Phantom Energy: Dark Energy with $w < -1$ Causes a Cosmic Doomsday

Robert R. Caldwell,[1] Marc Kamionkowski,[2] and Nevin N. Weinberg[2]

[1]Department of Physics & Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, New Hampshire 03755, USA

[2]Mail Code 130-33, California Institute of Technology, Pasadena, California 91125, USA

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We explore the consequences that follow if the dark energy is phantom energy, in which the sum of the pressure and energy density is negative. The positive phantom-energy density becomes infinite in finite time, overcoming all other forms of matter, such that the gravitational repulsion rapidly brings our brief epoch of cosmic structure to a close. The phantom energy rips apart the Milky Way, solar system, Earth, and ultimately the molecules, atoms, nuclei, and nucleons of which we are composed, before the death of the Universe in a "big rip."

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Hubble's discovery of the cosmological expansion, crossed with the mathematical predictions of Friedmann and others within Einstein's general theory of relativity, has long sparked speculation on the ultimate fate of the Universe. In particular, it has been shown that if the matter that fills the Universe can be treated as a pressureless fluid, which would be the case for galaxies, then the Universe expands forever (if it has a Euclidean or hyperbolic spatial geometry) or eventually recollapses (if its spatial geometry is that of a 3-sphere). Evidence from supernova searches [1,2] and the stunning cosmic microwave background (CMB) results from balloon and ground experiments [3–8] and now from Wilkinson Microwave Anisotropy Probe (WMAP) [9,10] that indicate an accelerating cosmological expansion show that this simple picture is not enough; the Universe additionally consists of some sort of negative-pressure dark energy.

The dark energy is usually described by an "equation-of-state" parameter $w \equiv p/\rho$, the ratio of the spatially homogeneous dark-energy pressure p to its energy density ρ. A value $w < -1/3$ is required for cosmic acceleration. The simplest explanation for dark energy is a cosmological constant, for which $w = -1$. However, this cosmological constant is 120 orders of magnitude smaller than expected from quantum gravity. Thus, although we can add this term to Einstein's equation, it is really only a placeholder until a better understanding of this negative pressure arises. Another widely explored possibility is quintessence [11–16], a cosmic scalar field that is displaced from, but slowly rolling to, the minimum of its potential. In such models, the equation-of-state parameter is $-1 < w < -1/3$, and the dark-energy density decreases with scale factor $a(t)$ as $\rho_Q \propto a^{-3(1+w)}$.

Figure 1 shows constraints to the w-Ω_m parameter space (where Ω_m is the pressureless-matter density in units of the critical density) from the cluster abundance, supernovae, quasar-lensing statistics (see Refs. [17,18] and references therein), and the first acoustic peak in the CMB power spectrum (values taken from Ref. [10]). As the figure shows, w seems to be converging to $w = -1$.

But what about $w < -1$? Might the convergence to $w = -1$ actually be indicating that $w < -1$? Why restrict our attention exclusively to $w \geq -1$? Matter with $w < -1$, dubbed "phantom energy" [19], has received increased attention among theorists recently. It certainly has some strange properties. For example, the energy density of phantom energy increases with time. It also violates the dominant-energy condition [20,21], a cherished notion that helps prohibit time machines and wormholes. However, it is hard to see how time machines and wormholes would arise with phantom energy. Although

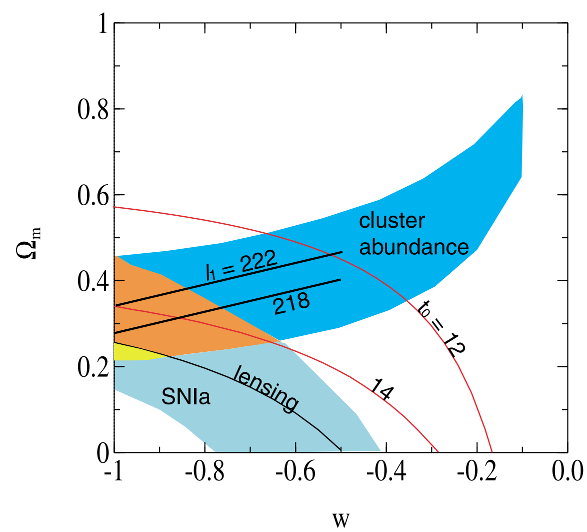

FIG. 1 (color). Current constraints to the w-Ω_m parameter space. The red solid curves show the age (in Gyr) of the Universe today (assuming a Hubble parameter $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$). The light shaded regions are those allowed (at 2σ) by the observed cluster abundance and by current supernova measurements of the expansion history. The dark orange shaded region shows the intersection of the cluster abundance and supernova curves, additionally restricted (at 2σ) by the location of the first acoustic peak in the cosmic-microwave-background power spectrum and quasar-lensing statistics.

