Observational signatures of dark energy produced in an ancestor vacuum: forecast for galaxy surveys

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Abstract. We study observational consequences of the model for dark energy proposed in [1]. We assume our universe has been created by bubble nucleation, and consider quantum fluctuations of an ultralight scalar field. Residual effects of fluctuations generated in an ancestor vacuum (de Sitter space in which the bubble was formed) is interpreted as dark energy. Its equation of state parameter \( w_{\text{DE}}(z) \) has a characteristic form, approaching \(-1\) in the future, but \(-1/3\) in the past. A novel feature of our model is that dark energy effectively increases the magnitude of the negative spatial curvature in the evolution of the Hubble parameter, though it does not alter the definition of the angular diameter distance. We perform Fisher analysis to forecast the constraints for our model from future galaxy surveys by Square Kilometre Array and Euclid, and point out that our model can be distinguished from the usual ΛCDM model for reasonable choices of the parameters. Due to degeneracy between dark energy and the spatial curvature, it might be difficult to fully determine the model parameters by galaxy surveys alone, but combination with other independent observations, such as CMB, will greatly improve the chance of determining them.

Keywords: dark energy theory, cosmological parameters from LSS, initial conditions and eternal universe

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1 Introduction

It has been established that the expansion of the present universe is accelerating. The first clear evidence for acceleration has been provided by observations of supernovae (SNe) of type Ia [2, 3]. Strong support has been given by the fact that other independent phenomena, such as cosmic microwave background (CMB) and baryon acoustic oscillation (BAO), consistently suggest cosmic acceleration (see e.g., [4] for a review). The source of the accelerating expansion is attributed to dark energy of unknown origin, which has the equation of state (EoS) parameter \( w_{\text{DE}} = p/\rho \) close to \(-1\), contributing about 68% of the critical density [5, 6].

There are models that describe dark energy (see [7] for a review), such as quintessence (scalar field slowly rolling down a potential) and modified gravity, but they typically do not explain its origin. It remains a mystery why its energy density is extremely small compared to the fundamental scale, \( \rho_{\text{DE}} \sim 10^{-122} M_\odot^4 \). It is expected that the next generation observations will determine \( w_{\text{DE}} \) to a percent level, and also its derivative with respect to the scale factor to a 10 percent level [4], giving important clues about the nature of dark energy.

Another issue in observational cosmology that should have connection to fundamental physics is whether our universe is flat or not. Inflation in the early universe will make the spatial curvature very small, but there is no reason to expect that the curvature is exactly zero. If our universe has been created by bubble nucleation due to Coleman-De Luccia instanton [8] as suggested by string landscape (see e.g., [9–14]), there should be negative curvature (i.e., positive energy fraction for the curvature, \( \Omega_{K,0} > 0 \)). It has been argued that a possible detection of positive curvature at the level of \( \Omega_{K,0} < -10^{-4} \) would rule out bubble nucleation [15]. Currently, the tightest bound on the curvature comes from the combination of Planck+BAO+SNe [5, 16], and is of order \(|\Omega_{K,0}| \lesssim 10^{-3}\), consistent with zero.

Although there is no doubt that great progress is being made in observations, one should also keep in mind that it is generally difficult to distinguish the effect of dark energy and the spatial curvature, as emphasised e.g., in [17, 18]. The constraints \(|\Omega_{K,0}| \lesssim 10^{-3}\) quoted above have been obtained by assuming \( w_{\text{DE}} = -1 \) exactly [5], or by treating \( w_{\text{DE}} \) as a free constant parameter [16]. If one allows time dependence of \( w_{\text{DE}} \), and takes \( w_0 \), \( w_a \) (defined as \( w_{\text{DE}}(a) = w_0 + (1-a)w_a \)) in addition to \( \Omega_{K,0} \) as free parameters, the constraint becomes substantially weaker [16, 19].
Attempts have been made at finding the constraints on \((w_0, w_a)\) (or more generally by taking \(w_{DE}\) as a piecewise continuous function in the redshift \(z\)) at the same time as \(\Omega_{K,0}\), from the existing data [19] or as forecast for future observations [19–22]. These “model independent” analyses are certainly important, but in view of the current situation, it would be also meaningful to take an alternative approach, namely, to fix a particular model for dark energy that is theoretically well-motivated,\(^1\) and find constraints on the model parameters including \(\Omega_{K,0}\).

