Mass-varying gauge boson that couples to the dark energy field

Jiheon Lee
KAIST
anffl0101@kaist.ac.kr

[2208.09229] & [2306.01291]
with Kunio Kaneta, Hye-Sung Lee, Jaeok Yi

Review on gauged quintessence

- Quintessence gauged under U(1) (quintessence + Dark gauge boson)

$$\mathcal{L} = -|D_\mu \Phi|^2 - V_0(\Phi) - \frac{1}{4}\mathbb{X}_{\mu\nu}\mathbb{X}^{\mu\nu}$$

$$\Phi = \frac{1}{\sqrt{2}}\phi\, e^{i\eta}$$

$$\mathbb{X}_{\mu\nu} = \partial_\mu \mathbb{X}_\nu - \partial_\nu \mathbb{X}_\mu$$

$$D_\mu = \partial_\mu + i g_X \mathbb{X}_\mu$$

- In Unitary gauge, $(\eta = 0, \quad X_\mu = \mathbb{X}_\mu + \frac{1}{g_X}\partial_\mu \eta)$

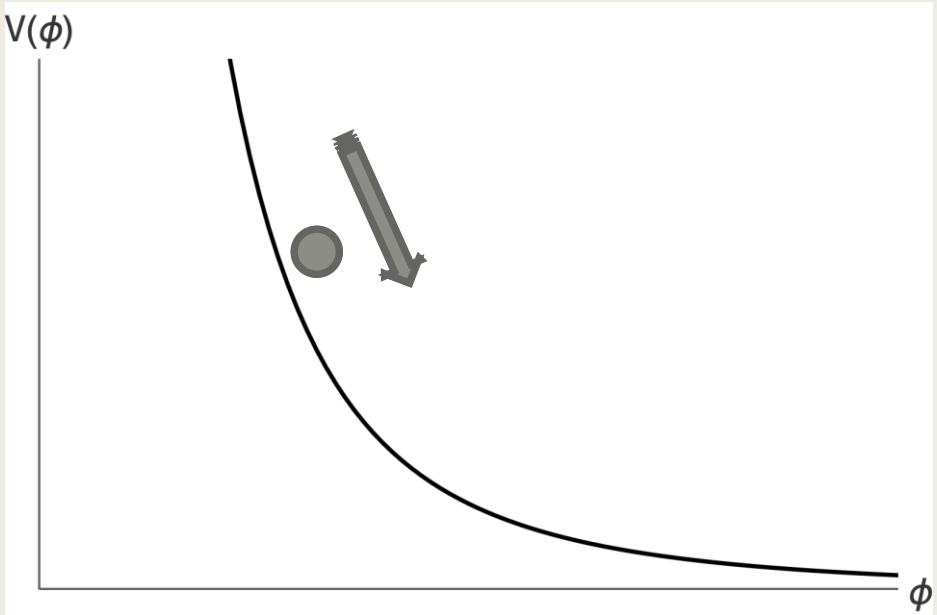
$$\mathcal{L} = \underbrace{-\frac{1}{2}(\partial_\mu \phi)^2 - V_0(\phi)}_{\text{Scalar (quintessence)}} \underbrace{- \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}g_X^2 \phi^2 X_\mu X^\mu}_{\text{Massive vector boson (dark gauge boson)}}$$

Ratra peebles potential (Inverse power)

