Contribution of Majoron and new gaage boson to Hubble tension in a realistic gauged $U(1)_{L\mu - L\tau}$ Model

Based on PTEP 2024 (2024) 7, 073E01

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PTEP 2021 (2021) 10, 103 • e-Print: 2103.07167 [hep-ph],
Phys.Rev.D 100 (2019) 9, 095012 • e-Print: 1909.08827 [hep-ph]

Plan of talk

1. Introduction
2. Renormalizable $L_\mu - L_\tau$ model
3. Time evolution for neutrino number density
4. Result
5. Summary

1. Introduction

Standard Model : Well established, however

Need to explain

ex) **neutrino mass/mixing, $g_\mu - 2$, Hubble Tension**, dark matter etc.

⇒ extension of SM

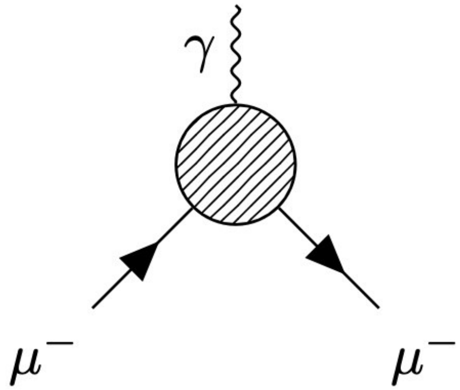
Here we consider a model to explain

- $\boldsymbol{g_\mu - 2}$
- **Hubble Tension**
- **Neutrino mass/mixing**

1. Introduction

$g_\mu - 2$ anomaly

Theoretical value ≠ Observed value



$$a_\mu = \frac{g_\mu - 2}{2}$$

Electron：Same

Muon：Significant difference

Muonic Interaction？

1. Introduction

Hubble Tension

Tension between two kinds of measurement for Hubble constant H_0

- Observation of near universe (direct measurement)

  Hubble's law with distance d and red shift z

$$cz = H_0 d$$

- Far universe (indirect measurement)

  Cosmic microwave background and $\Lambda\mathrm{CDM}$

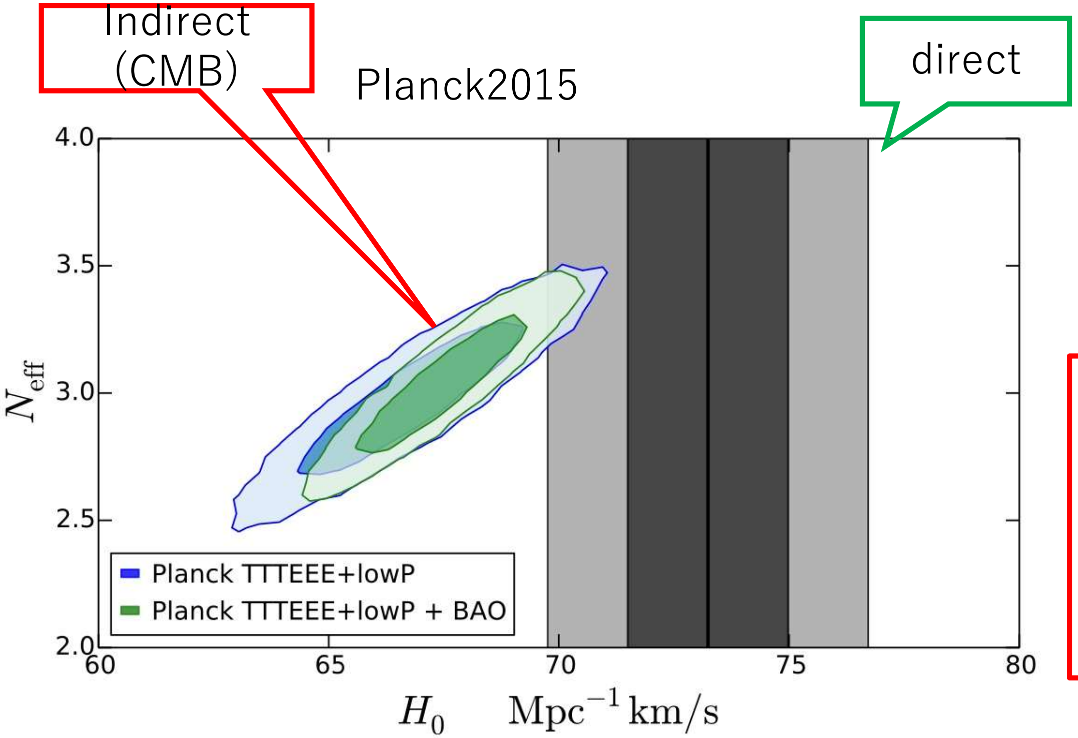
$\Lambda\mathrm{CDM}$ based on the **standard model**

