Misalignment mechanism for a mass-varying vector boson

Jaeok Yi

Department of Physics, KAIST

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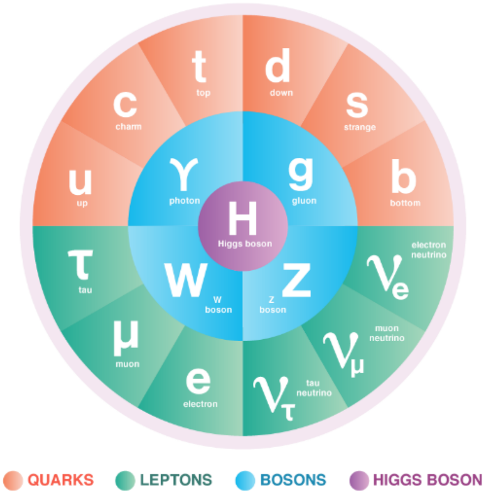
based on arXiv:2306.01291
with Kunio Kaneta, Hye-Sung Lee, and Jiheon Lee

Overview

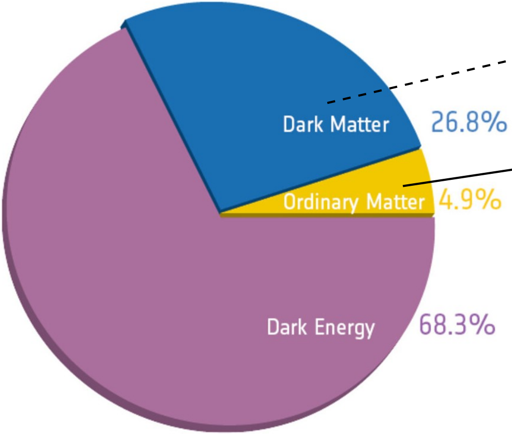
I. Introduction

Standard Model



$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

ΛCDM Model

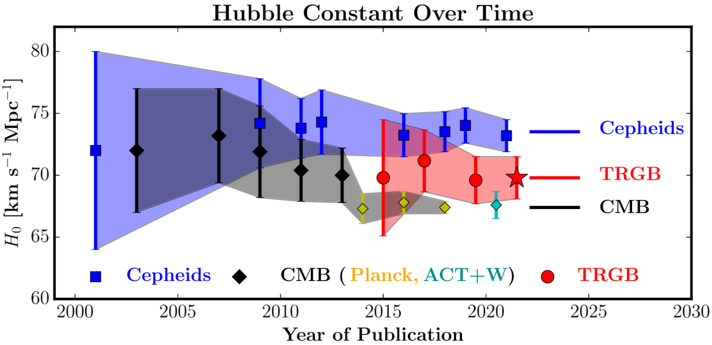


$U(1)_{PQ}$, $U(1)_X$, $U(1)_{B-L}$
Supersymmetry, $\cdots$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

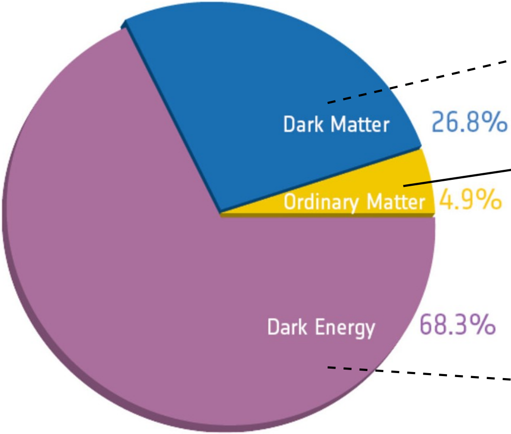
Challenges on ΛCDM Model

- Hubble Tension



- Small Scale Problem
- James Webb Telescope

New Symmetry on Dark Energy Sector?



$U(1)_{PQ}$, $U(1)_X$, $U(1)_{B-L}$
Supersymmetry, $\cdots$

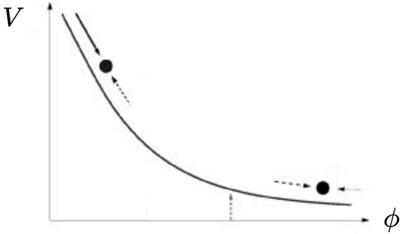
$SU(3)_C \times SU(2)_L \times U(1)_Y$

New symmetry?

