Inflaton vacuum fluctuations as dark matter and the potential $V(\phi)$ as dark energy

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Abstract

It is shown, using quantum field theory in curved spacetime, how the expansion of the universe during inflation produces an aggregate of particles and inflaton vacuum fluctuations at a temperature of $5 \times 10^{17}$ GeV and dense enough to make reheating unnecessary. The standard calculation that predicts the Hubble parameter has to be way smaller than the Planck energy is shown to be fallacious: it applies the conservation of the perturbative curvature $\mathcal{R}$ to a single inflaton fluctuation when it should be applied to the energy density contrast of an aggregate. The quantum inflaton fluctuations $\varphi$ are with respect to the classical value $\phi_0$ of the inflaton field $\phi = \phi_0 + \varphi$. Fluctuations $\varphi$ that have grown to the size of the horizon, or a pair of virtual particles that are separated by a distance the length of the horizon, are forced to become real and take energy from the potential $V(\phi_0)$. The slowing down of inflation is due to the eventual domination of the continuously being created radiation over the decreasing inflaton potential $V(\phi_0)$. It is not necessary at all for the potential $V(\phi_0)$ to go to zero. Since there is no need for reheating the inflaton field $\phi$ does not couple to matter (except gravitationally). After inflation, the fluctuations $\varphi$ quickly cool down and can be described as dark matter. Now the inverse process begins to occur. Inflaton fluctuations $\varphi$ that exited the horizon during inflation begin reentering it after inflation’s end. Then they are again causally connected and have a probability of undergoing the inverse of the quantum process they underwent before and give their energy back to the potential $V(\phi_0)$. The $\varphi$ fluctuations are turning into $V(\phi_0)$, which acts as dark energy and accelerates again the expansion of the universe. The disintegration of a perturbation is a quantum jump of cosmological size.

Key words: dark matter - dark energy - vacuum fluctuations - inflation - reheating

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1 Introduction.

Understanding dark matter as a modification of Newtonian dynamics suffered a blow due to the use of gravitational lensing. There are related covariant models that modify general relativity, sometimes with the addition of a scalar field, so that gravity acts differently on large scales and mimics dark matter. The recent observation of gravitational waves produced by the binary neutron merger in the NGC 4993 galaxy, simultaneously with the observation of a short gamma-ray burst, has made it possible to conclude that the speeds of light and of gravitational waves are the same up to one part in $10^{15}$. As a result extraordinarily tight constraints have been applied to the Horndeski and beyond-Horndeski theories that were designed with dark matter (and sometimes dark energy) in mind. An alternative explanation for dark matter are particles. Much effort is being done in this area in laboratories and through a variety of types of astronomical observations. So far the results have been on the negative. The conclusion would be, not that these models have been disproved, since there is not enough evidence to reach that conclusion, but that our limited knowledge certainly encourages fundamental theoretical work.

Here we take a different approach to the problem of dark matter. We go back to the inflationary epoch with the hope that it can shed light on the origin of dark matter. As usual, we are going to assume that the inflationary epoch is driven by the inflaton, a quantum scalar field $\phi$ with a potential energy density $V(\phi)$. The pressure $p$ and density $\rho$ for this field in an homogenous and isotropic universe are given by

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi) \quad \text{and} \quad p = \frac{\dot{\phi}^2}{2} - V(\phi).$$

(1)

The inflaton $\phi(t, x)$ is the sum of two terms: the classical field $\phi_0(t)$, which is a solution of the equations of motion generated by the Lagrangian density $\mathcal{L}$ of the system, and the quantum perturbative field $\varphi(t, x)$:

$$\phi(t, x) = \phi_0(t) + \varphi(t, x).$$

(2)