This paper takes a first step in the study of the constraints on the model for dark energy, recently proposed by five of the present authors [1]. This proposal is partially motivated by string landscape. We assume our universe has been created by bubble nucleation from a metastable de Sitter space (the “ancestor vacuum”), and interpret the residual effects of quantum fluctuations generated in the ancestor vacuum as the source of dark energy. Its equation of state parameter \(w_{DE}(z)\) has a characteristic form as a function of the redshift \(z\), see eq. (4.1) below. In this paper, we aim at testing this model with galaxy surveys by Square Kilometre Array (SKA) [24] and Euclid [25], planned to start operating in the early 2020’s. We will perform Fisher analysis and forecast the constraints on our model.\(^2\)

2 The setup

We consider bubble nucleation due to quantum tunneling, which occurs e.g., in a potential for a scalar field \(\Phi\) shown in figure 1, left panel. The Hubble parameter of the ancestor vacuum will be denoted \(H_A\). Our universe is inside the bubble, represented as Region I in figure 1, right panel. It should have negative spatial curvature [8]. After bubble nucleation, the ordinary inflation with the Hubble parameter \(H_I(\ll H_A)\) is assumed to occur.

We consider a scalar field \(\phi\) which is different from the tunneling field\(^3\) \(\Phi\) and has zero expectation value. We assume the field \(\phi\) to have mass \(m_A\) before tunneling, and \(m_0\) after tunneling.
tunneling, where \( m_A \) and \( m_0 \) could be different. The change of mass from \( m_A \) to \( m_0 \) occurs in the spacelike direction (horizontal direction in figure 1, right panel), and will not give rise to complicated non-equilibrium processes, such as particle production. Its effect is encoded in the initial condition, namely the value of \( \epsilon \), for the field \( \phi \) in our universe (Region I). The mass after tunneling \( m_0 \) is assumed to satisfy \( m_0 \ll H_0 \) where \( H_0 \sim 10^{-33} \text{eV} \) is the present Hubble parameter. A candidate for such an ultralight field is one of the axion-like fields, expected to exist in string compactifications. Extremely small mass \( m_0 \sim H_0 \) may exist because mass of a string axion is typically generated by instanton effects, and is exponentially sensitive to the instanton action \([30]\).

In \([1]\), the contribution from the field \( \phi \) to the vacuum expectation value of the energy-momentum tensor \( \langle T_{\mu\nu} \rangle \) has been computed, carefully taking into account the effect of the ancestor vacuum. In the free-field approximation, the energy-momentum tensor is quadratic in \( \phi \), thus \( \langle T_{\mu\nu} \rangle \) can be obtained by taking the coincident-point limit of the two-point function \( \langle \phi \phi \rangle \) computed by the method developed in\(^{4}\) \([35–37]\). We refer the reader to \([1]\) for details, and give an order-of-magnitude argument here. In the ancestor vacuum, quantum fluctuations give rise to the expectation value of the field-squared \( \langle \phi^2 \rangle \sim H_A^4/m_A^2 \), as in pure de Sitter space (see e.g., \([38]\)). The field \( \phi \) is almost frozen until now, due to the assumption \( m_0 \ll H_0 \) (and one more condition \( \epsilon \ll 1 \), to be mentioned below). If so, the energy-momentum tensor is dominated by the mass term, and takes the form of cosmological constant (\( w_{\text{DE}} = -1 \)), with the magnitude

\[
\langle T_{\mu\nu} \rangle \sim m_0^2 \langle \phi^2 \rangle g_{\mu\nu} \sim H_A^4 \left( \frac{m_0}{m_A} \right)^2 g_{\mu\nu} .
\]

It is not difficult for this to have the same order of magnitude as dark energy, \( \rho_{\text{DE}} \sim M_P^2 H_0^2 \), once we admit \( m_0 \sim H_0 \): we just need \( m_A/H_A \sim H_A/M_P \), i.e., \( H_A \) being the geometric mean of \( m_A \) and \( M_P \).