⇒Modification of SM ?

1. Introduction

Alleviation of Hubble Tension ：

Larger N_{eff} (effective degree of freedom of massless particle)



José Luis Bernal, et al. Journal of Cosmology and Astroparticle Physics, Vol. 2016, No. 10, p. 019 (2016)

$$N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

SM : $N_{\mathrm{eff}} = 3.044$

Larger N_{eff} →closer to direct measurement

⇒incleasing ρ_ν/ρ_γ for $N_{\mathrm{eff}} \cong 3.3 \sim 3.5$ を

N_{eff} in SM
K.Akita and M.Yamaguchi Journal of Cosmology and Astroparticle Physics, Vol. 2020, No. 08, p. 012 (2020)

1. Introduction

Can we explain both $g_\mu - 2$ anomaly and Hubble Tension ?

In addition to neutrino masses and lepton mixing

Model：Renormalizable gauged $L_\mu - L_\tau$ model

-> New particles：$U(1)_{L_\mu - L_\tau}$ gauge boson Z' 、 Majoron ϕ

- Winthin parameter region to explain $g_\mu - 2$ anomaly for Z'

  We solve Boltzmann eq. to get N_{eff}

- We **were** interested in scattering process of $\boldsymbol{Z'}$ **and** $\boldsymbol{\phi}$

  which is ignored in previous works.

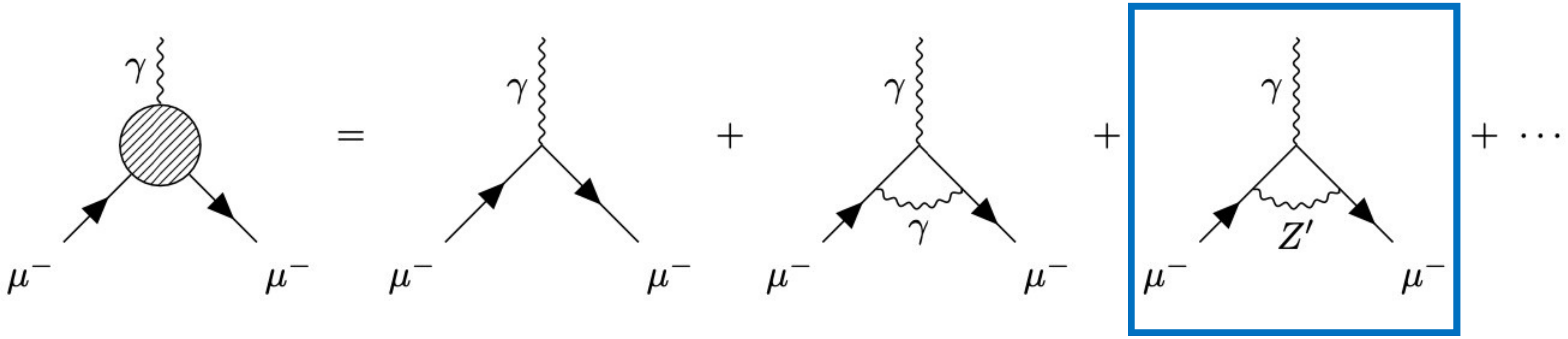
2. Renormalizable $\boldsymbol{L_\mu - L_\tau}$ Model

Gauge sym. in $\boldsymbol{L_\mu - L_\tau}$ model： $G_{\mathrm{SM}} \times U(1)_{L_\mu - L_\tau}$