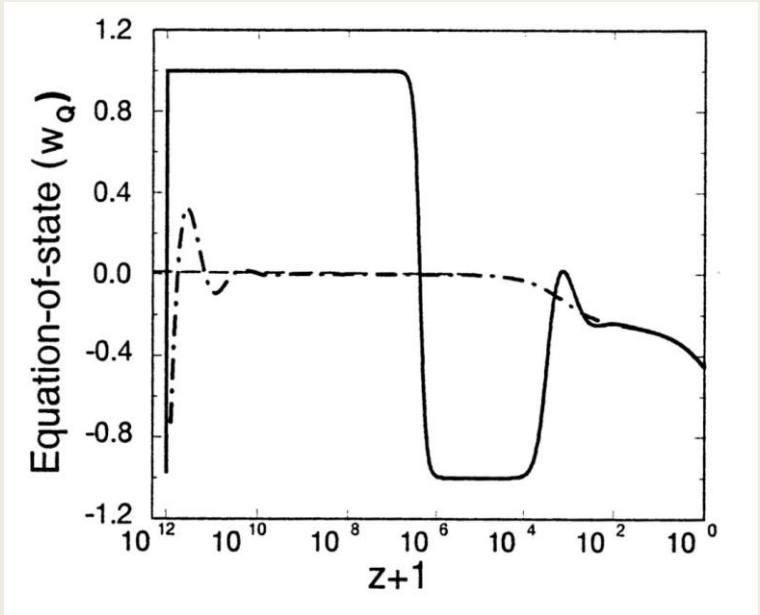
- Ratra-Peebles potential Ratra and Peebles Phys. ReV. D 37(1988)3406

$$V_0(\phi) = \frac{M^{\alpha+4}}{\phi^{\alpha}}$$

- The ϕ field runs toward to the larger value



- Tracking solution



Gauge Potential

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi)^2 - V_0(\phi) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \boxed{\frac{1}{2} g_X^2 \phi^2 X_\mu X^\mu}$$

$$\equiv V_{\rm gauge}$$

1.Give mass to X
2.Additional potential for ϕ

- Gauge potential affects the dynamics of ϕ and X.

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_0}{\partial \phi} + g_X^2 X_\mu X^\mu \phi = 0\,,$$

$$\partial_\mu X^{\mu\nu} + 3H X^{0\nu} - g_X^2 \phi^2 X^\nu = 0$$

Originated from $V_{\rm gauge}$

Production of coherent vector boson

Homogeneous in the observable universe

How the quintessence affects the relic vector boson density?

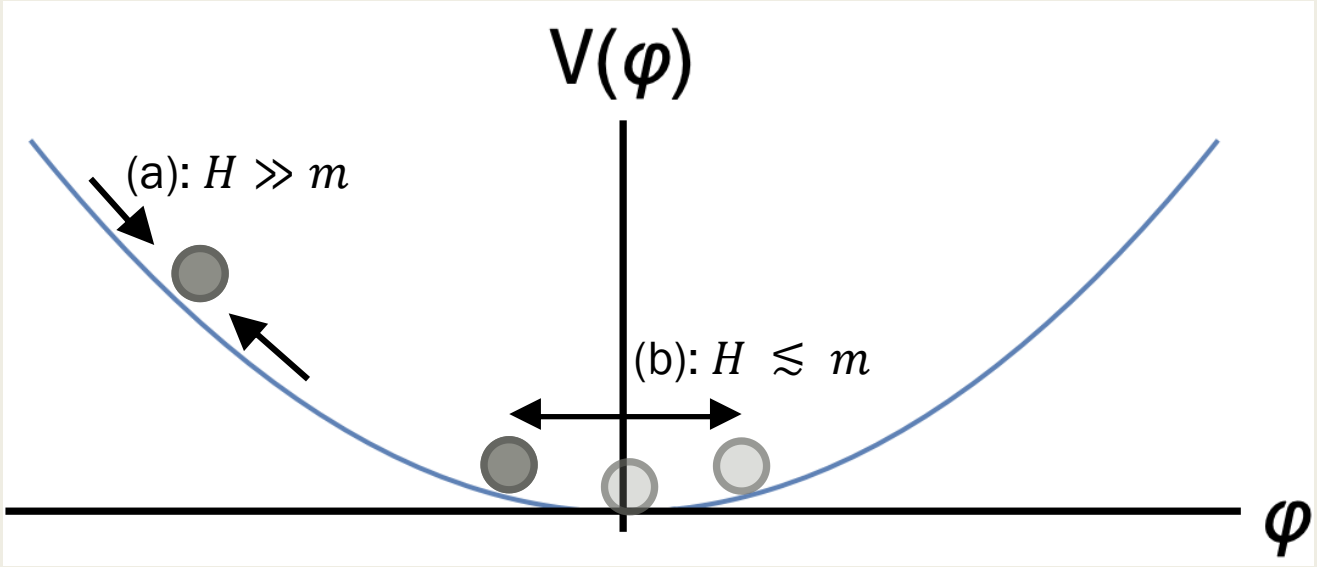
Misalignment Mechanism (Scalar)