### 3 Difference from quintessence

At the level of the above heuristic argument, it makes no difference whether \( \phi \) is a classical or quantum field. However, fully quantum mechanical analysis in \([1]\) has the following two important differences from the classical case.

First, there is no ambiguity in the initial condition for the field \( \phi \), unlike in the classical case, in which one has to assign e.g., the axion misalignment angle by hand. Our prediction (2.1) is unambiguous when \( H_A, m_A, m_0 \) are given. This is a virtue of bubble nucleation, which allows us to go past the beginning of the FLRW time and uniquely determine the vacuum state of a quantum field.

Second, the mode of \( \phi \) which gives the dominant contribution at late times is not strictly homogeneous. It is an eigenfunction of the Laplacian on the spatial slice \( H^3 \) with a non-zero eigenvalue. There is a peculiar feature of modes on a hyperboloid. Normalizable modes decay exponentially (since the volume grows exponentially) at large distances; they have eigenvalues \( \nabla^2 = -(k^2 + 1) \) with real \( k \). However, in an open universe created by bubble nucleation, there is the so-called supercurvature mode \([35, 36]\), which is non-normalizable on \( H^3 \), and has an eigenvalue with imaginary \( k = i(1 - \epsilon) \), i.e., \( \nabla^2 \sim -2\epsilon \) when \( \epsilon \ll 1 \).

\(^{4}\)For studies of the CMB in this framework, see e.g. \([26, 31–34]\).
parameter $\epsilon$ is determined by the properties of the ancestor vacuum,

$$\epsilon = c_\epsilon \left( \frac{m_A}{H_A} \right)^2,$$

when $m_A/H_A \ll 1$, with an order-one coefficient $c_\epsilon$ which depends on the size of the critical bubble\(^5\) [1]. The supercurvature mode gives rise to long-range correlations in the open universe, which can be interpreted as the superhorizon fluctuations in the ancestor vacuum, seen from the inside of the bubble. The other (subcurvature) modes decay faster than the supercurvature mode, and can be safely neglected in the late time universe that we are interested in.

To study backreaction from dark energy to the geometry, we should solve the coupled equations for the metric and the field $\phi$ self-consistently, in principle. However, since the mode that contributes to dark energy has wavelength much larger than the horizon scale, it will be good enough for the observational purposes to approximate the energy density for $\phi$ to be homogeneous, and substitute it into the right hand side of the Friedmann equation.

### 4 Observational signature

The energy-momentum tensor for $\phi$ at late times is dominated by the contribution from the supercurvature mode. The spatial derivative term in $\langle T_{\mu\nu} \rangle$ gives a non-zero contribution, $\langle (\nabla \phi)^2 \rangle = -\langle \phi \nabla^2 \phi \rangle \sim 2\epsilon \langle \phi^2 \rangle$. If $\epsilon \ll 1$ and $m_0 \ll H_0$ (though these inequalities do not have to be very strong, in practice), the time-derivative term is negligible [1]. Then, the EoS parameter $w_{DE}$ can be obtained by simply taking the ratio of $p$ to $\rho$, and becomes

$$w_{DE} = -\frac{2}{3} \left( \frac{\epsilon}{R_c^2} \right) + \frac{m_0^2 a^2}{2 \langle \frac{\epsilon}{R_c^2} \rangle + m_0^2 a^2} = -\frac{1}{1+2\tilde{\epsilon}(1+z)^2},$$

where $R_c$ is the comoving radius of curvature, which is constant.\(^6\) The final expression shows that the functional form of $w_{DE}(z)$ depends on a single parameter,$^7$

$$\tilde{\epsilon} = \frac{\epsilon}{(m_0/H_0)^2} \Omega_{K,0} = \xi \Omega_{K,0},$$

where $\Omega_{K,0} = 1/H_0^2 R_c^2$ is the fractional energy density of the spatial curvature at present. We show examples of $w(z)$ with some choices of the parameters in figure 2. At late times, the mass term is dominant in (4.1), thus $w_{DE}(z) \to -1$. At early times,\(^8\) the spatial derivative term becomes dominant, thus $w_{DE}(z) \to -1/3$.