Here $\phi_0(t) = \langle 0 | \phi(t, x) | 0 \rangle$, that is, $\phi_0$ is the vacuum expectation value of the quantum field $\phi$. During the inflationary epoch the value of the Hubble horizon $H^{-1}$ remains fairly constant except near the epoch’s end. We assume a very small kinetic energy term, so the inflaton acts as a perfect fluid with an equation of state $\rho = -p$. The two Friedmann equations that govern the inflationary expansion (with no space curvature nor cosmological constant) are:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho}{3}, \quad -3\ddot{a}/a = 4\pi G (\rho + 3p).$$

(3)

One concludes that the solution is a fast-growing exponential $a(t) = \exp(tH)$, where $H = (8\pi G \rho/3)^{1/2}$, the Hubble parameter, is approximately constant. It is assumed that $V(\phi_0)$ has a small slope, so that the value of $\phi_0$ is almost constant. Notice that the potential $V(\phi_0)$ with the argument $\phi_0$, the classical part of $\phi$, acts as a repulsive cosmological constant.

In a Minkowski spacetime there are always vacuum fluctuations forming from the quantum vacuum, but they soon disappear. But in a Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime the existence of a Hubble horizon $H^{-1}$ results in the formation of a bath of Gaussian fluctuations at Gibbons-Hawking temperature $T = H/2\pi$. Most of these
fluctuations are virtual, but the ones that are larger than the horizon do not have enough
time to disappear and thus become real. They grow in size and acquire energy and become
seeds for gravitational accretion of the dark matter and particles that populate the universe.
It is usually assumed that the strength of an inflaton fluctuation determines the strength of
an energy density contrast $\delta \rho/\rho$ later on, after inflation.

We shall calculate the temperature and density of the particles and inflaton vacuum
fluctuations produced from the vacuum during inflation using standard results of quantum
field theory in curved spacetime. [16] It turns out that during inflation there are no individual
fluctuations to speak of; instead, what is present is a thermal bath of fluctuations at a
temperature of about $5 \times 10^{17}$ GeV, one such bath created every $e$-folding. Furthermore, the
bath is not simply made up of inflaton fluctuations, but of all kinds of elementary particles.
With all this matter there is no need to have a reheating period at the end of inflation. These
results rise another question immediately: where are today all these inflaton fluctuations?
The thing is, they would be an excellent candidate for dark matter. Since reheating is not
necessary anymore, we can assume the inflaton does not interact with any other particle
(except gravitationally), just like dark matter does not. Also, the amounts of dark matter
and normal matter would be comparable, as they are observed to be.

In Section 2 we will discuss in more detail the topic of the smallness of the universe’s
density fluctuations and of the inflaton fluctuations during inflation. In Section 3 we calculate
the quantity of particles created from the vacuum during inflation using the temperature of
the thermal bath at the cosmological event horizon and its spectral radiance. In Section
4 we study the transition between inflation and the rest of the Big Bang, a period usually
associated with reheating and preheating.

In Section 5 we give a summary of the paper and also discuss an interesting offshoot of the
idea that dark matter is made up of inflaton fluctuations. Briefly, the idea there examined
is as follows: Although both inflaton fluctuations and elementary particles are created from
the quantum vacuum, their development in the FLRW universe is quite different. The size of
elementary particles is fixed, while the inflaton fluctuations grow proportionally to the scale
factor. If a perturbative inflaton’s wavefunction is larger than the horizon $H^{-1}$ it becomes
impossible, due to causality, for the perturbation to disappear back into the vacuum. Now,
the fluctuation has at least a size $H^{-1}$, maybe more (perhaps when created it was larger
than the horizon). It has to become real instantaneously, which implies that the energy it
needs has to be supplied to it locally. This energy must come from the inflaton potential
$V(\phi_0)$, which must then be locally very slightly modified and weakened. The potential is
imprinted with a negative of the shape of the fluctuation. The fluctuation remains outside
of the horizon for some time and eventually, some time after the end of inflation, it goes
back inside due to the slowing down of the cosmic expansion and the increase in size of
the horizon. We shall argue in last section that, once the fluctuation reenters the horizon,
it can disintegrate (as causality does not forbid it to do so anymore), and return to the
background inflaton potential $V(\phi_0)$. This process is a cosmological-size quantum transition,
and is equivalent to a bit of dark matter turning into gravitationally repulsive material,
or dark energy. With time more and more fluctuations disintegrate and strengthen the
background potential $V(\phi_0)$, until it again dominates over inflaton fluctuations and matter
particles, and the expansion begins to accelerate.
2 Some implications of the large particle and inflaton fluctuation production from the quantum vacuum.