Equation of motion

$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$

Energy density

$$\rho_\varphi = \frac{1}{2}\dot{\varphi}^2 + \frac{1}{2}m^2\varphi^2$$



- (a): $H \gg m$ The field is initially frozen due to Hubble friction.

$$\varphi \sim \text{constant} \qquad \rho_\varphi \sim \text{constant}$$

- (b): $H \lesssim m$ A coherent oscillation begins as the Hubble parameter drops below the mass.

$$\varphi \propto a^{-3/2} \qquad \rho_\varphi \propto a^{-3}$$ (Same as the non-relativistic matter)

Misalignment Mechanism (Vector)

Equation of motion

$$\ddot{X} + H\dot{X} + m_X^2 X = 0$$

Energy density

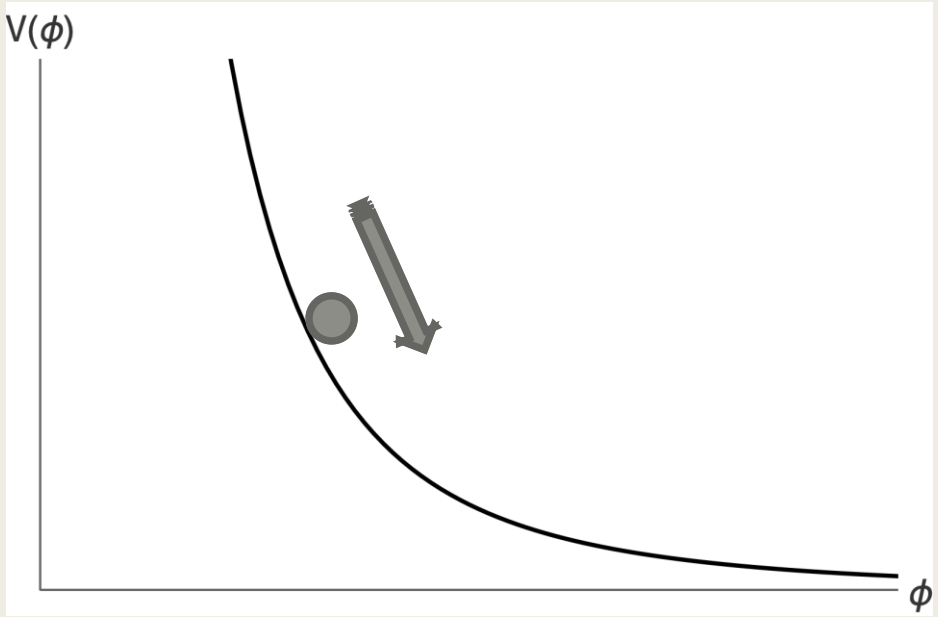
$$\rho_X = \frac{1}{2a^2}\left(\dot{X}^2 + m_X^2 X^2\right)$$

