

# Gauged Quintessence

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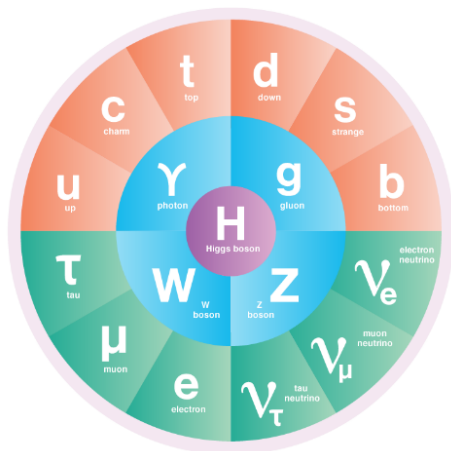
based on arXiv:2208.09229 with Kunio Kaneta, Hye-Sung Lee, and Jiheon Lee

# Overview

- 1 Introduction
- 2 Quintessence
- 3 Gauged Quintessence
- 4 Hubble Tension
- 5 Summary

# I. Introduction

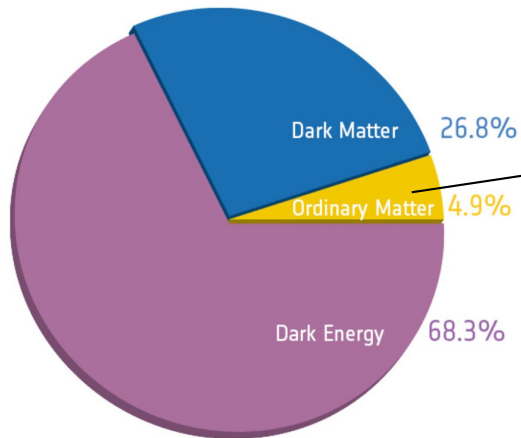
# Standard Model



● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

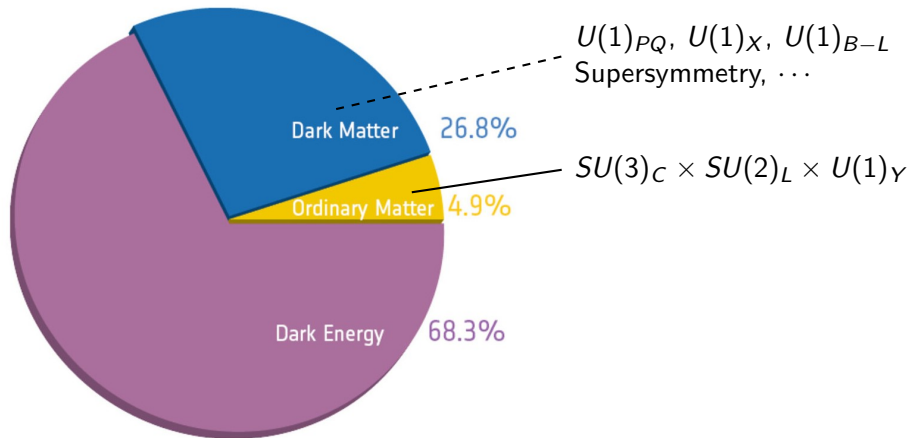
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

# $\Lambda$ CDM Model



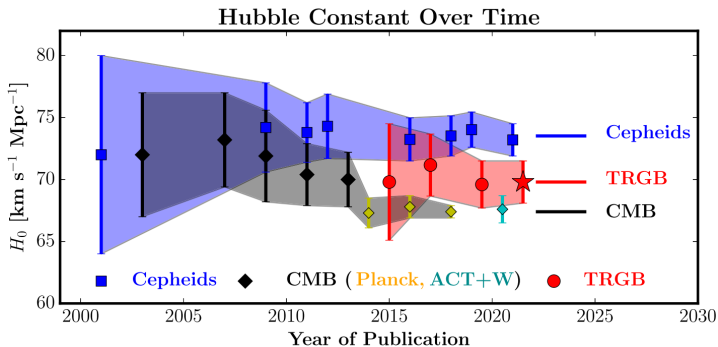
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