In the previous section we introduced the idea that dark matter may be composed of the same inflaton fluctuations that are believed nowadays to be the source of the anisotropy observed in our universe. Usually this idea would be rejected right away based on the consideration that the inflaton fluctuations should have an intensity of the same order of magnitude as the energy density contrasts \( \frac{\delta \rho}{\rho} \) of the later universe, that is, of the order of \( 10^{-5} \). Since we know that dark matter makes up about 27\% of the energy density of the universe, if dark matter were made from inflaton fluctuations there would exist far too little of it today. However, if we believe that during inflation large amounts of dark and normal matter were created, then what can be concluded is that the small fluctuations during inflation are simply energy density contrasts \( \frac{\delta \rho}{\rho} \) of an aggregate of inflaton fluctuations and normal matter.

In next section we are going to show, using the theory of quantum fields in curved spacetime, that there is a large particle and fluctuation production from the vacuum during inflation. We shall call it "vacuum production", for the sake of brevity. Since the temperature of the resulting thermal bath is proportional to the horizon \( H \), we need to study what are the possible values of \( H \) in a slow-roll regime. To keep the exposition short, we assume only one inflaton scalar field and only one type of potential, the large field or chaotic inflation potential \( V(\phi_0) = \frac{1}{2} m^2 \phi_0^2 \).

In order for the inflaton to be in the slow-roll regime, it is well-known that the two inequalities

\[
\epsilon = \frac{M_P^2}{16\pi} \left( \frac{V'}{V} \right)^2 \ll 1, \quad \eta = \frac{M_P^2}{8\pi} \left| \frac{V''}{V} \right| \ll 1,
\]

must be satisfied. (We are using the symbol \( M_P \equiv G^{-1/2} \), the Planck mass.) For the chosen potential both conditions are equivalent to

\[
\epsilon = \eta = \frac{M_P^2}{4\pi \phi_0^2} \ll 1.
\]

Let us choose \( \epsilon = \eta = 1/120 \), a small number to be further justified below. Then

\[
\phi_0/M_P = \sqrt{120/4\pi} = 3.1,
\]

and thus the classical field \( \phi_0 \) has to take super-Planckian values. The particular choice of \( \epsilon = \eta = 1/120 \) is to obtain 60 e-foldings for the inflationary period of inflation. [17] For our choice of potential the number of e-foldings is given by

\[
N \approx 2\pi \phi_0^2/M_P^2 = 60.
\]

Since the energy density should be small enough that the system does not enter the quantum gravity regime, the condition \( \frac{1}{2} m^2 \phi_0^2 \ll M_P^2 \) must also be fulfilled. For the value of \( \phi_0/M_P \) above this inequality leads to \( 4.8m^2/M_P^2 \ll 1 \). As a working hypothesis let us take \( 4.8m^2/M_P^2 \) to be one hundred times smaller than 1, in which case the value of \( m \) comes out
to be $m/M_P = 1/22$. The value of $H$ compatible with this value of $m/M_P$ can be found from Friedmann’s equation (3) for $H$:

$$H_{M_P} = \sqrt{\frac{8\pi G}{3 \cdot 2} \frac{m}{M_P}} = 2.0 \cdot \frac{1}{22} \cdot 3.1 = 0.28$$

(4)

This is a remarkable result because it puts the value of $H$ at $M_P$ or a few orders of magnitude smaller.