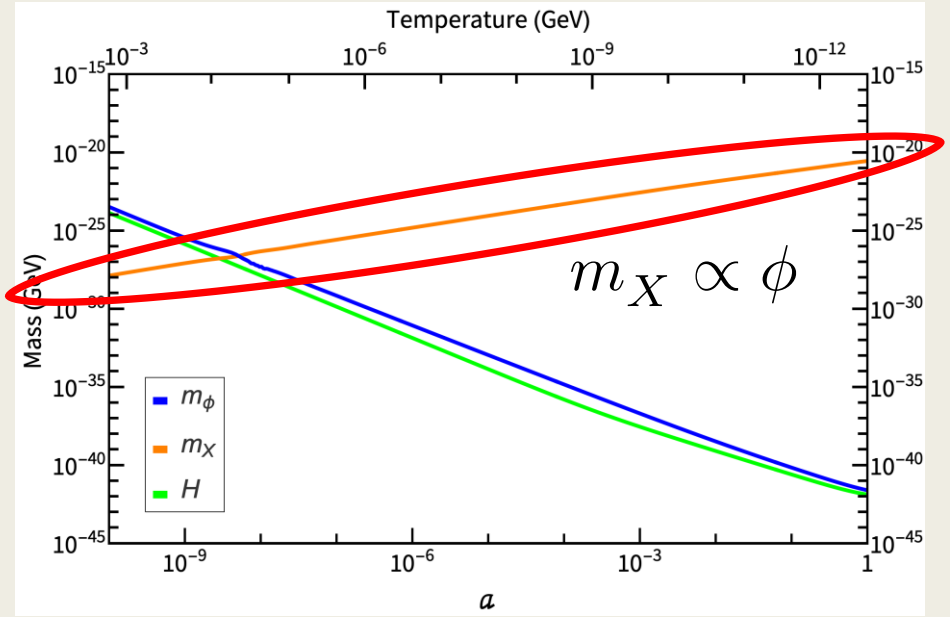
- The field is initially frozen due to Hubble friction. But energy decreases as $\rho_X \propto a^{-2}$

❖ This gives $\sim e^{-120}$ suppression during inflation.

➢ Relic vector density from the misalignment mechanism is negligibly small.

Vector misalignment in the gauged quintessence





- Quintessence (ϕ) field rolls down the potential.
  - The mass of the vector boson increases