II. Gauged Quintessence

Quintessence

- Dynamic dark energy model proposed by Ratra and Peebles.
  [Bharat Ratra and P. J. E. Peebles PRD37(1988)3406]
- A scalar ϕ rolls down a potential slowly in the present universe.



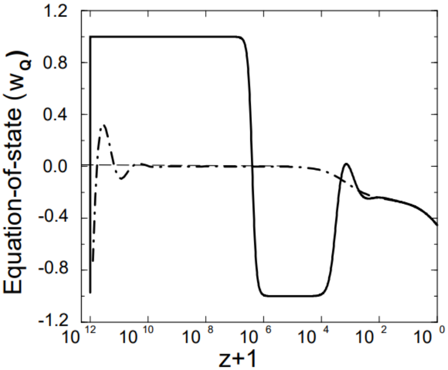
- Equation of state assuming slow roll condition $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx -1$$

Tracking Behavior

- The initial value of ϕ does not matter. Only the potential determines the present time value of and its equation of state (addressing the cosmological coincidence problem).

[Steinhardt, Wang, Zlatev PRL82(1999)896]



Gauged Quintessence

- The gauged quintessence model includes complex scalar $\Phi = \phi e^{i\eta}/\sqrt{2}$ and $U(1)_{\rm dark}$ gauge boson $\mathbb{X}_\mu$. Φ is charged under the $U(1)_{\rm dark}$ gauge symmetry and ϕ behaves as dark energy.

[KK, HL, JL, and **JY** JCAP02(2023)005]

- Under the unitary gauge, $\eta = 0$ and $X_\mu = \mathbb{X}_\mu + \frac{1}{g_X}\partial_\mu \eta$, the Lagrangian of gauged quintessence model is given by

$$\mathcal{L} \supset \sqrt{-g}\Big[-\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - V_0(\phi) - \frac{1}{2}(g_X\phi)^2 X_\mu X^\mu \Big]$$

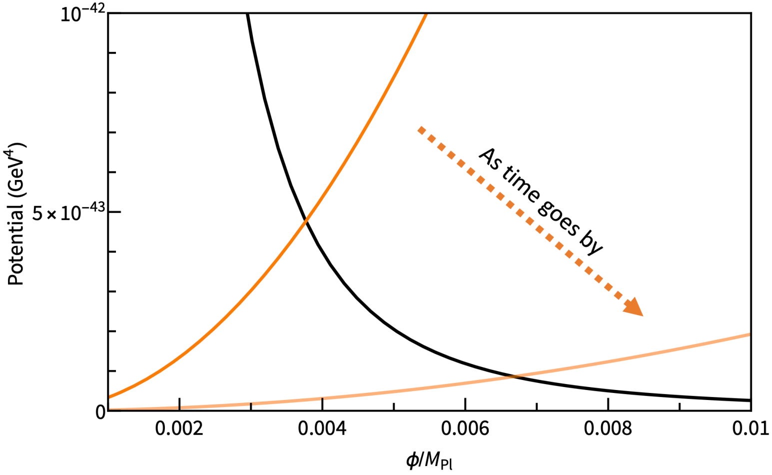
where g_X is the dark gauge coupling constant.

- We chose $V_0(\phi)$ to be the inverse power potential,

[Bharat Ratra and P. J. E. Peebles PRD37(1988)3406]

$$V_0(\phi) = \frac{M^{\alpha+4}}{\phi^\alpha}, \quad \alpha > 0$$

Potential



10^{-42}
5×10^{-43}
0
Potential (GeV^4)
0.002
0.004
0.006
0.008
0.01
ϕ/M_{Pl}
As time goes by

Mass-varying Behavior

- The masses of ϕ and X are given as

$$m_\phi^2 = \frac{\partial^2 V_{\text{eff}}}{\partial \phi^2}, \quad m_X^2 = g_X^2 \phi^2$$

- When the tracking and rolling of quintessence begin, m_X increases. Also, there exists an energy flow from ϕ to X.
- Boltzmann equation of ϕ is given by

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = -2\frac{\dot{m}_X}{m_X} V_{\text{gauge}}$$

- Mass-varying behavior indicates the energy flow from ϕ to X.

Hubble Tension

- To relieve Hubble tension, $w(DE) < -1$ is favored in the recent era.