# $\Lambda$ CDM Model



# Challenges on $\Lambda$ CDM Model

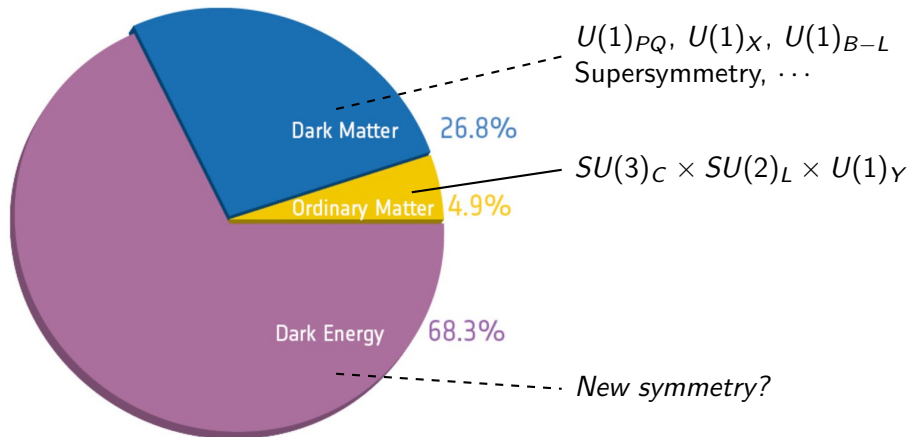
## ■ Hubble Tension



## ■ Small Scale Problem

## ■ James Webb Telescope

## New Symmetry on Dark Energy Sector?





## II. Quintessence

## Accelerating Expansion

- According to the Friedmann equation, to have accelerating expansion, we need

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3} > 0$$

where  $\Lambda$  is the cosmological constant.

- $\Lambda$ CDM model assigns positive  $\Lambda$  to get accelerating expansion.
- If  $\Lambda$  vanishes, it is necessary that  $p < -\rho/3$ , or

$$w = \frac{p}{\rho} < -\frac{1}{3}$$

## Problems Related to $\Lambda$

### ■ Cosmological Constant Problem

[J Martin, Comptes Rendus Physique 13(2012)566-665]

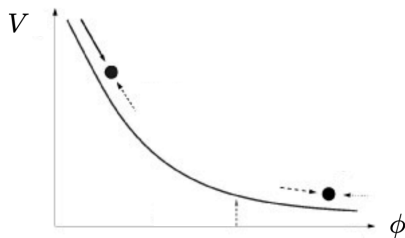
$$10^{-47} \text{ GeV}^4 \sim \frac{\Lambda_{\text{obs}}}{8\pi G} = \frac{\Lambda}{8\pi G} + \rho_{\text{vac}} \sim \frac{\Lambda}{8\pi G} - 10^8 \text{ GeV}^4$$

### ■ Cosmological Coincidence Problem

$$\rho_{\text{DM}}^0 \sim \rho_{\text{DE}}^0, \quad \text{but} \quad \rho_{\text{DM}} \propto a^{-3}, \quad \rho_{\text{DE}} = \text{constant}$$

## Quintessence

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



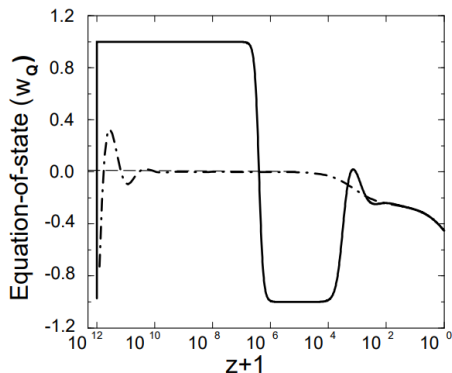
- Equation of state assuming slow roll condition  $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$