$$\rho_X = \frac{1}{2a^2}\left(\dot{X}^2 + m_X^2 X^2\right)$$

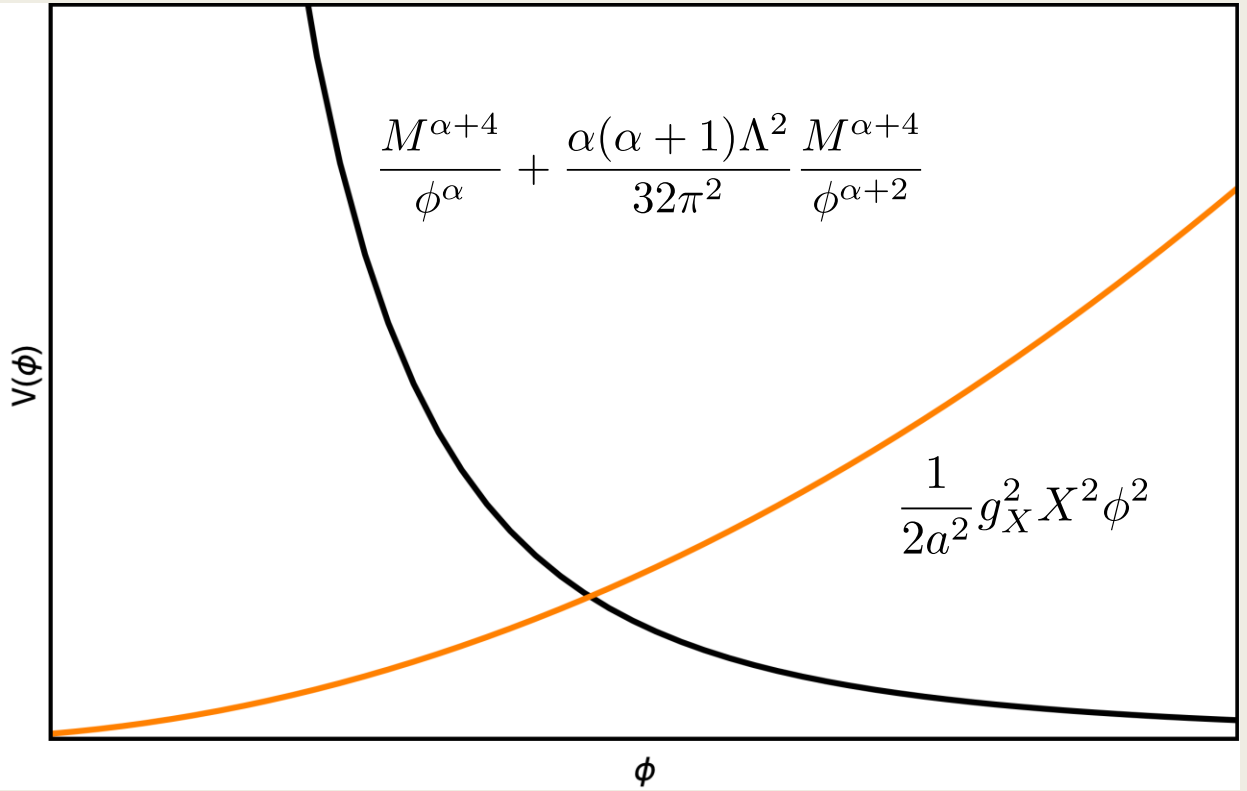
$$m_X = g_X \phi$$

Energy density can be amplified!

Coupled dynamics Revisited

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_0}{\partial \phi} + g_X^2 X_\mu X^\mu \phi = 0\,,$$

$$\partial_\mu X^{\mu\nu} + 3HX^{0\nu} - g_X^2 \phi^2 X^\nu = 0$$



- Equation of motion of ϕ

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_{\rm eff}}{\partial \phi} = 0$$

$$V_{\rm eff} = V_0 + V_{\text{1-loop}} + V_{\rm gauge}$$

- Equation of motion of X

$$\ddot{X} + H\dot{X} + g_X^2 \phi^2 X = 0$$ ⇐ Similar to the damped oscillator with time varying frequency ($g_X \phi = m_X$)

X dynamics

* $H \gg m_X$

w_b : background equation of state

$$\overline{X} \equiv X/a, \quad \overline{X} + 3H\overline{X} + \frac{1-3w_b}{2}H^2\overline{X} = 0$$

- Kinetic energy dominated: $\frac{1}{2a^2}\dot{X}^2 \gg \frac{1}{2a^2}m_X^2X^2$

$$X \propto a^{-1}, \quad \rho_X \propto H^2 a^{3w_b-1}$$

- Potential energy dominated: $\frac{1}{2a^2}\dot{X}^2 \ll \frac{1}{2a^2}m_X^2X^2$

$$X \sim \text{constant}, \quad \rho_X \propto \phi^2 a^{-2}$$

* $H \ll m_X$

- Coherent Oscillation

(WKB approximation)

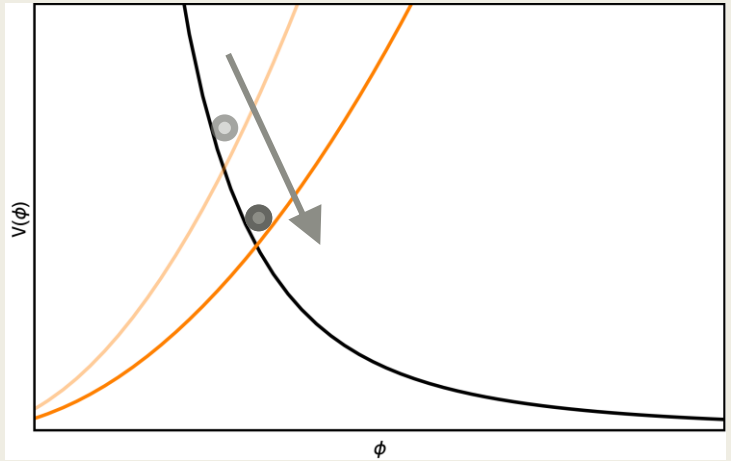
$$X \propto \frac{1}{\sqrt{\phi a^3}}$$

$$\rho_X \propto \phi a^{-3} \, (\propto m_X a^{-3})$$

Non-relativistic. But mass-varying.