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sound waves in quintessence travel at the speed of light, it does not automatically follow that disturbances in phantom energy must propagate faster than the speed of light; in fact, there are already several scalar-field models for phantom energy in which the sound speed is subluminal [19,21–25]. It is true that these models feature unusual kinetic terms in their Lagrangians, but such terms may arise in supergravity [26] or higher-derivative-gravity theories [27]. Theorists have also discussed stringy phantom energy [28] and brane-world phantom energy [29]. Connections with the deSitter–conformal field theory correspondence have also been made [30]. To be sure, phantom energy is not something that any theorist would have expected; on the other hand, not too many more theorists anticipated a cosmological constant. Given the limitations of our theoretical understanding, it is certainly reasonable to ask what empirical results have to say.

In Fig. 2 we generalize the analysis of cosmological constraints to a parameter space that extends to $w < -1$. As indicated here, there is much acceptable parameter space in regions with $w < -1$; see also Refs. [32,33]. With certain prior assumptions, the best fit is actually at $w < -1$.

As we now show, if $w < -1$ persists, then the fate of the Universe is quite fantastic and completely different from the possibilities previously discussed. To begin, let us review these other fates. In a flat or open Universe *without* dark energy, the expansion continues forever, and the horizon grows more rapidly than the scale factor; the Universe becomes colder and darker, but with time the comoving volume of the observable Universe evolves so that the number of visible galaxies grows. If the expansion is accelerating, as a consequence of dark energy with $-1 \leq w < -1/3$, then the expansion again continues forever. However, in this case, the scale factor grows more rapidly than the horizon. As time progresses, galaxies disappear beyond the horizon, and the Universe becomes increasingly dark. Still, structures that are currently gravitationally bound, such as the Milky Way and perhaps the local group, remain unaffected. Thus, although extragalactic astronomy becomes less interesting, galactic astronomy can continue to thrive [33].

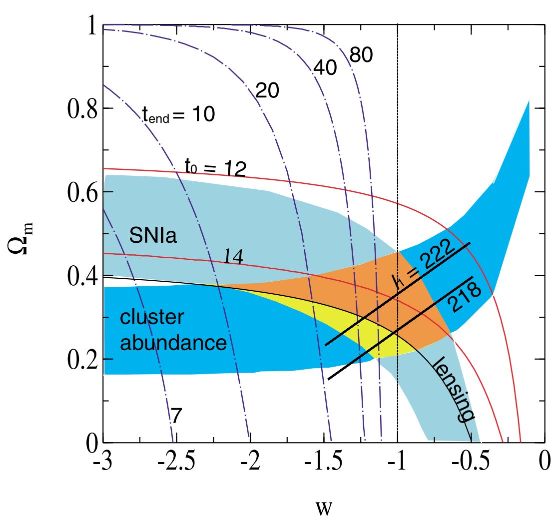

FIG. 2 (color). Same as in Fig. 1, except extended to $w < -1$. Here, the blue dot-dashed curves show for phantom-energy ($w < -1$) models the time (in Gyr) remaining in the Universe (assuming a Hubble parameter $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$).

With phantom energy, the Friedmann equation governing the time t evolution of the scale factor $a(t)$ becomes $H^2 \equiv (\dot{a}/a)^2 = H_0^2[\Omega_m/a^3 + (1-\Omega_m)a^{-3(1+w)}]$, where H_0 is the Hubble parameter, and the dot denotes a time derivative. If $\Omega_m \simeq 0.3$, then the Universe is already dark-energy–dominated, and for $w < -1$ it will become increasingly dark-energy–dominated in the future. We thus approximate the subsequent evolution of the scale factor by neglecting the first term on the right-hand side. Doing so, we find that the scale factor blows up in a time $t_{\mathrm{rip}} - t_0 \simeq (2/3)|1+w|^{-1}H_0^{-1}(1-\Omega_m)^{-1/2}$ from the current time t_0. For example, for $w = -3/2$ and $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, the time remaining before the Universe ends in this "big rip" [30] is 22 Gyr.

As in a cosmological-constant Universe, the scale factor grows more rapidly than the Hubble distance H^{-1} and galaxies will begin to disappear beyond the horizon. With phantom energy, the expansion rate H grows with time, the Hubble distance decreases, and so the disappearance of galaxies is accelerated as the horizon closes in on us. More intriguing is that the increase in the dark-energy density will ultimately begin to strip apart gravitationally bound objects.

To first approximation, bound objects such as stars, globular clusters, galaxies, and galaxy clusters are like small beads swimming through the rarified cosmological fluid. They have detached from the Hubble flow and stabilized, so that their internal dynamics are independent of the cosmic expansion. Of course, there is some dark energy present today in the solar system, for example, since the dark energy is effectively uniform on such "small" scales. As an ultralight scalar field, quintessence dark energy fluctuates only on horizon-size scales. And a cosmological constant is, naturally, constant everywhere. The present-day abundance of dark energy in bound objects is too small to have an effect on the internal dynamics. Nor will there be an effect at later times for dark energy with $w \geq -1$, since the density remains constant or decays in the future. For phantom energy, with $w < -1$, the density grows in the future. And since the phantom fields are similarly uniform on small scales, the abundance of phantom energy within a bound object actually grows with time, thereby exerting a growing influence on the internal dynamics. Ultimately, the repulsive phantom energy overcomes the forces holding the object together, and rips it apart.