However, the previous calculation is usually mistrusted because it is possible to calculate $m$ and $H$ with precision on the basis of the primordial scalar amplitude $\Delta_R$, a quantity that can be measured with accuracy from the anisotropies of the cosmic microwave background radiation, and the resulting values for $m$ and $H$ are much smaller than the values given by the above calculation. Let us discuss this other calculation.

Soon after inflation was introduced it was noticed that there was a fundamental quantity, the curvature perturbation $R$ in the comoving reference frame, which has a constant value from the time it exits the horizon during the inflationary epoch, until the time it reenters it during the modern universe. [18, 19] This quantity $R$ allows to correlate the size of fluctuations during the inflationary period with the size of fluctuations in the modern universe. Its value, defined in terms of the power spectrum, [20] is $\Delta_R = 5.0 \times 10^{-5}$, quoting significant figures common to those reported by the different groups. This value of the perturbative space curvature can be used to find the mass parameter $m$ of the potential $V(\phi_0)$ we have chosen. The result is: [21]

$$\frac{m}{M_P} = \sqrt{\frac{3}{4\pi} \cdot \frac{\pi}{N_e} \cdot \Delta_R} = 1.3 \times 10^{-6},$$

where we are taking $N_e = 60$, $N_e$ being the number of $e$-foldings. Armed with this value for $m$ it is possible to immediately find $H$’s value using a Friedmann equation (3):

$$H_{M_P} = \sqrt{\frac{8\pi}{3 \cdot 2} \frac{m}{M_P} \cdot \frac{\phi_0}{M_P}} = 8.2 \times 10^{-6}.$$  

(5)

The resulting values are far smaller than those of the previous calculation. But this calculation is predicated on the near-emptiness of the universe during the inflationary regime. If we assume that the inflationary universe is continuously creating large quantities of particles and fluctuations the smallness of $\Delta_R$ simply would refer to the smallness of the energy density contrast $\delta \rho/\rho$ during inflation, which is a statement on the degree of instability of the inflationary fluid. If one assumes that there is only one inflaton fluctuation, then the smallness of $\Delta_R$ is a statement on the dynamical development of the inflationary process, a completely different kind of information. Thus this calculation has been improperly applied.

The origin of the observed anisotropies would be thermal fluctuations in the bath of particles that have resulted from quantum vacuum production.
3 Calculation of the quantity of particle production from the vacuum during inflation.

In the quantum vacuum of Minkowski spacetime, particles are constantly appearing and disappearing, but it is impossible for them to become real since the principle of conservation of energy forbids it. But in a spacetime that possesses a causal horizon, such as the FLRW, if a pair of virtual particles become separated by a distance larger than the horizon (the Hubble horizon in this case), they will not have time to reunite and are therefore forced to become real particles. Similarly, if a fluctuation of the inflaton field \( \phi \) becomes equal or larger than the Hubble horizon, the causal microprocesses necessary to take the fluctuation back into nothingness do not have enough time to act and the fluctuation necessarily has to remain in existence. The energy \( \Delta E \) available for vacuum production is given by the uncertainty principle \( \Delta E \Delta t \approx 1 \), and one gets the approximate result \( \Delta E \approx \Delta t^{-1} \approx H \).

It is to be expected that this energy \( \Delta E \) has to come from the potential energy \( V(\phi_0) \), so that the value of \( \phi_0 \) has to change by a small amount \( \delta \phi_0 = \phi'_0 - \phi_0 \), where \( \phi'_0 \) differs from \( \phi_0 \) only locally. An energy \( \Delta E \) has become available and equal the integral over space of \( V(\phi_0) - V(\phi'_0) \). We assume that during inflation this happens constantly and ubiquitously so that the background field remains basically homogeneous, of the form \( \phi_0(t) \).