Quintessence dynamics

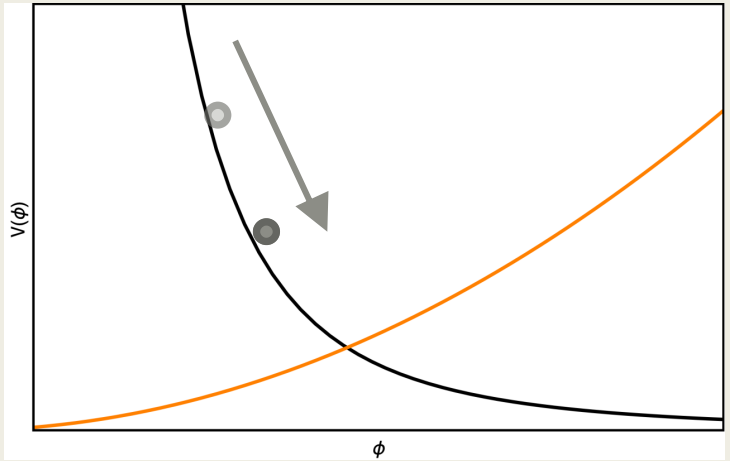
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_{\rm eff}}{\partial \phi} = 0$$



$* \quad m_\phi \gtrsim H, \quad \frac{\partial^2 V_{\rm gauge}}{\partial \phi^2} \gtrsim H^2$

ϕ follows the minimum

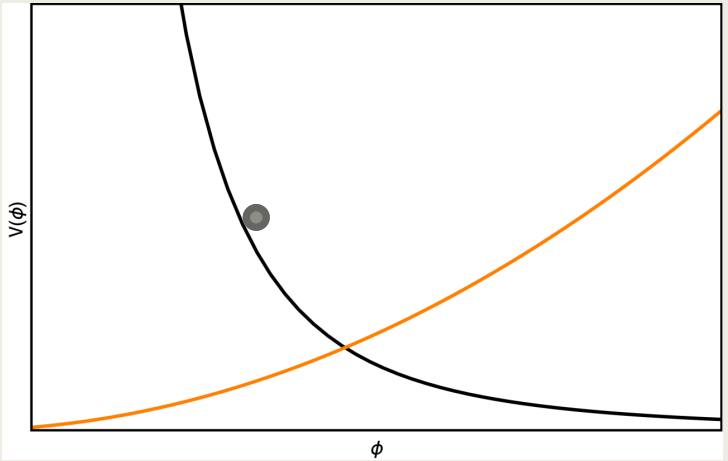
$$\phi \propto a^{\frac{2}{\alpha+4}} \quad (H \gg m_X)$$
$$\phi \propto a^{\frac{2}{\alpha+3}} \quad (H \ll m_X)$$



$* \quad m_\phi \sim H, \quad \frac{\partial^2 V_{\rm gauge}}{\partial \phi^2} \ll H^2$

