Phantom dark energy and cosmological solutions without the Big Bang singularity

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Introduction

Equations of state

$$p = \alpha \rho$$

Possible variants

$\alpha = \frac{1}{3}$	Relativistic matter
$\alpha = 0$	Non-relativistic matter
$-\frac{1}{3} > \alpha > -1$	Quintessence
$\alpha = -1$	Cosmological constant
$\alpha < -1$	Phantom energy

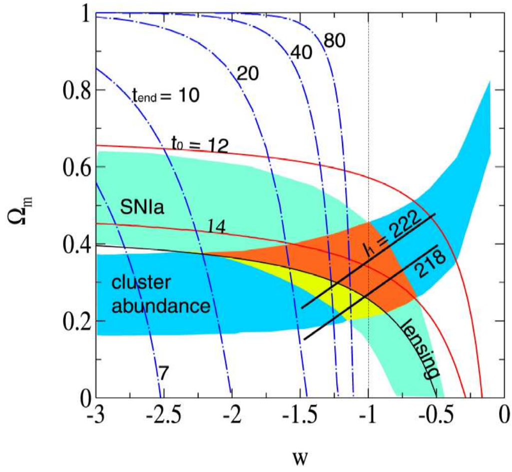


Figure: Caldwell, Kamionkowski, & Weinberg, 2003

Phantom energy models

$$\mathcal{L} = -\frac{\partial_\xi \phi \, \partial^\xi \phi}{2} - V(\phi)$$

$$\rho = -\dot{\phi}^2/2 + V(\phi), \quad p = -\dot{\phi}^2/2 - V(\phi)$$

$$\alpha \equiv \frac{p}{\rho} = \frac{\left(-\dot{\phi}^2/2 - V(\phi)\right)}{\left(-\dot{\phi}^2/2 + V(\phi)\right)}$$

Phantom energy properties for various $V(\phi)$

- If the potential is not very steep (grows slower than $V(\phi) \propto \phi^4$), then α tends to -1, and the density becomes infinite only when $t \to \infty$.
- For steeper potentials a big rip singularity appears even if $\alpha \to -1$.
- Even the parameter α can tend to $-\infty$ for a very steep $V(\phi)$.
- A very steep potential is necessary to provide a constant $\alpha < -1$: for any polynomial potential, for instance, α tends to -1.

The case of $V(\phi) = m^2\phi^2/2$

$$\ddot{\phi} + 3H\dot{\phi} - m^2\phi = 0$$

$$\dot{\phi} \simeq mM_p\sqrt{\frac{2}{3}}, \quad H \simeq \frac{m}{M_p}\frac{\phi}{\sqrt{6}}$$

The inevitability of the phantom field decay

Particle production in the cosmological gravitational field

Batista, Fabris, & Houndjo, 2007

- The universe is filled with a perfect fluid with $\alpha = \mathit{const} < -1$
- The influence of the 'normal' matter on the universe expansion was neglected.
- the conformal time η is chosen so that $\eta < 0$, and the density becomes infinitive when $\eta \to -0$

$$\rho_{norm} = C\eta^{\beta}, \quad \text{where} \quad \beta = \frac{4}{1+3\alpha}$$

The system of cosmological equations for $\alpha = -4/3$

We denote the phantom energy density by ϖ and its initial value by ϖ_0

$$\varpi \propto \eta^{-\frac{2}{3}}$$

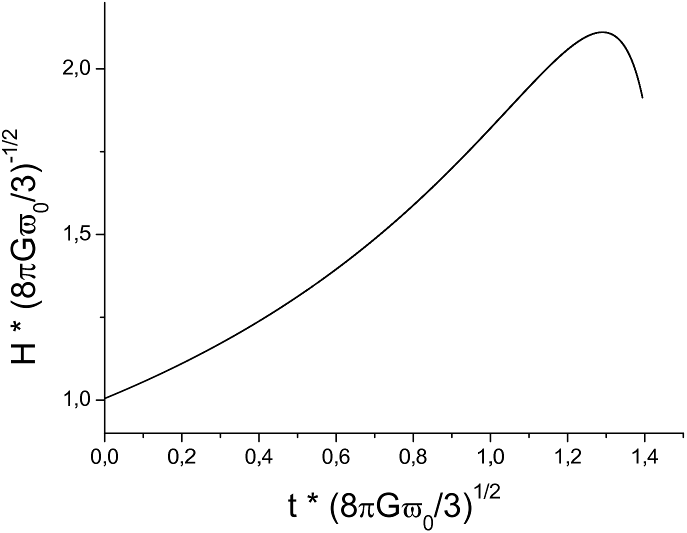
$$\left(\frac{1}{a^2}\frac{da}{d\eta}\right)^2 = \frac{1}{3M_p^2}(\varpi + C\eta^{-\frac{4}{3}}) \quad (1)$$

$$\frac{d(\varpi + C\eta^{-\frac{4}{3}})}{d\eta} = \frac{1}{a}\frac{da}{d\eta}(\varpi - 4C\eta^{-\frac{4}{3}}) \quad (2)$$

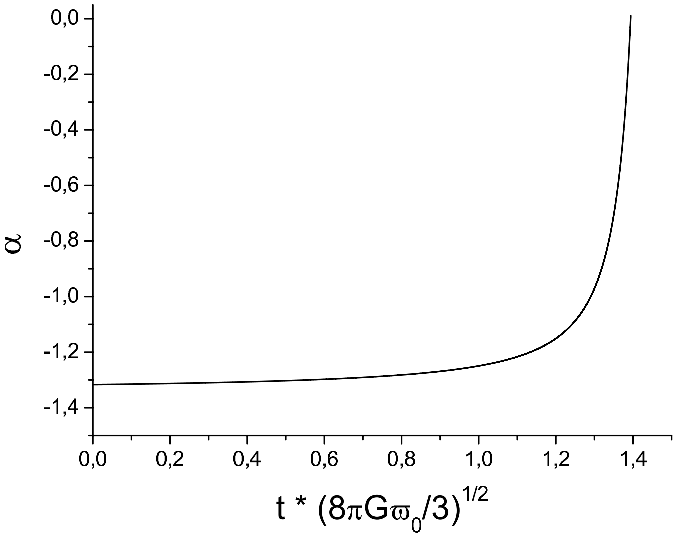
$$dt = a d\eta \quad (3)$$

$$H \equiv \frac{1}{a}\frac{da}{dt} = \frac{1}{a^2}\frac{da}{d\eta}$$

Time dependence of the Hubble constant H



Time dependence of the Hubble of α



The universe properties after the phantom field decay

- It has just passed through the stage of very rapid (at least, exponential) expansion.
- It is flat and homogeneous.
- It is 'normal' matter-dominated.
- The Hubble constant is very large.

It is precisely these physical conditions that existed in our universe ~ 13.7 milliard years ago, just after the inflation. Let us assume that the inflation was caused by the phantom field!

Steady State on the average universe

- The universe leaves inflation being matter-dominated.
- As it expands the density of matter decreases, while the phantom density grows: eventually the universe passes into the phantom-dominated stage.
- The total density and the Hubble constant stop diminishing and begin to increase. Gradually the expansion becomes very fast, leading to an inflation-lake stage.
- The phantom field decays into 'normal' matter.
- The cycle repeats.

Thus, the universe eternally expands, while its density and other physical parameters oscillate over a wide range, never reaching the Plank values.