Testing *ancestor* vacuum fluctuations as the origin of dark energy from galaxy surveys

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Inflation
+ Quantum tunneling
+ Dark energy
= Fun! 😊
Ultralight scalar field and quantum backreaction

1. Superhorizon fluctuations can contribute to $\langle \phi^2 \rangle$

$$\langle \phi^2 \rangle = \int_{k < 1/aH} \frac{d^3 k}{(2\pi)^3} \langle |\phi_k|^2 \rangle \approx \frac{H_I^4}{m_0^2}$$

2. To have the same order of magnitude of DE, we need

$$\langle T_{\mu\nu} \rangle \approx m_0^2 \langle \phi^2 \rangle g_{\mu\nu} \approx H_I^4 g_{\mu\nu}$$

3. The low-energy scale of inflation is required.

$$H_I^4 \approx \rho_\Lambda = \Omega_\Lambda H_0^2 M_P^2$$
Our model

- Assumptions:

  - Our Universe have been created by bubble nucleation due to Coleman-De Luccia (CDL) quantum tunneling

  - Consider a scalar field $\sigma$ to realize the false vacuum decay

  - Consider another ultralight scalar field $\phi$ with $<\phi>=0$ (i.e., fully quantum field)
Our model

✓ The field $\phi$ has the mass $m_A$ before tunneling and $m_0$ after tunneling.

$V(\sigma, \phi)$

(1/2)$m_A\phi^2$

Ancestor vacuum

True vacuum

light field : $\phi$

heavy field : $\sigma$

(1/2)$m_0\phi^2$
Order-of-magnitude argument

- In the \textit{ancestor vacuum}, the 2pt func is \( \langle \phi^2 \rangle \approx \frac{H_A^4}{m_A^2} \)

- Assuming \( m_0 \lesssim H_0 \), the field is almost frozen until now.

- The energy-momentum tensor for \( \phi \) can read

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

- To have \( \rho \sim \rho_\Lambda \sim M_P^2 H_0^2 \), we just need

\[
\frac{m_A}{H_A} \sim \frac{H_A}{M_P} \quad \rightarrow \text{Easier to realize!}
\]
Difference from *quintessence*

- There is no ambiguity of the initial condition for the field, (unlike in classical analysis).

- The mode of $\phi$ is *NOT* strictly homogeneous due to the gradient term $<(\nabla \phi)^2>$. 

\[
\rho = \frac{1}{a^2} \left< \frac{1}{2} \phi'^2 + \frac{1}{2} (\nabla \phi)^2 + \frac{1}{2} m^2 a^2 \phi^2 \right>
\]
\[
P = \frac{1}{a^2} \left< \frac{1}{2} \phi'^2 - \frac{1}{6} (\nabla \phi)^2 - \frac{1}{2} m^2 a^2 \phi^2 \right>
\]

[almost frozen] $w=-1/3$  

$w=-1$
Observational features

- Universe created by CDL bubble nucleation should have negative spatial curvature: $\Omega_{K,0} > 0$

- There is a pre-inflationary phase: Ancestor vacuum de Sitter expansion with Hubble $H_A (>H_i)$

- A "Supercurvature mode" represents the residual effect of the ancestor vacuum.
Power spectrum for scalar/tensor

\[ k^3 P(k) / 2\pi^2 \]

- **Scalar** mode:
  - \( k^3 \) for \( k \leq k_{\text{curv}} \)
  - \( \sim 2k_{\text{curv}} \)

- **Tensor** mode:
  - \( k^3 \) for \( k \geq k_{\text{curv}} \)

- **Supercurvature mode**:
  - \( k_{\text{SC}} \)

(若干の適当さを含みます)
Energy-momentum tensor for SC

\[
\begin{align*}
\rho_{SC} &\approx \left( \frac{2\epsilon}{R_{curv}^2 a^2} + \frac{1}{2} m_0^2 \right) \langle \phi^2 \rangle_{SC} \\
P_{SC} &\approx - \left( \frac{2\epsilon}{3R_{curv}^2 a^2} + \frac{1}{2} m_0^2 \right) \langle \phi^2 \rangle_{SC}
\end{align*}
\]

with \[ \langle \phi^2 \rangle_{SC} \approx \frac{H_A^4}{m_A^2} \]

The ancestor vacuum fluctuations can affect the evolution of the present Universe through EMT, and thus we can test the model of the ancestor vacuum DE.
Observational signatures

- The equation-of-state (EOS) parameter can be obtained by taking the ratio of $P$ and $\rho$, and becomes

$$w \approx \frac{2\epsilon}{3 R_{\text{curv}}^2 a^2} + \frac{1}{2} m_0^2 \approx 1 + \frac{2}{3} \tilde{\epsilon}(1 + z)^2$$

- The EoS parameter depends on a single parameter:

$$\tilde{\epsilon} = \frac{\epsilon}{m_0^2 R_{\text{curv}}^2} \approx \frac{(m_A/H_A)^2}{(m_0/H_0)^2} \Omega_{K,0}$$
Observational signatures

- The amplitude of the energy density is determined by the cosmological constant:

\[ \rho_{SC} \approx 3M_P^2 H_0^2 \Omega_\Lambda \left[ 1 + 2\varepsilon(1 + z)^2 \right] \]

- To extract the information of the ancestor vacuum, we need to detect \( \tilde{\varepsilon} \) (or \( \xi \)) from observations!

\[ \tilde{\varepsilon} \approx \frac{(m_A/H_A)^2}{(m_0/H_0)^2} \Omega_{K,0} = \xi \Omega_{K,0} \]
Meaning of $\xi$

- The ancestor vacuum parameter $H_A$ and $m_A$ are fixed in terms of $\xi$ (and $\Omega_\Lambda$):

$$H_A = \mathcal{O}(1) \xi^{1/2} M_P$$

$$m_A = \mathcal{O}(1) \xi \frac{m_0}{H_0} M_P$$

Determination of $\xi$ from observations corresponds to testing the energy-scale of the ancestor vacuum!

Note: If other observable, which is sensitive to not $\tilde{\varepsilon}$ but $\varepsilon$ itself, we can distinguish $m_A$ from $m_0$. 
Degeneracy along $(1 + 2\xi \Omega_{\Lambda}) \Omega_{K,0} = \text{const}$
Discussion

- There is a strong degeneracy along \((1 + 2\xi\Omega_{\Lambda})\Omega_{K,0} = \text{constant direction.}\)

\(\text{(``.``)}\) The background equations strictly coincide with those in open-$\Lambda$CDM with the modified $\Omega_{K,0}$:

\[
\frac{H^2}{H_0^2} = \frac{\Omega_{m,0}}{a^3} + \frac{(1 + 2\xi\Omega_{\Lambda})\Omega_{K,0}}{a^2} + \Omega_{\Lambda}
\]

The angular diameter distance $D_A(z)$, which is defined by using the true $\Omega_{K,0}$, can break this degeneracy.