ϕ follows the tracking solution of Ratra-Peebles potential

$$\phi \propto a^{\frac{3(1+w_b)}{\alpha+1}}$$

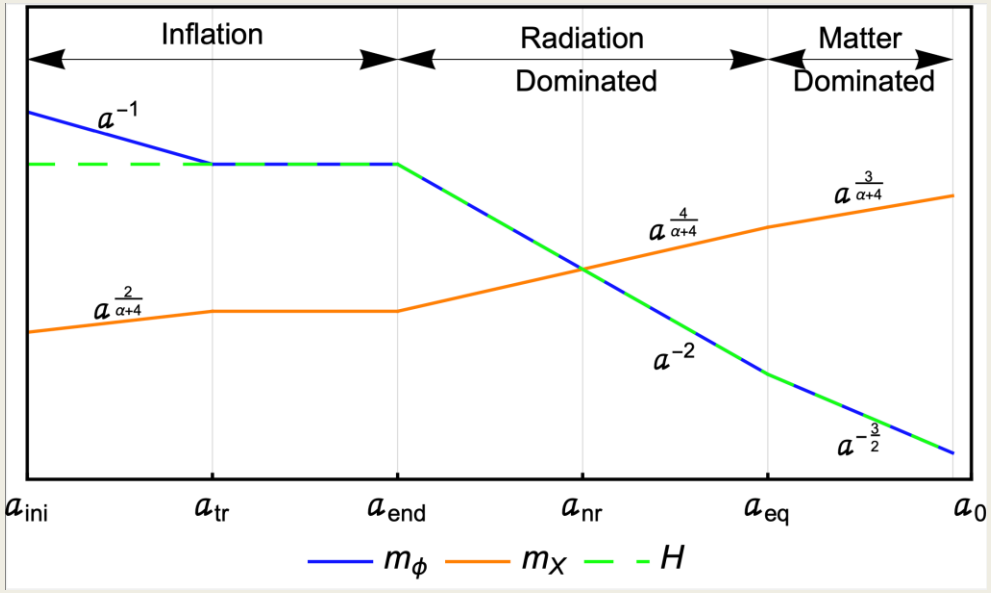


$* \quad m_\phi \ll H$

$\dot{\phi} \ll H\phi : \phi$ is frozen

$$\phi \sim \text{constant}$$

Viable Scenario



	$\overline{X}$	$\phi \propto m_X$	ρ_X
$a_{\rm ini} < a < a_{\rm tr}$	$\propto a^{-1}$	$\propto a^{\frac{2}{\alpha+4}}$	$\propto a^{-\frac{2\alpha+4}{\alpha+4}}$
$a_{\rm tr} < a < a_{\rm end}$	$\propto a^{-1}$	$\approx$ constant	$\propto a^{-2}$
$a_{\rm end} < a < a_{\rm nr}$	$\propto a^{-1}$	$\propto a^{\frac{4}{\alpha+4}}$	$\propto a^{-\frac{2\alpha}{\alpha+4}}$
$a_{\rm nr} < a < a_{\rm eq}$	$\propto a^{-\frac{3\alpha+16}{2\alpha+8}}$	$\propto a^{\frac{4}{\alpha+4}}$	$\propto a^{-\frac{3\alpha+8}{\alpha+4}}$
$a_{\rm eq} < a < a_0$	$\propto a^{-\frac{3\alpha+15}{2\alpha+8}}$	$\propto a^{\frac{3}{\alpha+4}}$	$\propto a^{-\frac{3\alpha+9}{\alpha+4}}$