The past asymptotic value $w_{DE}(z) \to -1/3$ is unlikely to be realized as a result of quantum fluctuations in the ordinary inflation: $\langle T_{\mu\nu} \rangle$ in de Sitter space with a de Sitter invariant vacuum should have $w = -1$; evolution of wave functions after inflation will give rise to non-zero time derivatives, not only spatial derivatives. We regard the functional form

\(^5\)The dependence on the bubble size is not very strong: $c_\epsilon = 1/3$ in the small bubble limit, and $c_\epsilon = 2/9$ when the bubble occupies half of the ancestor de Sitter space.

\(^6\)The convention in [1] was to take $R_c = 1$. Here we take the scale factor at present to be 1, $a_0 = 1$, so that $a = 1/(1 + z)$.

\(^7\)This corresponds to the $p = 2$, $w_0 = -1$, $w_1 = -1/3$ case in [39] (referred to “parametrization II” in [22]).

\(^8\)Though we call it early times, we are assuming it to be later than the time when the supercurvature mode becomes dominant over the continuous modes.
of $w_{\text{DE}}(z)$ in (4.1) to be an indication of fluctuations generated before ordinary inflation, but in fact, this may not be specific to open universe or bubble nucleation. If an infrared part of the fluctuations is enhanced relative to the usual magnitude $H_0$ and is frozen until now, it will contribute to the spatial-derivative and mass terms of the energy-momentum tensor, giving the EoS parameter similar to (4.1). This can happen e.g., in a double inflation model in [40, 41].

We should note that there is another possibility for realizing $w_{\text{DE}}(z)$ of (4.1): by having two independent sources, one with $w = -1/3$ (such as cosmic strings) and the other with $w = -1$ (cosmological constant).

Eq. (4.1) leads to a simple relation between $w_0$ and its derivative $w_a = -dw/da|_{a=1}$: when $\tilde{\epsilon} \ll 1$, we have $w_a = 2(w_0 + 1) - 8\tilde{\epsilon}/3$. If one could test this relation, leaving $\Omega_{K,0}$ as free parameter (which may not be easy, as remarked in Introduction) by ongoing observations such as Dark Energy Survey [42], it will be a first step toward testing our model.

Eq. (4.1) yields the energy density of dark energy as a function of the redshift,

$$\rho_{\text{DE}}(z) = 3M_P^2 H_0^2 \Omega_{\Lambda,0} (1 + 2\tilde{\epsilon}(1 + z)^2).$$

The mass term in the energy-momentum tensor gives the time-independent contribution $3M_P^2 H_0^2 \Omega_{\Lambda,0}$ to (4.3). The spatial derivative term gives a contribution with the relative factor $2\tilde{\epsilon}(1 + z)^2$. In terms of the model parameters, $\Omega_{\Lambda,0}$ is given by

$$\Omega_{\Lambda,0} = \frac{1}{6} \frac{\tilde{\epsilon}}{\tilde{c}_s} \frac{H_A^4}{H_0^2 M_P^2} \left( \frac{m_0}{m_A} \right)^2,$$

with $\tilde{c}_s = c_s (H_I/H_A)^{2\epsilon}$, where $c_s$ depends on the size of the critical bubble [1]. We can take $(H_I/H_A)^{2\epsilon} \sim 1$ when $\epsilon$ is sufficiently small. The parameters $H_A, m_A, m_0$ in the model are related to the observables, $\Omega_{\Lambda,0}$ and $\xi$ as

$$\frac{H_A}{M_P} = \sqrt{\frac{6\xi \Omega_{\Lambda,0}}{\tilde{c}_s c_s}}, \quad \frac{m_A}{M_P} = \sqrt{\frac{6\xi \Omega_{\Lambda,0}}{\tilde{c}_s c_s}} \frac{m_0}{H_0}.$$

---

The fractional energy density of dark energy at present is the sum of the two terms, $\Omega_{\text{DE},0} = (1 + 2\tilde{\epsilon})\Omega_{\Lambda,0}$, but since $\tilde{\epsilon} \ll 1$, one can take $\Omega_{\text{DE},0} \approx \Omega_{\Lambda,0}$, in practice.