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

## Tracking Behavior

- The initial value of  $\phi$  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]



### III. Gauged Quintessence

## Gauged Quintessence

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

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

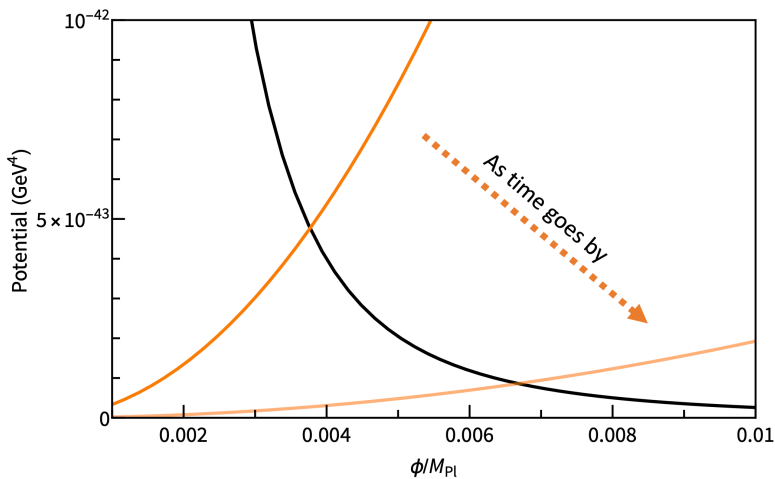
where  $g_X$  is the dark gauge coupling constant.

- 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





## Coupled Dynamics

- The masses of  $\phi$  and  $X$  are given as

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

- Coupled equations of motion determine dynamics of  $X$  and  $\phi$ .

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} + g_X^2 X_\mu X^\mu \phi = 0, \quad \partial_\mu X^{\mu\nu} + 3HX^{0\nu} - g_X^2 \phi^2 X^\nu = 0$$

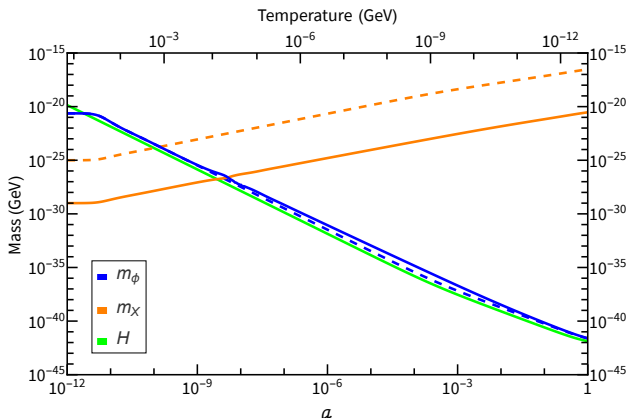
where  $V = V_{\text{eff}} - V_{\text{gauge}}$  and  $V_{\text{gauge}} = \frac{1}{2}g_X^2 \phi^2 X_\mu X^\mu$ .

- Boltzmann equation gives

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

## Mass-varying Behavior

- When the tracking and rolling of quintessence begin,  $m_X$  increases. Also, there exists an energy flow from  $\phi$  to  $X$ .



## Quantum Correction

- From Coleman-Weinberg potential, the quantum correction for  $V$  and  $m_\phi$  can be calculated.