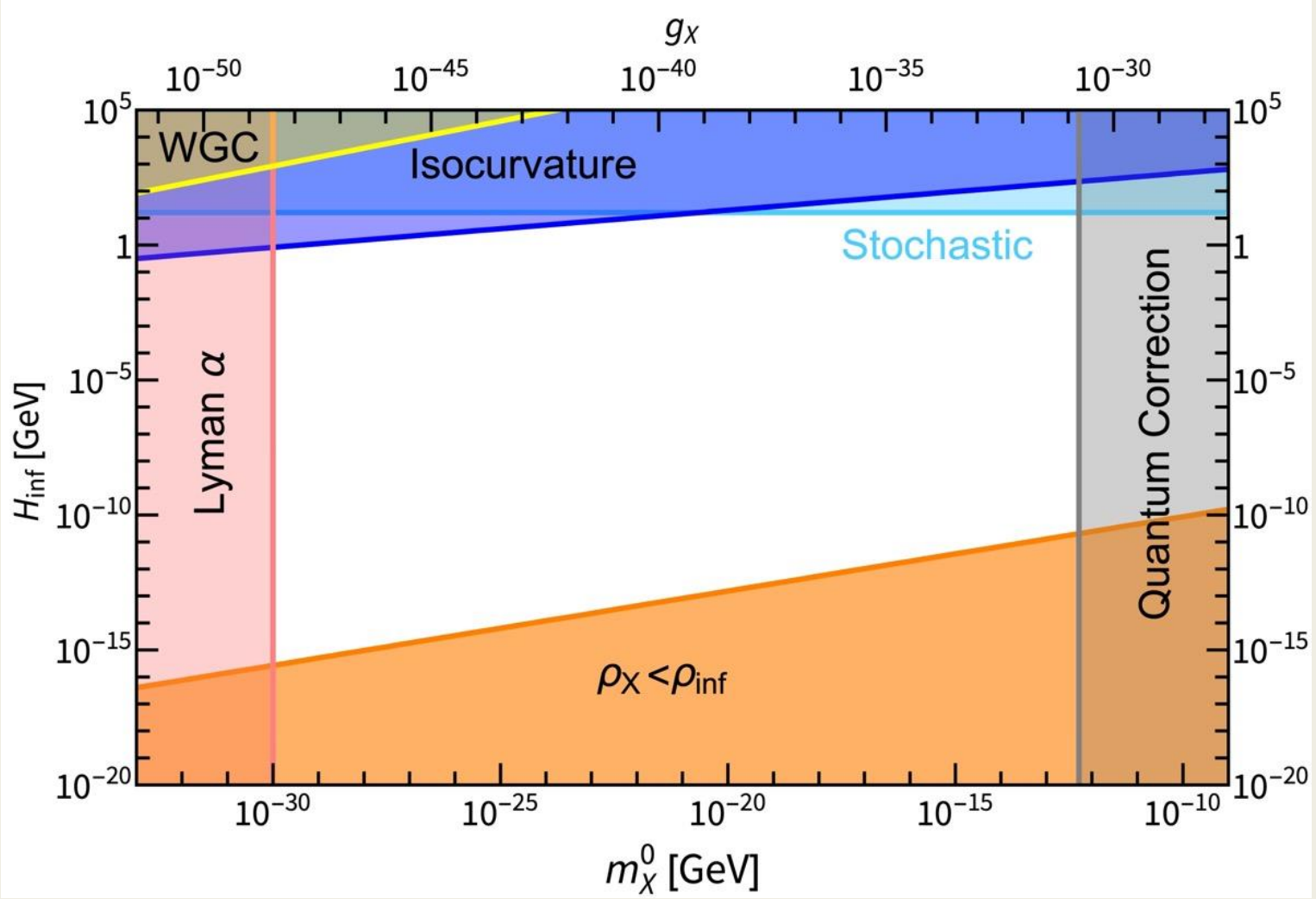
- This scenario requires initial potential energy domination of X $\frac{1}{2a^2}\dot{X}^2 \ll \frac{1}{2a^2}m_X^2 X^2$
- ϕ field joins the tracking solution during the inflation

Misalignment production in the gauged quintessence

$\alpha = 1,\ M = 2.2 \times 10^{-6}\,\mathrm{GeV}$

$$V_0 = \frac{M^{\alpha+4}}{\phi^{\alpha}}$$

$$\Omega_X h^2 \sim 0.12$$



- The mass-increasing effect allows to produce sufficient amount of vector boson density

Summary and remark

- Gauged quintessence: quintessence + U(1) gauge symmetry (dark gauge boson)
  - ➢ The mass of dark gauge boson can increase during cosmic history

- Misalignment production of coherent vector boson is extremely suppressed
  - ➢ The mass-increasing effect can amplify the energy density of vector boson

    So, a large amount of relic density can be produced (comparable to CDM)
  - ❖ We expect the mass-increasing effect generically help the misalignment production of vector boson

Thank you!