Charge : $L_\mu - L_\tau$ in $U(1)_{L_\mu - L_\tau}$

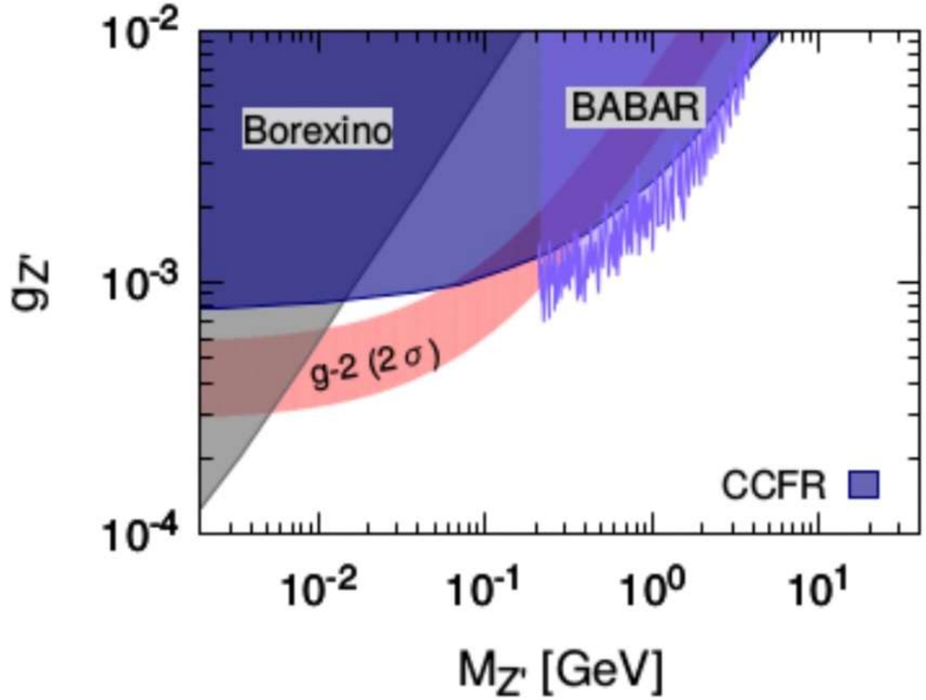
New particle：**$\boldsymbol{U(1)_{L_\mu - L_\tau}}$ gauge boson $\boldsymbol{Z'}$**

New contribution to a_μ



2. Renormalizable $\boldsymbol{L_\mu - L_\tau}$ model

Parameter region for $g_\mu - 2$ anomaly （$g_{Z'} = g_{\mu-\tau}$）



T. Araki et al. Phys. Rev. D, Vol. 95, p. 055006, 2017.

In this work

$m_{Z'} = 13\ \mathrm{MeV},\ g_{\mu-\tau} = 5.0 \times 10^{-4}$

Half of allowed region
is denied

2. Renormalizable $\boldsymbol{L_\mu - L_\tau}$ model

Symmetry in $\boldsymbol{L_\mu - L_\tau}$ model : $G_{\mathrm{SM}} \times U(1)_{L_\mu - \mathrm{L}_\tau} \times U(1)_L$

Lepton number
$U(1)_L$

$U(1)_{L_\mu - L_\tau}$

Symmetry breaking

Light scalar $\boldsymbol{\phi}$ (Majoron)
∵ L must be broken softly

Mass for Z'

2. Renormalizable $\boldsymbol{L_\mu - L_\tau}$ model

- **$\boldsymbol{Z'}$ interaction**

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'^{\rho\sigma} Z'_{\rho\sigma} + \frac{1}{2} m_{Z'}^2 Z'^{\rho} Z'_{\rho} + g_{\mu-\tau} Z'_{\rho} J^{\rho}_{\mu-\tau}$$

$$Z'_{\rho\sigma} \equiv \partial_\rho Z'_\sigma - \partial_\sigma Z'_\rho$$

$$J^{\rho}_{\mu-\tau} \equiv \bar{\mu}\gamma^\rho \mu + \bar{\nu}_\mu \gamma^\rho P_L \nu_\mu - \bar{\tau}\gamma^\rho \tau - \bar{\nu}_\tau \gamma^\rho P_L \nu_\tau$$