There is a large literature on thermal radiation baths present in accelerated frames and gravitational fields. [16] Under some circumstances these particles should become real, the best well-known example being that of the radiation emitted by a black hole. It was observed in [22] that a de Sitter spacetime with a repulsive cosmological constant \( \Lambda \) contains a cosmological event horizon with a particle thermal bath. Gibbons and Hawking succeeded in finding the temperature of the particle bath in terms of the surface gravity \( \kappa \) of the cosmological event horizon as seen by an observer stationed there. Their result was

\[
T = \frac{\kappa}{2\pi} = \sqrt{\frac{\Lambda}{3}/2\pi} = \frac{H}{2\pi}.
\]  

(6)

If instead one assumes that inflation is caused by the inflaton field, then, according to a Friedmann equation [3], the Hubble horizon would be given by \( H^2 = 8\pi G \rho / 3 \). One of the branches of a de Sitter spacetime is equivalent to a FLRW spacetime with an increasing exponential scale factor. Since both expansions are physically equivalent we conclude that the temperature at the cosmological event horizon must given by \( T = \sqrt{8\pi G \rho / 3}/2\pi \).

Physical consequences of the thermodynamics of cosmological event horizons (and other types of horizons, too) have been studied in [23]. One very natural idea put forward there is that the energy of the radiation produced from the vacuum must come from the source of the gravitational fields or accelerations involved in the creation of the horizons. If we assume that the accelerating expansion of the universe is due to the inflaton field, then the energy of this field must be weakened by vacuum production. This situation was studied in detail in [24] and the dynamic development of an accelerated expanding universe was described. Here we are not going to concern ourselves with the time dependence of the Hubble horizon. We are going to assume the slow-roll regime and take the horizon \( H \) (and thus the temperature) to be constant.

We want to know how much radiation is being created per unit volume per unit time during inflation. We assume that there is a thermal bath at the cosmological event horizon,
at a temperature \( T \) given by formula (5) above. We take the event horizon to have a spherical shape with diameter \( H^{-1} \). In the surface of the sphere we take a small area \( dA \) and calculate the energy flux leaving the sphere through that area (for a certain type of particle) using the spectral radiance:

\[
B = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT - 1)} = \frac{\omega^3}{2\pi^2} e^{\omega/T - 1},
\]

where the last expression on the right is in natural units, \( h = c = k = 1 \). The spectral power flux \( P_\omega \) passing through the small area \( dA \) is

\[
P_\omega dA = dA \int_0^{\pi/2} \sin \theta \cos \theta d\theta \int_0^{2\pi} d\phi B = \pi B dA,
\]

a calculation done using "Lambert’s cosine law", since the flux leaving the sphere through \( dA \) has a \( 2\pi \text{sr} \) spread. To find the total energy density flowing out of the sphere we have to integrate over the surface of the sphere (which is done simply by multiplying by its area \( A = 4\pi(H^{-1}/2)^2 \)), and over all possible frequencies using the differential \( d\nu = d\omega/2\pi \):

\[
\Phi = A \int_0^\infty P_\omega d\omega / 2\pi.
\] (7)

In Refs. [22, 24] it is assumed that the Hubble horizon of an exponentially accelerated expansion is a true cosmological event horizon and that all the particles in the thermal bath do become real, in which case the upper limit of the definite integral \( \Phi \) should be \( \infty \). However, there does not seem to be a mandatory reason for the virtual particles with wavevectors \( k/a > H, \) which have not exited the horizon, to become real. They can, instead, go back to the vacuum within the period allowed by the uncertainty principle, so that the upper limit in \( \Phi \) should be \( H \). In any case, taking infinity instead of \( H \) as the upper limit of the integral only increases its value by 13%. We will use infinity as the upper limit simply because it results in an exact Bose-Einstein integral. To perform the integration in \( \Phi \) we proceed as follows:

\[
\Phi = A \int_0^\infty \frac{\omega^3 d\omega}{e^{\omega/T} - 1} = AT^4 \int_0^\infty \frac{x^3 dx}{e^x - 1} = \frac{\pi T^2}{240}.
\]

This is the flux of energy flowing out of the sphere.

