ancestor : someone from whom you are descended, “祖先”

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

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Based on
arXiv:1807.07904

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Inflation

+ Quantum tunneling

+ Dark energy

= Fun! ☺

# Ultralight scalar field and quantum backreaction

- Superhorizon fluctuations can contribute to <ϕ$^2$>

$$\langle \phi^2 \rangle = \int_{k<1/aH} \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} \langle |\phi_{\boldsymbol{k}}|^2 \rangle \approx \frac{H_{\mathrm{I}}^4}{m_0^2}$$

$$\Rightarrow \langle T_{\mu\nu} \rangle \approx m_0^2 \langle \phi^2 \rangle g_{\mu\nu} \approx H_{\mathrm{I}}^4 g_{\mu\nu}$$

- To have the same order of magnitude of DE, we need

$$H_{\mathrm{I}}^4 \approx \rho_\Lambda = \Omega_\Lambda H_0^2 M_{\mathrm{P}}^2$$

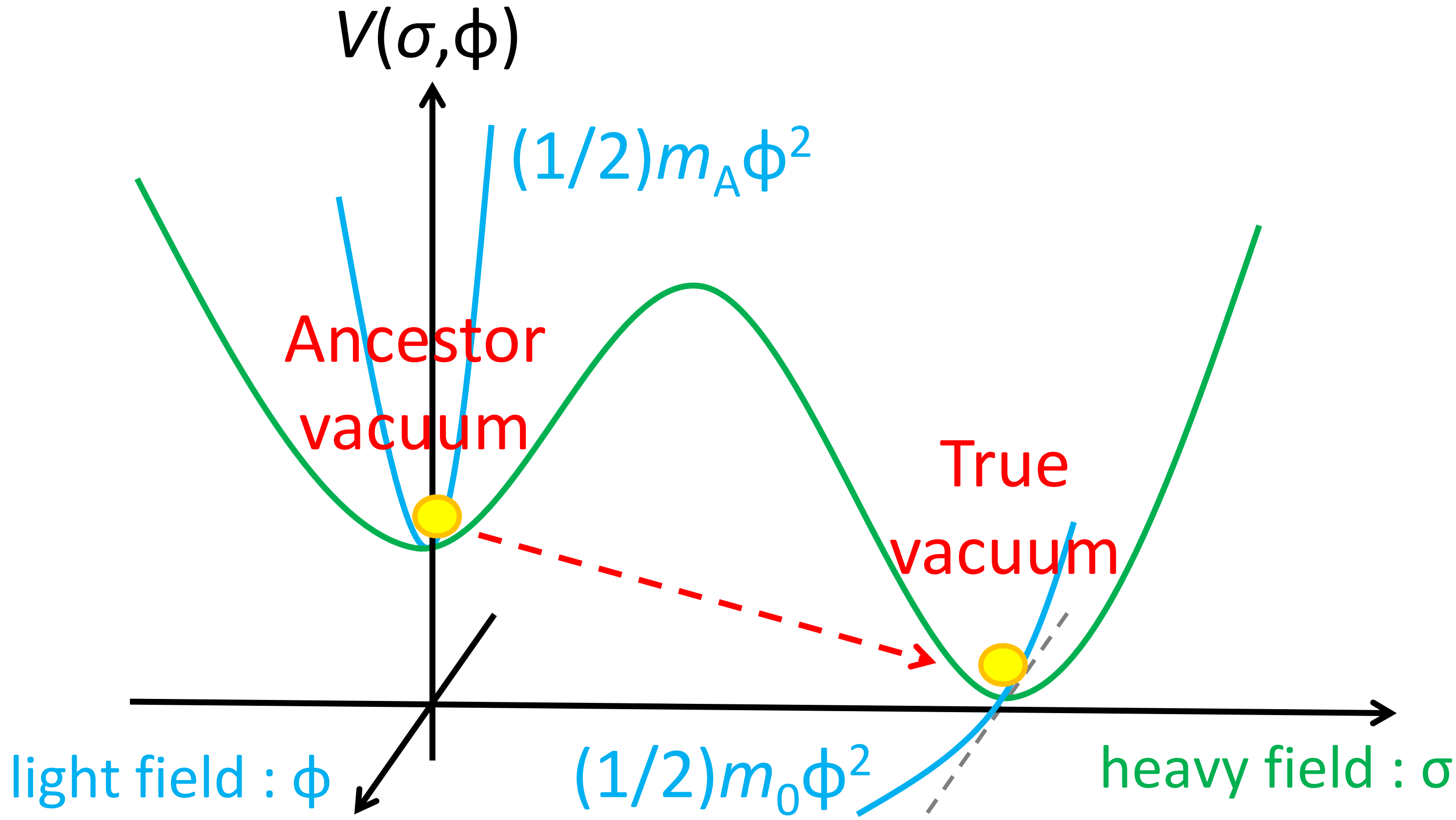
The low-energy scale of inflation is required.