- **$\boldsymbol{\phi}$ interaction**

$$\mathcal{L}_{\phi} = h_{\alpha\beta}\, \bar{\nu}_{L,\alpha}\, \nu^c_{L,\beta}\, \phi + h.c.$$

- $Z' \leftrightarrow \nu_{\alpha'} \bar{\nu}_{\alpha'}$ $\quad (\alpha' = \mu, \tau)$
- $\phi \leftrightarrow \nu_\alpha \nu_\beta$

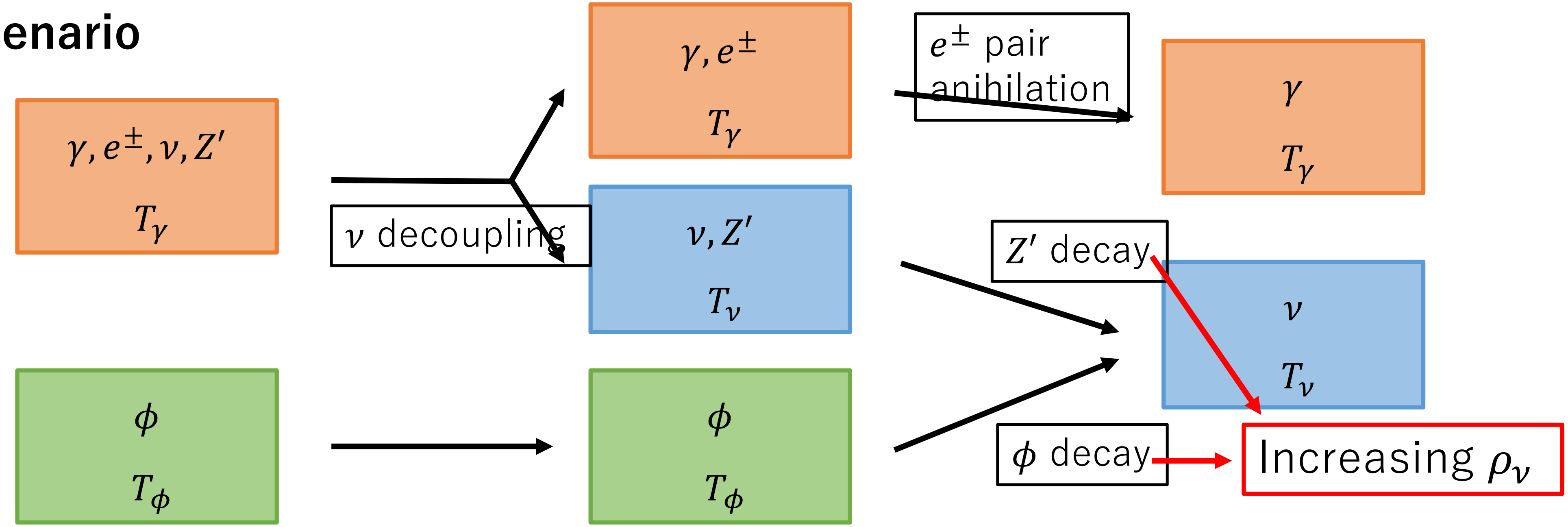
In addition to the above

- $Z' \nu_\alpha \leftrightarrow \phi \bar{\nu}_\beta$ $\quad (\nu \leftrightarrow \bar{\nu})$
- $Z' \phi \leftrightarrow \nu_\alpha \nu_\beta$ $\quad (\nu \leftrightarrow \bar{\nu})$

Scattering process

3. Time Evolution

Scenario



Boltzmann eq.