We have $c_s = 3/8\pi^2$ in the small bubble limit, and $c_s = 3/4\pi^2$ when the bubble occupies half of the ancestor de Sitter space.
Detection of non-zero $\tilde{\epsilon}$ will be a clear sign of departure from the usual $\Lambda$CDM model. A quantity of more fundamental importance than $\tilde{\epsilon}$ is $\xi$. Its definition is independent of $\Omega_{K,0}$ and it is not constrained to be very small; we expect $\xi = \mathcal{O}(1)$ as a natural choice. If we can determine $\xi$ from observations, (4.5) allows us to determine an important parameter $H_A$.

5 Fisher analysis for galaxy surveys

SKA [24] is a ground based array of radio telescopes which covers about 3/4 of the sky and observes galaxies by detecting the 21 cm emission line of neutral hydrogen. Euclid [25] is a satellite based telescope working in the visible and near-infrared wavelength domains. SKA phase 2 (SKA2) and Euclid are both expected to observe a billion galaxies up to the redshift $z \sim 2$. In our analysis, we use the survey specifications described in [43] for SKA, and in [44] for Euclid. We take the power spectrum of galaxy distribution as an observable, and forecast the constraints on the parameters, following the standard procedure (see e.g., [46, 47, 49–51]).

As the fiducial cosmological model, we take a $w$CDM model whose dark energy is characterized by $w$ in (4.1) with the negative spatial curvature. The Hubble parameter $H(z)$ obeys

$$\frac{H^2}{H_0^2} = \Omega_{m,0}(1 + z)^3 + \Omega_{K,0}(1 + z)^2 + \Omega_{A,0},$$

(5.1)

$$\frac{H}{H_0} = -\frac{3}{2}\Omega_{m,0}(1 + z)^3 - \Omega_{K,0}(1 + z)^2.$$  

(5.2)

Interestingly, the spatial derivative term in the energy-momentum tensor contributes exactly in the same way as the spatial curvature to eqs. (5.1) and (5.2), effectively replacing $\Omega_{K,0}$ with $\tilde{\Omega}_{K,0} \equiv (1 + 2\xi \Omega_{A,0}) \Omega_{K,0}$. Thus there is a tendency for degeneracy between $\Omega_{K,0}$ and $\xi$. On the other hand, the angular diameter distance, $D_A(z) = (1 + z)H_0\sqrt{\Omega_{K,0}}^{-1}\sinh (H_0\sqrt{\Omega_{K,0}} \cdot \int_0^z H^{-1}(z')dz')$, is defined in terms of the true curvature $\Omega_{K,0}$. This fact is expected to break the degeneracy, in principle.

We consider a model for galaxy distribution in the linear regime. The matter density contrast $\delta_m$ satisfies the $k$-independent equation at the linear level (see e.g., [52]),

$$\delta_m + 2H\delta_m - \frac{3}{2}H^2\Omega_m\delta_m = 0.$$  

(5.3)

An object of interest is the linear growth rate $f \equiv \frac{d\ln \delta_m}{d\ln a}$. The observed galaxy power spectrum in the redshift space is well described by

$$P_g(k; z) = \left(b(z) + f(z)\mu^2\right)^2 P_m(k; z)e^{-k^2\mu^2\sigma_{NL}^2},$$

(5.4)

where $P_m(k, z)$ is the linear matter power spectrum, and $b(z)$ is the so-called galaxy bias function, which should be chosen according to the type of target galaxies for the particular observation: for SKA, $b(z) = c_1 \exp(c_2 z)$ with constant $c_1$ and $c_2$; for Euclid, $b = \sqrt{1 + z}$. The term $f\mu^2$, where $\mu$ is the cosine of the angle between the line of sight and the wave vector $k$, represents the redshift space distortion [45], due to the contribution to the observed redshift from the peculiar velocity driven by the clustering of matter (making dense region look denser). The factor $e^{-k^2\mu^2\sigma_{NL}^2}$ with a free parameter $\sigma_{NL} \approx 7\text{Mpc}$ to be marginalized, is introduced to approximate peculiar velocity effects on nonlinear scales, which results in
the line-of-sight smearing. Further, taking into account the geometrical effects due to the difference between the possibly incorrect reference cosmology and the true one, the so-called Alcock-Paczynski (AP) effect [48], the observed power spectrum is given by [47]

\[
P_{\text{obs}}(k^\parallel, k^\perp; z) = \left( \frac{D_A^\text{ref}(z)}{D_A(z)} \right)^2 \frac{H(z)}{H^\text{ref}(z)} P_g(k^\perp, k^\parallel; z) .
\]