# Our model

- Assumptions:
  - ✓ Our Universe have been created by **bubble nucleation** due to *Coleman-De Luccia* (CDL) quantum tunneling
  - ✓ Consider **a scalar field σ** to realize **the false vacuum decay**
  - ✓ Consider another **ultralight scalar field ϕ** with <ϕ>=0 (i.e., fully quantum field)

# Our model

- ✓ The field ϕ has the mass $\begin{cases} m_A \text{ before tunneling} \\ m_0 \text{ after tunneling} \end{cases}$



# Order-of-magnitude argument

- In the **ancestor vacuum**, the 2pt func is $\langle \phi^2 \rangle \approx \frac{H_{\rm A}^4}{m_{\rm A}^2}$
- Assuming $m_0 \lesssim H_0$, the field is almost frozen until now.
- The energy-momentum tensor for ϕ can read

$$\langle T_{\mu\nu} \rangle \approx m_0^2 \langle \phi^2 \rangle g_{\mu\nu} \approx H_{\rm A}^4 \left( \frac{m_0}{m_{\rm A}} \right)^2 g_{\mu\nu}$$

- To have $\rho \sim \rho_\Lambda \sim M_{\rm P}^2 H_0^2$, we just need

$$\frac{m_{\rm A}}{H_{\rm A}} \sim \frac{H_{\rm A}}{M_{\rm P}}$$

→ Easier to realize!

# Difference from *quintessence*

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

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

$$\rho = \frac{1}{a^2}\left\langle \frac{1}{2}\phi'^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2a^2\phi^2 \right\rangle$$