Solving Boltzmann equation around ν decoupling

$$\frac{dT}{dt} = -\left(\frac{\partial\rho}{\partial T}\right)^{-1}\left(3H(\rho+P) - \frac{\delta\rho}{\delta t}\right)$$

$\frac{\delta\rho}{\delta t}$ ：Energy transition rate

3. Time Evolution

Miguel Escudero, JCAP 02 (2019) 007

T. Araki, et al. Progress of Theoretical and Experimental Physics, Vol. 2021, No. 10, 2021. 103B05.

Equations

$\gamma, e^{\pm}$

T_γ

$$\frac{dT_\gamma}{dt} = -\left(\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}\right)^{-1}\left(4H\rho_\gamma + 3H(\rho_e + P_e) - \frac{\delta\rho_\gamma}{\delta t} - \frac{\delta\rho_e}{\delta t}\right)$$

ν, Z'

T_ν

$$\frac{dT_\nu}{dt} = -\left(\frac{\partial\rho_\nu}{\partial T_\nu} + \frac{\partial\rho_{Z'}}{\partial T_\nu}\right)^{-1}\left(4H\rho_\nu + 3H(\rho_{Z'} + P_{Z'}) - \frac{\delta\rho_\nu}{\delta t} - \frac{\delta\rho_{Z'}}{\delta t}\right)$$

ϕ

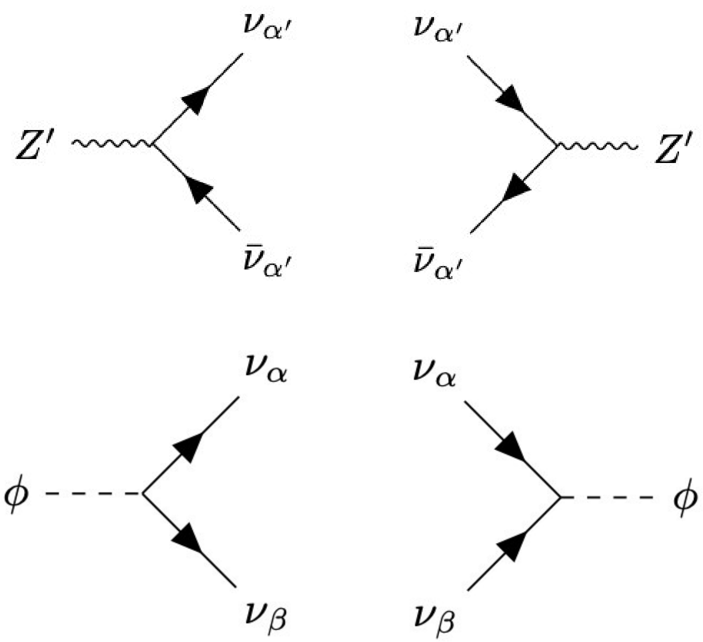
T_ϕ

$$\frac{dT_\phi}{dt} = -\left(\frac{\partial\rho_\phi}{\partial T_\phi}\right)^{-1}\left(3H(\rho_\phi + P_\phi) - \frac{\delta\rho_\phi}{\delta t}\right)$$

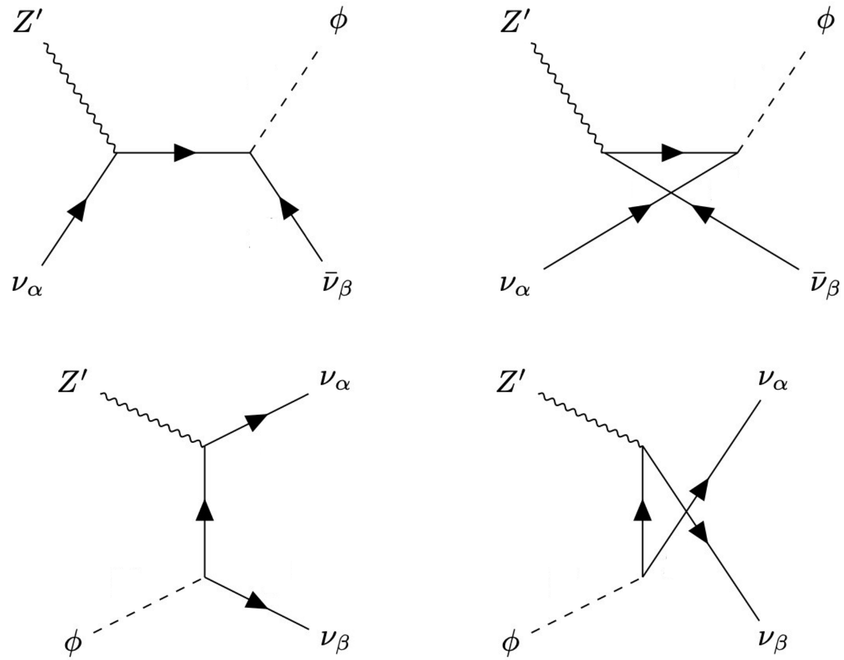
3. Time Evolution

Reaction processes for Z', ϕ and ν

decay・inverse decay



Z', ϕ scattering (New!)