According to general relativity, the source for the gravitational potential is the volume integral of $\rho + 3p$. So, for example, a planet in an orbit of radius R around a star of mass M will become unbound roughly when $-(4\pi/3)(\rho + 3p)R^3 \simeq M$. With $w \geq -1$, $-(\rho + 3p)$ is decreasing with time, so if $-(4\pi/3)(\rho + 3p)R^3$ is smaller than M today, then it will remain so ever after. Thus, any system that is currently gravitationally bound (e.g., the solar system, the Milky Way, the local group, galaxy clusters) will herafter remain so.

With phantom energy, $-(\rho + 3p)$ increases, and so at some point in time every gravitationally bound system will be dissociated. With the time evolution of the scale factor and the scaling of the phantom-energy density with time, we find that a gravitationally bound system of mass M and radius R will be stripped at a time $t \simeq P\sqrt{2|1 + 3w|}/[6\pi|1 + w|]$, where P is the period of a circular orbit around the system at radius R, before the big rip (see Table I). Interestingly, this time is independent of H_0 and Ω_m.

Thus, for example, for $w = -3/2$, the interval is $t \simeq 0.3P$ before the end of time. In this case, clusters will be stripped roughly a billion years before the end of time. In principle, if w were sufficiently negative, the Andromeda galaxy would be torn from the local group before it could fall into the Milky Way; however, given current upper limits to $-w$, this is unlikely. For $w = -3/2$, the Milky Way will get stripped roughly 60×10^6 years before the big rip. Curiously, when this occurs the horizon will still be $\sim$70 Mpc, so there may still be other observable galaxies that we will also see stripped apart (although given the time delay from distant objects, we will see the Milky Way destroyed first). A few months before the end of time, the Earth will be ripped from the Sun, and $\sim$30 min before the end the Earth will fall apart. Similar arguments also apply to objects bound by electromagnetic or strong forces. Thus, molecules and then atoms will be torn apart roughly 10^{-19} s before the end, and then nuclei and nucleons will get dissociated in the remaining interval. In all likelihood, some new physics (e.g., spontaneous particle production or extradimensional, string, and/or quantum-gravity effects) may kick in before the ultimate singularity, but probably after the sequence of events outlined above.

TABLE I. The history and future of the Universe with $w = -3/2$ phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First three minutes	Light elements formed
$\sim 10^5$ yr	Atoms formed
$\sim$1 Gyr	First galaxies formed
$\sim$15 Gyr	*Today*
$t_{\rm rip}$ − 1 Gyr	Erase galaxy clusters
$t_{\rm rip}$ − 60 Myr	Destroy Milky Way
$t_{\rm rip}$ − 3 months	Unbind solar system
$t_{\rm rip}$ − 30 min	Earth explodes
$t_{\rm rip} - 10^{-19}$ s	Dissociate atoms
$t_{\rm rip}$ = 35 Gyr	Big rip

The end of structure, from cosmic, macroscopic scales down to the microscopic, leads us to note that our present epoch is unique from the viewpoint that at no other time are nonlinear structures possible. When the phantom energy becomes strong enough, gravitational instability no longer works and the Universe becomes homogeneous. Eventually, individual particles become isolated: points separated by a distance greater than $3\delta t(1 + w)/(1 + 3w)$ at a time $t_{\rm rip} - \delta t$ cannot communicate before the big rip. Therefore, the dominance of the phantom energy signals the end of our brief era of cosmic structure which began when the nonrelativistic matter emerged from the radiation. In such a Universe, certain cosmic questions have new significance. The "why now?" question in a cosmological-constant universe asks why our epoch happens to be so close to the time at which Λ comes to dominate. On the infinite timeline of cosmic history it seems unlikely that these two events would be so close together unless linked by some common phenomenon. If the timeline were finite, as in the case of the big rip, the proximity of these two events would be much less enigmatic. In fact, if we consider the existence of nonlinear structure as a precondition for the present epoch, then unlike the Λ universe, only a narrow range of times satisfies this demand. Nonlinear structure did not exist in the distant past, and will cease to exist in the near future when the big rip tears everything apart. Hence, it is natural to find ourselves living close to the onset of acceleration if the structure is soon destroyed and the Universe does not survive much longer afterwards [30]. A big rip renders the "why now?", or question of cosmic coincidence, irrelevant.

The current data indicate that our Universe is poised somewhere near the razor-thin separation between phantom energy, cosmological constant, and quintessence. Future work, and the longer observations by WMAP, will help to determine the nature of the dark energy. In the meantime we are intrigued to learn of this possible new cosmic fate that differs so remarkably from the recollapse or endless cooling considered before. It will be necessary to modify the adopted slogan among cosmic futurologists—"Some say the world will end in fire, Some say in ice" [36]—for a new fate may await our world.

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