  [Bum-Hoon Lee *et al* JCAP04(2022)004]

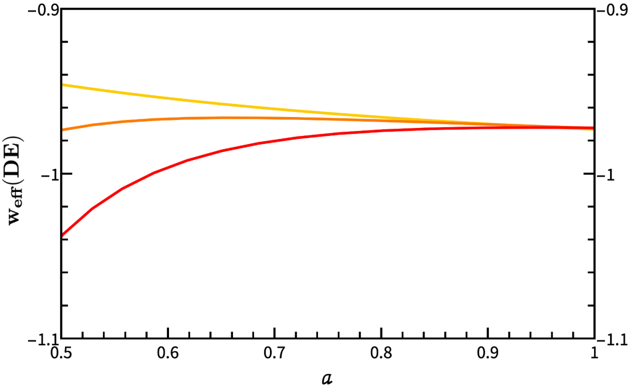
- In the gauged quintessence model,

$$w_{\text{eff}}(\widetilde{DE}) = -1 + \frac{1}{\rho_{\widetilde{DE}}}\left((1+w_\phi^0)\rho_\phi + \left(\frac{m_X}{m_X^0} - 1\right)\frac{\rho_X^0}{a^3}\right)$$

where $\rho_{\widetilde{DE}} = \rho_\phi + \rho_X - \rho_X^0 a^{-3}$ and ^{0} implies the present value.

- $w_{\text{eff}}(\widetilde{DE})$ can be smaller than -1 due to the mass-varying effect.

Hubble Tension



$\rho^0_X/\rho^0_{\rm CDM} = 0.013$ $\rho^0_X/\rho^0_{\rm CDM} = 0.09$ $\rho^0_X/\rho^0_{\rm CDM} = 0.27$

III. Misalignment

Misalignment Mechanism

- The misalignment mechanism is a mechanism for retaining the correct relic density of dark matter.
  - Homogeneous condensate due to inflation.
  - Coherent oscillation.
- Assuming spatial homogeneity, the equation of motion and the energy density of the scalar field φ are given as

$$\ddot{\varphi} + 3H\dot{\varphi} + m_\varphi^2 \varphi = 0, \quad \rho_\varphi = \frac{1}{2}(\dot{\varphi}^2 + m_\varphi^2 \varphi^2)$$

- φ is frozen and ρ_ϕ is constant during inflation due to the large Hubble friction. As H becomes smaller than m_φ, φ begins coherent oscillation and $\rho_\varphi \propto a^{-3}$ like usual cold dark matter.

Misalignment Mechanism for Gauge Boson

- The misalignment mechanism does not work well for the vector field.

[Kazunori Nakayama JCAP10(2019)019]

Assuming homogeneity, the equation of motion and the energy density of the vector boson $X_\mu = (0,0,0,X)$ are given as

$$\ddot{X} + H\dot{X} + m_X^2 X = 0, \quad \rho_X = \frac{1}{2a^2}(\dot{X}^2 + m_X^2 X^2)$$

- By solving the equation of motion, we have

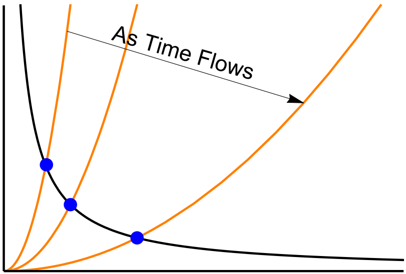
$$\rho_X \propto \begin{cases} m_X^2 a^{-2} & (m_X \ll H) \\ m_X a^{-3} & (m_X \gg H) \end{cases}$$

- Due to the scale factor, ρ_X becomes tiny after inflation.

$$\frac{a_{\rm end}}{a_{\rm ini}} = e^{60} \quad \Rightarrow \quad \frac{\rho_X(a_{\rm end})}{\rho_X(a_{\rm ini})} \sim e^{-120} \quad \text{(60 e-folding inflation)}$$

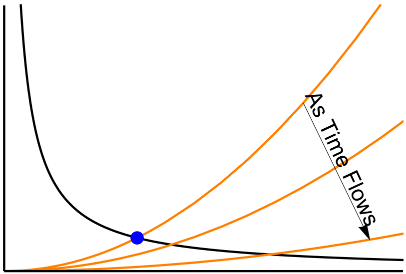
Dynamics of ϕ

$m_\phi \gg H$



- ϕ follows the minimum of V.
- m_ϕ decreases.

