}^2}{2} - V(\phi, \psi)$$

$$\begin{aligned} \dot{\phi}^2 + \dot{\psi}^2 &= (1+\eta)\rho_d + (1+\gamma)\rho_m \\ 2V(\phi,\psi) &= (1-\eta)\rho_d + (1-\gamma)\rho_m \end{aligned}$$

Subsequent similar approaches

- S.M. Carroll, A. De Felice and M. Trodden, “Can we be tricked into thinking that w is less than -1?”, astro-ph/0408081
- A. Lue and G.D. Starkman, “How a brane cosmological constant can trick us into thinking that w < -1”, astro-ph/0408246
- C. Csaki, N. Kaloper and J. Terning, “Exorcising w < -1”, astro-ph/0409596

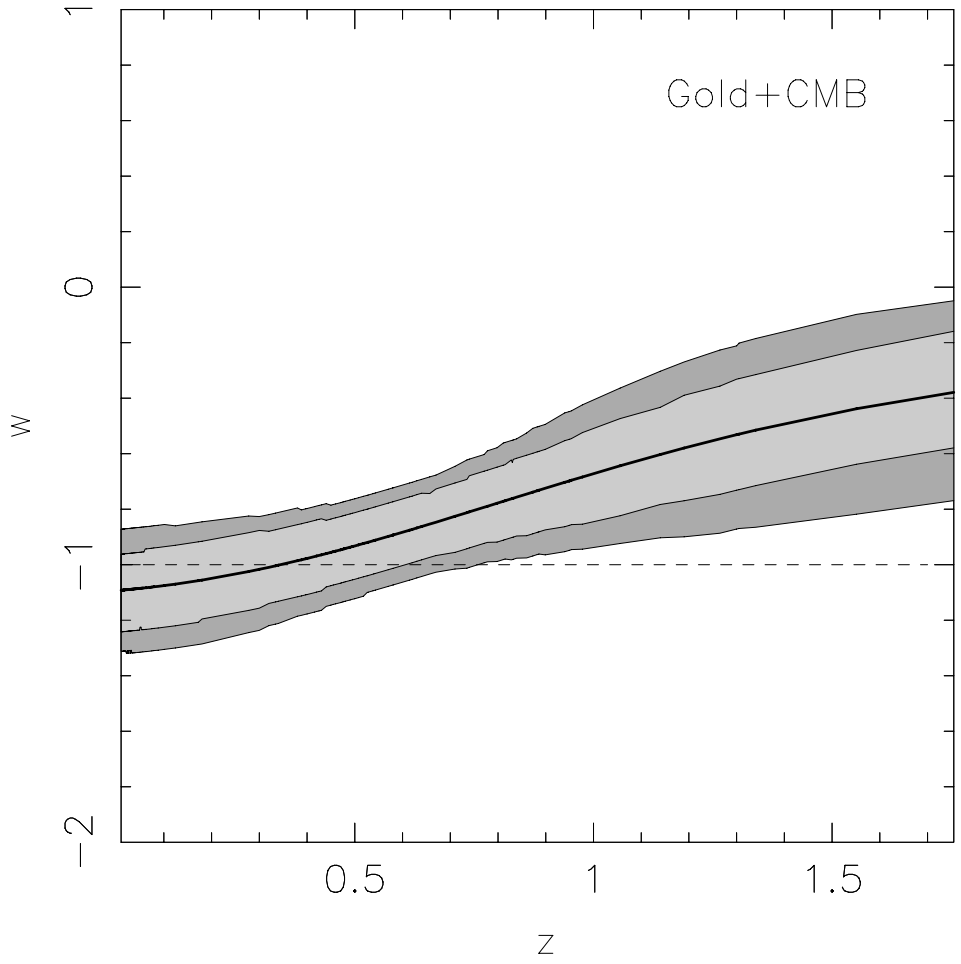
Composition of the universe

- WMAP

  ~ 73 % dark energy
  ~ 23 % dark matter
  ~ 4 % baryonic matter

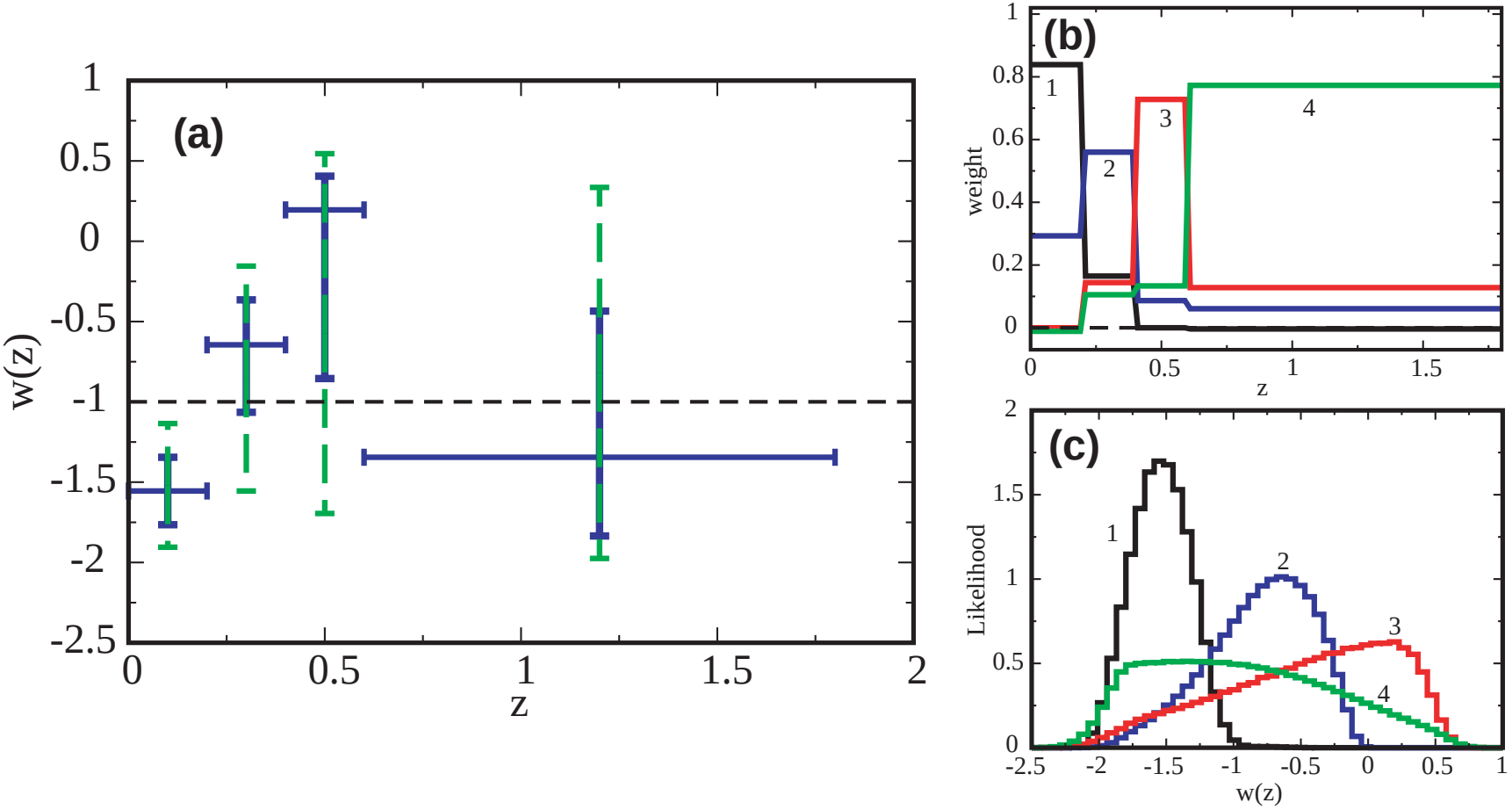
- Accelerated expansion of the universe

Cosmological observations



U. Alam, V. Sahni, A.A. Starobinsky, astro-ph/0403687

Cosmological observations



D. Huterer, A. Cooray, astro-ph/0404062

Energy conditions

- Null energy condition: $\rho + p \geq 0$
- Weak energy condition: $\rho \geq 0 \qquad \rho + p \geq 0$
- Strong energy condition: $\rho + 3p \geq 0 \qquad \rho + p \geq 0$
- Dominant energy condition: $\rho \geq | \, p \, |$

Microscopic models

- Models with negative kinetic term

$$\rho_\phi = -\frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p_\phi = -\frac{1}{2}\dot{\phi}^2 - V(\phi)$$
$$\Rightarrow \quad w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 + V(\phi)}{\frac{1}{2}\dot{\phi}^2 - V(\phi)}$$

- Strong constraints on the applicability of the quantum microscopis models - low effective theory cut-off scale

S.M. Carroll, M. Hoffman, M. Trodden, Phys. Rev. D68 (2003) 023509

J.M. Cline, S. Jeon, G.D. Moore, hep-ph/0311312

Microscopic models

- k-essence models

$$\mathcal{L} = f(\phi)g(X) - V(\phi) \qquad X \equiv \dot{\phi}^2/2$$

A. Melchiorri, L. Mersini, C.J. Ödman, M. Trodden, Phys. Rev. D68 (2003) 043509