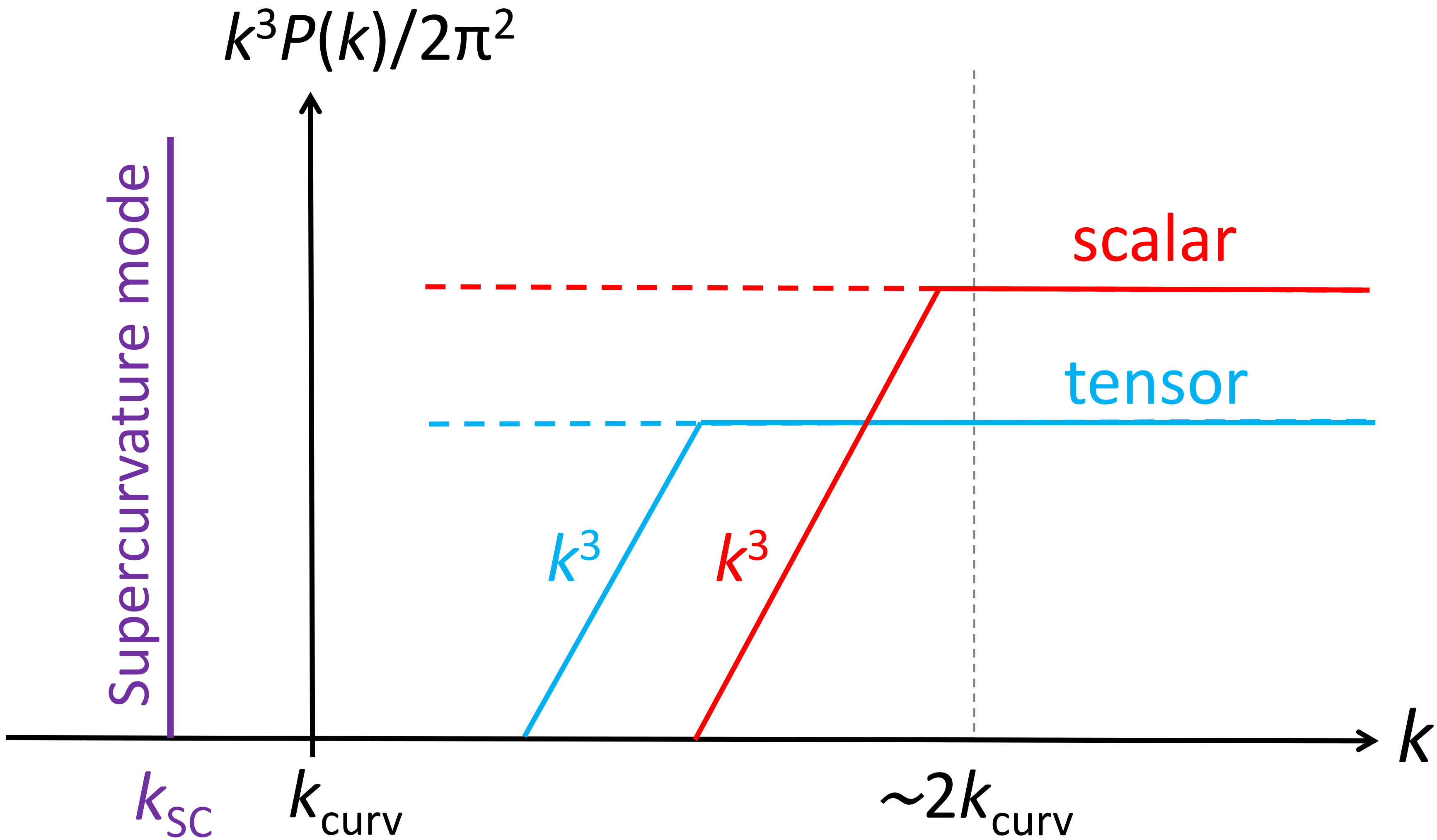
$$P = \frac{1}{a^2}\left\langle \frac{1}{2}\phi'^2 - \frac{1}{6}(\nabla\phi)^2 - \frac{1}{2}m^2a^2\phi^2 \right\rangle$$

[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




(若干の適当さを含みます)

[Aoki+Iso+Lee+Sekino+Yeh(2017)]

# Energy-momentum tensor for SC

$$\rho_{\rm SC} \approx \left( \frac{2\epsilon}{R_{\rm curv}^2 a^2} + \frac{1}{2} m_0^2 \right) \langle \phi^2 \rangle_{\rm SC}$$

$$P_{\rm SC} \approx -\left( \frac{2\epsilon}{3R_{\rm curv}^2 a^2} + \frac{1}{2} m_0^2 \right) \langle \phi^2 \rangle_{\rm SC}$$

with $\langle \phi^2 \rangle_{\rm SC} \approx \dfrac{H_{\rm A}^4}{m_{\rm A}^2}$

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.

[Aoki+Iso+Lee+Sekino+Yeh(2017)]

# Observational signatures

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

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

- The EoS parameter depends on a single parameter:

$$\widetilde{\epsilon} = \frac{\epsilon}{m_0^2 R_{\rm curv}^2} \approx \frac{(m_{\rm A}/H_{\rm A})^2}{(m_0/H_0)^2}\Omega_{\rm K,0}$$

# Observational signatures

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

$$\rho_{\rm SC} \approx 3M_{\rm P}^2 H_0^2 \Omega_\Lambda \left[1 + 2\widetilde{\epsilon}(1+z)^2\right]$$

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

$$\widetilde{\epsilon} \approx \frac{(m_{\rm A}/H_{\rm A})^2}{(m_0/H_0)^2}\Omega_{\rm K,0} = \xi\Omega_{\rm K,0}$$