By the symmetry of the physical problem the flux of energy leaving the sphere has to equal the flux of energy entering it. The power density inside is the amount of energy entering per unit time, divided by the volume \( V = \frac{4}{3}\pi(H^{-1}/2)^3 \), or:

\[
\Phi/V = \pi T^2 / 240V = \pi^2 T^4 H / 10.
\]

Furthermore, the energy density \( \rho_{\text{e-folding}} \) created in one e-folding would be the power inside the sphere times \( H^{-1} \), leading to the result

\[
\rho_{\text{e-folding}} = \pi^2 T^4 / 10.
\] (8)

We mention for purposes of comparison this density is slightly larger than the energy of a photon gas at temperature \( T \), which is \( u_\gamma = \pi^2 T^4 / 15 \). Notice the production of radiation due to the expansion of the universe is a dissipative mechanism.
Finally, let us assume that there are about 120 degrees of freedom in the high energy standard model. Every fundamental particle must have its own thermal bath (unless the mass of a particle is larger than the temperature), since the arguments for the existence of a bath for a type of particle are completely generic, given a fundamental particle. The density \( \rho \) is for photons, which have two helicities. For the standard model we should then have a density 60 times larger. Thus, a density

\[
\rho = 6\pi^2 T^4
\]

is being created every \( \epsilon \)-folding. The temperature can be calculated from \( H \) as given by (4) and (6) and is

\[
T = 0.3 M_p / 2\pi = 5 \times 10^{17} \text{GeV}.
\]

This temperature is higher than that needed for grand unification symmetry breaking, even assuming supersymmetry.

4 The transition between inflation and the rest of the Big Bang.

It is usually assumed that the slow-roll lasts about 60 \( \epsilon \)-foldings, and that then (or soon after) reheating begins. It is assumed that during reheating there is a total conversion of the potential energy of the inflaton into particles so that at the end of inflation \( V = 0 \). The purpose of the reheating phase is to explain the origin of the matter of the universe. Since reheating requires a strong interaction of the inflaton field with other particles, it seems necessary the inflaton potential should be zero by the end of the reheating period, as otherwise it would interact with the particles in the universe later on, in processes that have not been observed. But if one assumes that vacuum production results in large quantities of inflaton fluctuations and particles being created throughout the slow-roll, then there is no need to assume a reheating period at all. Matter is created beforehand from the vacuum by quantum gravity effects.

During inflation the inflaton rolls slowly down the potential \( V(\phi_0) \), spending the energy its is gaining in sustaining the production from the vacuum. Towards the end of the slow-roll the domination of the inflaton is put into question by the accumulated particles and inflaton fluctuations that have been produced from the vacuum, and by the fact that the potential \( V(\phi_0) \) itself has diminished. During this transition period the Hubble horizon \( H^{-1} \) begins to increase but there is still vacuum production (colder now since the \( H \) is smaller). Eventually radiation dominates, but there would still be potential \( V(\phi_0) \) left, in a quantity comparable to the amount of inflaton perturbations \( \varphi \) and particle radiation. Since it does not interact with matter it would be invisible today (except gravitationally).

After the end of inflation there would be a large quantity of inflaton fluctuations, comparable with the quantity of particle radiation present at that same time. These fluctuations do not interact with matter at all (except gravitationally), and their kinetic energy term has a \( 1/a^2(t) \) factor so they rapidly cool down with the expansion of the universe. They are good candidates for dark matter.
5 Summary and a possible role of the inflaton potential $V(\phi_0)$ as dark energy.