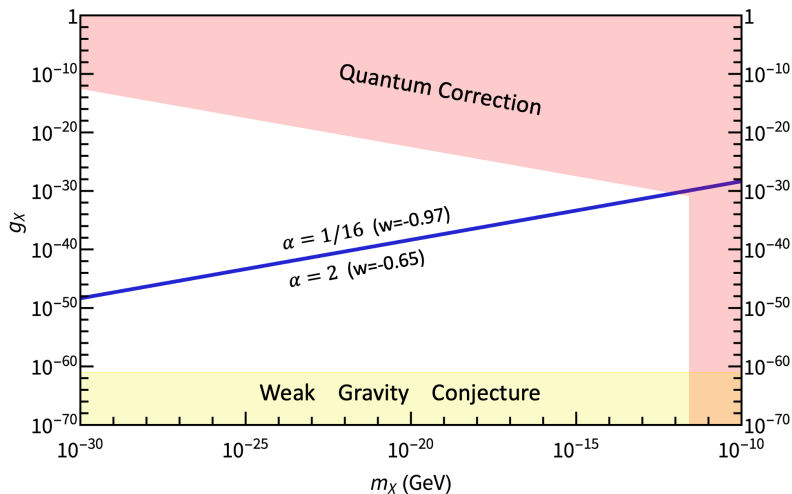
$$V_{\text{eff}} = V_0 + \frac{1}{2} g_X^2 X_\mu X^\mu \phi^2 + \frac{\Lambda^2}{32\pi^2} V_0'' + \frac{(V_0'')^2}{64\pi^2} \left( \ln \frac{V_0''}{\Lambda^2} - \frac{3}{2} \right) + \frac{3(m_X^2|_0)^2}{64\pi^2} \left( \ln \frac{m_X^2|_0}{\Lambda^2} - \frac{5}{6} \right)$$

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

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

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

# Constraint from Quantum Correction

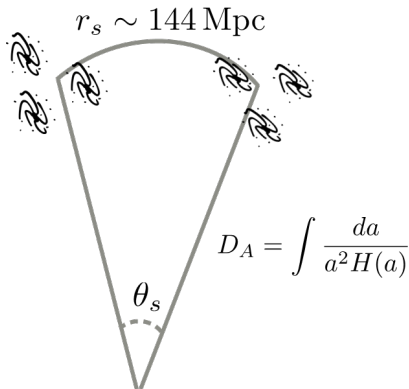


## IV. Hubble Tension

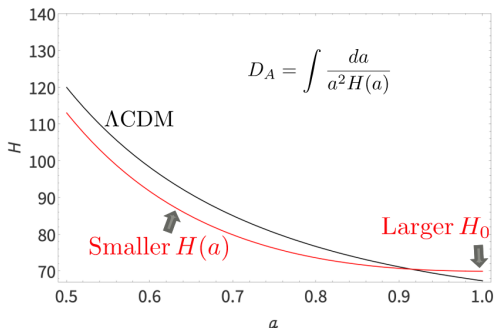
## Baryon Acoustic Oscillation and Hubble Tension

- 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
- $\theta_s$  : experimentally determined

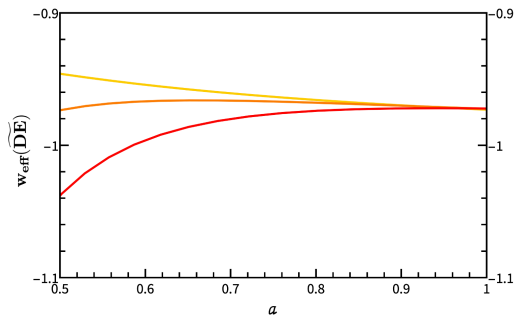


## Gauged Quintessence and Hubble Tension

- 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.



- $\rho_X^0/\rho_{\text{CDM}}^0 = 0.013$
- $\rho_X^0/\rho_{\text{CDM}}^0 = 0.09$
- $\rho_X^0/\rho_{\text{CDM}}^0 = 0.27$

## V. Summary



## Summary

- $\Lambda$ CDM model is severely challenged these days.
- Gauged quintessence model is a  $U(1)$  charged quintessence model.
- Due to the quantum correction, tiny gauge coupling is necessary.
- It might relieve Hubble tension since  $w_{\text{eff}}(\widetilde{DE}) < -1$  can be achieved.
- More researches on dark energy sector including gauged quintessence model are warranted.

*Thank you for listening*