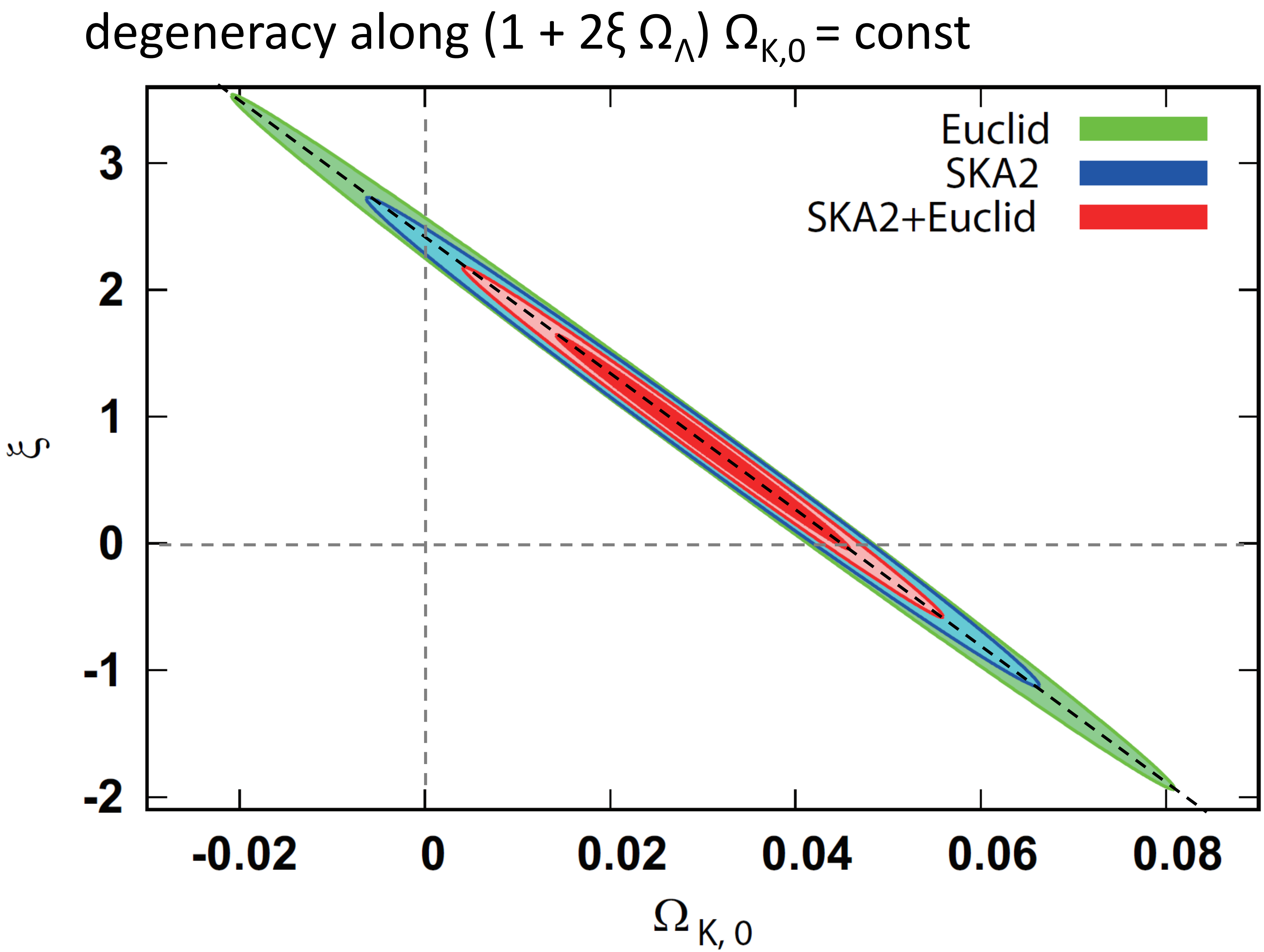
# Meaning of $\xi$

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

$$H_{\rm A} = \mathcal{O}(1)\xi^{1/2} M_{\rm P}$$
$$m_{\rm A} = \mathcal{O}(1)\xi \frac{m_0}{H_0} M_{\rm P}$$

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 + 2ξ Ω_Λ) Ω_K,0 = const
Euclid
SKA2
SKA2+Euclid
3
2
1
0
-1
-2
ξ
-0.02
0
0.02
0.04
0.06
0.08
Ω K, 0

# Discussion

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

(∵) The background equations strictly coincide with those in open-ΛCDM with the modified $\Omega_{K,0}$ :

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

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