We have shown that during inflation there is a production from the quantum vacuum of an energy density of $6\pi^2 T^4$ per $e$-folding, due to quantum gravity effects. The temperature is high, of the order of $5 \times 10^{17}$GeV, enough to break the grand unification symmetry, even assuming supersymmetry. The calculation that restrained the value of the Hubble parameter $H$ to be low was shown to be invalid, since it is based on an incorrect application of the conservation of the perturbative curvature $\mathcal{R}$. The fallacy is to apply, during inflation, this conservation law to a single inflaton perturbation. Since what is present then is, already, an aggregate, the conservation law has to be applied to an energy density contrast $\delta \rho/\rho$.

The large quantity of matter already produced makes reheating, and thus the coupling of the inflaton to matter, unnecessary. In our picture inflation ends when the fluctuations and particle radiation dominate over the potential $V(\phi_0)$, and the universe enters a period of radiation domination. At the end of inflation there will be a hot aggregate of particles and inflaton fluctuations, and some potential $V(\phi_0)$ left. The process does not increase very much the value of $\phi_0^2$ so that the inflaton background field $\phi_0$ satisfies an equation of state $p \approx -\rho$. It is our contention in this paper that the inflaton vacuum fluctuations, which do not interact with matter except gravitationally, are the dark matter observed in the universe.

Fluctuations with scales $k$ were created during the $e$-foldings of the slow-roll, and each one came out of the horizon when $k/a = H$, during the inflationary epoch. After inflation’s end the fluctuations have been reentering the horizon, one by one, with the scales of smaller physical size reentering first, larger ones last. When a virtual vacuum fluctuation, during inflation, reaches the Hubble horizon, it has to become real. It, along with the metric field $g_{\mu\nu}$ which is part of the solution, has to transform locally (within small distances that are still causally connected) in order for it to become a classical solution of the equations of motion. To be able to do this, it must locally take energy from $\phi_0$, and in so doing leave a small dent in $V(\phi_0)$. The fluctuation leaves a negative image of itself in the potential $V(\phi_0)$. Time passes and the inflaton fluctuation eventually reenters the horizon. Once this happens, it is possible, since causality is no longer an issue, for the fluctuation to undergo the inverse of the quantum process that originally created it, and go back to the vacuum. The dented volume, the fluctuation’s negative image that it left in $V(\phi_0)$, has expanded at the same rate as the fluctuation and they are sharing the same location. It is as if there were a puzzle, and one piece of it is lifted up; then if both the piece and the puzzle expand together at the same rate they should still fit. There would be a quantum amplitude for the fluctuation to go back to the vacuum. Since the quantum process occurred in one direction in time, there should be a finite probability for it to occur in the opposite direction.

The fluctuation that has reentered the horizon is not obliged to go back to the vacuum; it only has a probability of doing so. This inverse process is a disintegration and, as such, it has a half-life. The process for a fluctuation to go back into the vacuum can take a long time because of two completely different reasons:

- It is possible that either the fluctuation $\varphi$ or the potential $V(\phi_0)$ have being distorted gravitationally by other objects before reentry, in which case the quantum amplitude...
would become smaller or zero, since the path integral is strongly inhibited by the resulting gradients.

• Even if the quantum process of vacuum reabsorption of the inflaton fluctuation actually begins to take place, the time scale of the quantum transition is large because of the cosmological distances involved. Depending on the scale involved, the quantum process of disintegration could take hundreds or thousands of millions of years.

As more and more fluctuations enter the horizon and become eligible for disintegration back into $V(\phi_0)$, the chance for some of them to go back to being part of the potential $V(\phi_0)$ increases, and eventually many will. This potential $V(\phi_0)$ satisfies $p \approx -\rho$, precisely as has been observed nowadays for dark energy. As a result of the disintegrations, the amount of potential $V(\phi_0)$ will increase and eventually dominate over the $\varphi$ fluctuations, and the expansion of the universe begins accelerating again.

The inflaton has dominated the evolution of the universe. Initially the potential $V(\phi_0)$ was the direct cause of inflation. Then, in the form of vacuum fluctuations, it is dark matter and helped the formation of structure. Later, the potential $V(\phi)$ grew again and became dark energy.

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