Here the angular diameter distance \( D_A \) and the Hubble parameter \( H \) in the reference cosmology are distinguished by the subscript ‘ref’, while those in true cosmology have no subscript. The wave number across and along the line-of-sight in the two cosmologies are related through \( k^\parallel = \frac{H}{H^\text{ref}} k^\parallel^\text{ref} \) and \( k^\perp = \frac{D_A}{D_A^\text{ref}} k^\perp^\text{ref} \).

6 The forecast

The Fisher matrix for a set of parameters \( \{\theta^\alpha\} \) is defined as \( F_{\alpha\beta} = \left( \frac{\partial}{\partial \theta^\alpha} \frac{\partial}{\partial \theta^\beta} \log \mathcal{L} \right) \) where \( \mathcal{L} \) is the likelihood function when we regard \( \{\theta^\alpha\} \) as probabilistic variables which depends on the data set. The matrix \( F_{\alpha\beta} \) is the inverse of the covariance matrix, and the minimum 1σ error on \( \theta_\alpha \) is given by \( \sqrt{(F^{-1})_{\alpha\alpha}} \) (no sum on \( \alpha \)). In terms of galaxy power spectrum, the Fisher matrix can be written as [47, 49]

\[
F_{\alpha\beta} = \sum_{z_i} \int_{k_{\text{min}}}^{k_{\text{max}}} \frac{d^3k}{(2\pi)^3} V_{\text{eff}}(k; z_i) \frac{\partial \ln P_{\text{obs}}(k; z_i)}{\partial \theta^\alpha} \frac{\partial \ln P_{\text{obs}}(k; z_i)}{\partial \theta^\beta} ,
\]

where the effective volume of the survey is given by

\[
V_{\text{eff}}(k; z_i) \approx \left( \frac{n_g(z_i) P_{\text{obs}}(k; z_i)}{n_g(z_i) P_{\text{obs}}(k; z_i) + 1} \right)^2 V_{\text{survey}}(z_i) .
\]

The survey volume is divided into bins with the width \( \Delta z = 0.1 \) in the redshift. Here \( V_{\text{survey}}(z_i) \) is the comoving volume of the redshift slice centered at \( z_i \). The minimum wavelength is \( k_{\text{min}}(z_i) = 2\pi / V_{\text{survey}}(z_i) \). The maximal wavelength is taken to be the scale beyond which non-linearities become non-negligible. It is estimated as \( k_{\text{max}}(z_i) = 0.14(1 + z_i)^{2/(2 + n_s)} \) Mpc\(^{-1}\). Our forecast is performed for the parameter set: \( \{h, \Omega_{\Lambda,0}, \Omega_{K,0}, h^2 \Omega_b, \sigma_8, n_s, \sigma_{\text{NL}}, b(z_i)\} \) and \( \bar{\epsilon} \) or \( \xi \). The fiducial values are taken as \( h = 0.67, h^2 \Omega_b = 0.0222, \Omega_{\Lambda,0} = 0.6817, \sigma_8 = 0.834, n_s = 0.962, \Omega_{K,0} = 0.03, \) and \( \bar{\epsilon} = 0.24, \xi = 0.8 \).