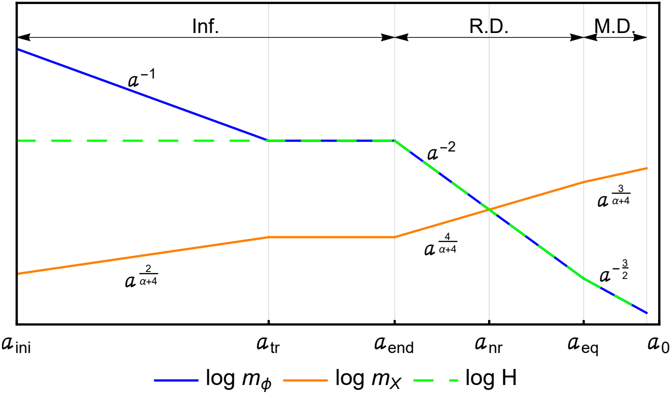
$m_\phi \approx H$



- ϕ shows tracking behavior.
- m_ϕ is fixed since H is constant.

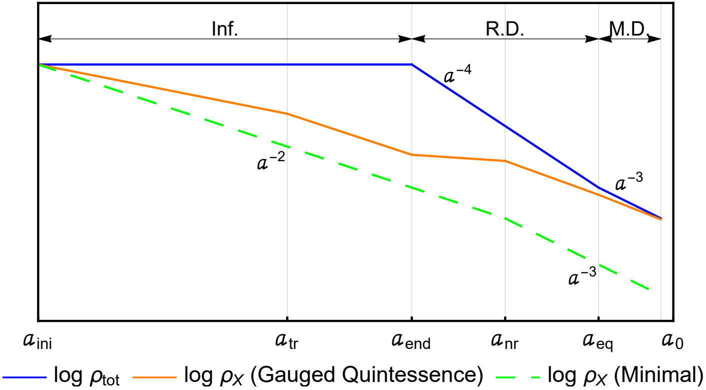
Evolution of Masses

- Initially, m_ϕ is determined by minimum of V.
- Once $m_\phi \approx H$, the evolution of m_ϕ follows that of H (tracking).
- Due to the rolling of ϕ, m_X increases over time.



Evolution of ρ_X

- More ρ_X survives in the gauged quintessence model.



IV. Constraints

Constraint from Misalignment

- Initial ρ_X should be smaller than the inflaton energy density.

$$\rho_X(a_{\mathrm{ini}}) \ll \rho_{\mathrm{inf}}(a_{\mathrm{ini}})$$

- ρ_X at the present should be comparable to CDM density.

$$\rho_X(a_0) \approx \rho_{\mathrm{CDM}}(a_0)$$

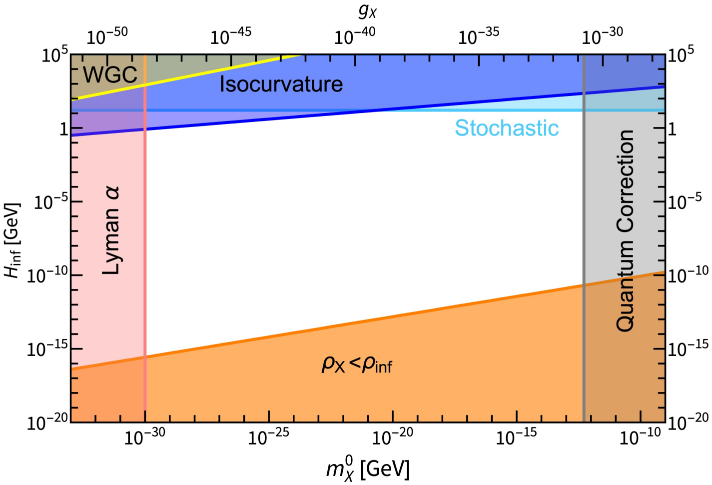
- In the minimal vector boson model, these relations exhaust all the parameter space.
- However, this constraint becomes weaker in the gauged quintessence model.