Figure 3 shows the forecast 1σ and 2σ contour in the \( \left( \Omega_{K,0}, \bar{\Omega}_{K,0} \right) \), \( \left( \Omega_{K,0}, \bar{\epsilon} \right) \) and \( \left( \Omega_{K,0}, \xi \right) \) planes for SKA2 and Euclid. There is some degeneracy between the true spatial curvature \( \Omega_{K,0} \) and the quantity \( \bar{\Omega}_{K,0} \). This fact is not specific to our model, and will be relevant e.g., when there are cosmic strings (which have \( w = -1/3 \)) as source of the energy of the universe. For the fiducial value taken in figure 3, the parameter \( \bar{\epsilon} \) can be distinguished from zero, i.e., the difference from the ΛCDM model (\( \bar{\epsilon} = 0 \)) can be seen, at least at the 1σ level with SKA+Euclid. The parameter \( \xi \), which has more fundamental meaning \( \bar{\epsilon} \) in our model, is strongly degenerate with \( \Omega_{K,0} \). They both contributes to \( \bar{\Omega}_{K,0} \), and the dependence of \( D_A \) on \( \Omega_{K,0} \) does not seem to be strong enough to break the degeneracy. It might be difficult to determine \( \xi \) from the results of SKA and Euclid alone.
Figure 3. Forecast 1σ and 2σ marginal contours in the plane of \((\Omega_{K,0}, \tilde{\Omega}_{K,0})\) (left panel), \((\Omega_{K,0}, \xi)\) (middle panel) and \((\Omega_{K,0}, \xi)\) (right panel) for SKA2 galaxy survey (blue), Euclid (green), and the combined analysis (red). All of them have equivalent fiducial values, \((\Omega_{K,0}, \tilde{\Omega}_{K,0}) = (0.03, 0.06), (\Omega_{K,0}, \xi) = (0.03, 0.24), (\Omega_{K,0}, \xi) = (0.03, 0.8)\).

7 Conclusions and discussion

In this paper, we presented forecasts for the constraints from galaxy surveys by SKA and Euclid to a model of dark energy proposed in [1]. Dark energy in this model contains a part which has \(w = -1/3\) which contributes in the same way as the negative spatial curvature to the evolution of Hubble parameter. The energy fraction of curvature plus this part is called \(\tilde{\Omega}_{K,0}\). This part of dark energy is different from the true spatial curvature, since it does not affect the definition of the angular diameter distance. There is some degree of degeneracy between \(\tilde{\Omega}_{K,0}\) and \(\Omega_{K,0}\) in the forecast for SKA/Euclid, as shown in figure 3, left panel. This result will be of interest not only for our model, but also e.g., in the case when there are cosmic strings which have \(w = -1/3\). Depending on the model parameter, we could distinguish our model from the ΛCDM model, but it might be difficult to find the value of \(\xi\), a parameter which has fundamental meaning in our model, from SKA and Euclid alone due to the degeneracy mentioned above.

To break this degeneracy, it will be essential to combine different types of observations. First, it will be important to perform a detailed analysis using the existing data of CMB+BAO+SNe by fixing the model to the one considered here, and obtain precise constraints at present.\(^{11}\) Then, it would be interesting to obtain a detailed forecast using these constraints as a prior. We hope to report progress in these directions in future publications.

If the results of galaxy surveys are consistent with our model with non-zero \(\xi\), we may wonder whether this rules out other models. For instance, there is a quintessence model, called "scaling freezing" model\(^{12}\) whose EoS parameter approaches \(w_{DE} \rightarrow -1\) in the future and \(w_{DE} \rightarrow 0\) in the past, and the transition occurs around \(a \sim a_t\). Although it would be difficult for galaxy surveys at \(z \lesssim 2\) to distinguish the past asymptotic values \(w_{DE} \rightarrow -1/3\) and \(w_{DE} \rightarrow 0\), in fact, there is already a strong constraint for the latter [53, 54]: the existing data of CMB, BAO, SNe, suggest that the transition has to occur quite early \(a_t < 0.11\) (i.e., \(z > 8.1\)). Thus, the model with the past asymptotic behavior \(w_{DE} \rightarrow 0\) should have \(w_{DE} \approx -1\) at \(z \lesssim 2\), and cannot be responsible for the possible deviation from \(w_{DE} = -1\) discussed in this paper.

\(^{11}\)It is possible that the resulting constraints are stronger than the one obtained in this paper from SKA/Euclid alone.

\(^{12}\)It is defined by the potential \(V(\phi) = V_1 e^{-\lambda_1 \phi/\lambda_1} + V_2 e^{-\lambda_2 \phi/\lambda_2}\) with \(\lambda_1 > 1\) and \(\lambda_2 \lesssim 1\). Its EoS parameter is well approximated by \(w_{DE}(a) = -1 + 1/(1 + (a/a_t)^{1/\tau})\) with \(\tau = 0.33\).
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