Quantum Fluctuations

- The fluctuation of X is an independent degree of freedom from the inflaton fluctuation, so the isocurvature fluctuation is generated from the quantum fluctuation of the X.
- Since it is constrained by CMB spectrum, the isocurvature fluctuation suggests a constraint.
- The fluctuation of ϕ can generate stochastic random jumps of ϕ.
- This stochastic perturbation should be small for the homogeneous mode of ϕ to dominate so it suggests another constraint.

Constraint Plot

- Misalignment production is available for the gauged quintessence model.



V. Summary

Summary

- ΛCDM model is severely challenged these days.
- Gauged quintessence model is a $U(1)$ charged quintessence model.
- Due to the mass-varying effect of gauged quintessence model, the misalignment mechanism can provide a sufficient amount of dark gauge boson.
- More researches on dark energy sector including gauged quintessence model are warranted.

Thank you for listening

Back-up Slides

Quantum Correction

- From Coleman-Weinberg potential, the quantum correction for V and m_ϕ can be calculated.

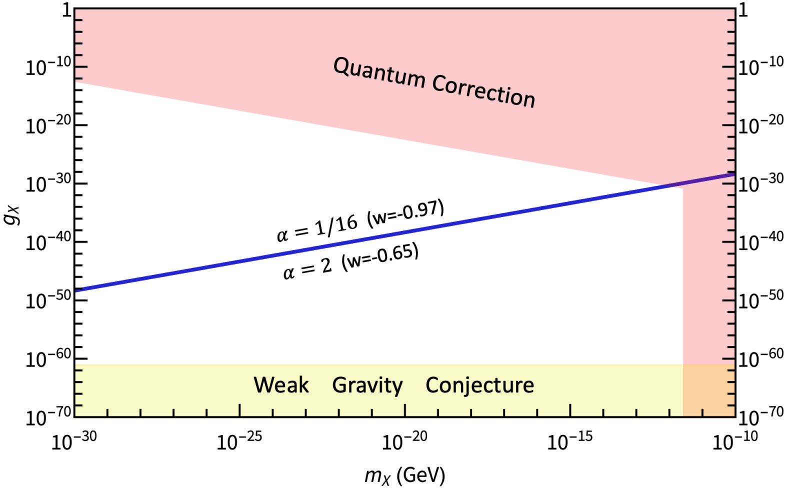
$$V_{\text{eff}} = V_0 + \frac{1}{2} g_X^2 X_\mu X^\mu \phi^2 + \frac{\Lambda^2}{32\pi^2} V_0'' + \frac{(V_0'')^2}{64\pi^2}\left(\ln \frac{V_0''}{\Lambda^2} - \frac{3}{2}\right) + \frac{3(m_X^2|_0)^2}{64\pi^2}\left(\ln \frac{m_X^2|_0}{\Lambda^2} - \frac{5}{6}\right)$$

$$m_\phi^2 = V_0'' + g_X^2 X_\mu X^\mu + \frac{\Lambda^2}{32\pi^2} V_0'''' + \frac{V_0'' V_0''''}{32\pi^2}\left(\ln \frac{V_0''}{\Lambda^2} - 1\right) + \frac{9 g_X^2 m_X^2|_0}{16\pi^2}\left(\ln \frac{m_X^2|_0}{\Lambda^2} + \frac{1}{3}\right)$$

- To satisfy dark energy density and tracking condition, we need

$$V_{\text{eff}} \sim 3 \times 10^{-47}\ \text{GeV}^4, \quad m_\phi^2 \sim H_0^2 \sim 10^{-42}\ \text{GeV}$$

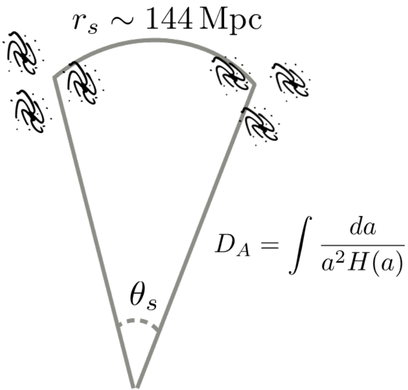
Constraint from Quantum Correction



Baryon Acoustic Oscillation and Hubble Tension

- To relieve Hubble tension, $w(DE) < -1$ is favored in the recent era.

[Bum-Hoon Lee *et al* JCAP04(2022)004]



- r_s : determined by early universe
- θ_s : experimentally determined