3. Time Evolution

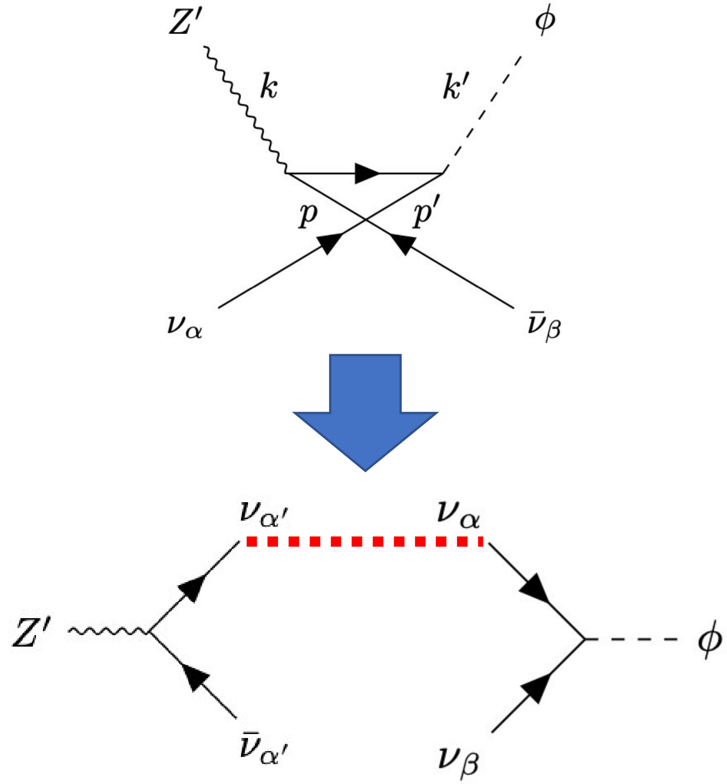
Intermediate state for the scattering process

$Z'\nu_\alpha \leftrightarrow \phi\bar{\nu}_\beta$ (u-channel) can be on-shell

→ **Amplitude $|\mathcal{M}|^2$ diverge**

→ **energy transition rate also diverge**

$$\left|\mathcal{M}^{u}_{Z'\nu\leftrightarrow\phi\bar{\nu}}\right|^2 \propto \frac{1}{(k-p')^4} = \frac{1}{\left(m_{Z'}^2 - 2k\cdot p'\right)^2}$$



There are several ideas to treat the divergence

Here we separate the divergent part mathematically

3. Time Evolution

Kento Asai, Tomoya Asano, Joe Sato, Masaki J.S. Yang,
PTEP 2024 (2024) 7, 073E01

$2k \cdot p' = X$, divergence comes from

$$\boxed{I = \int_0^\infty \frac{f(X)}{\left(m_{Z'}^2 - X\right)^2 + \epsilon^2} dX \quad \cdots (*)}$$

integrant：at $X = m_{Z'}^2$ widthe ϵ, divergence of $\mathcal{O}(1/\epsilon^2)$

$\rightarrow I$ はis divergent of $1/\epsilon$

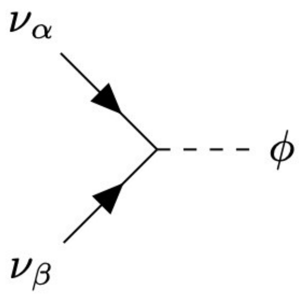
$$I = \frac{\alpha_{-1}}{\epsilon} + \alpha_0 + \epsilon\alpha_1 + \cdots$$

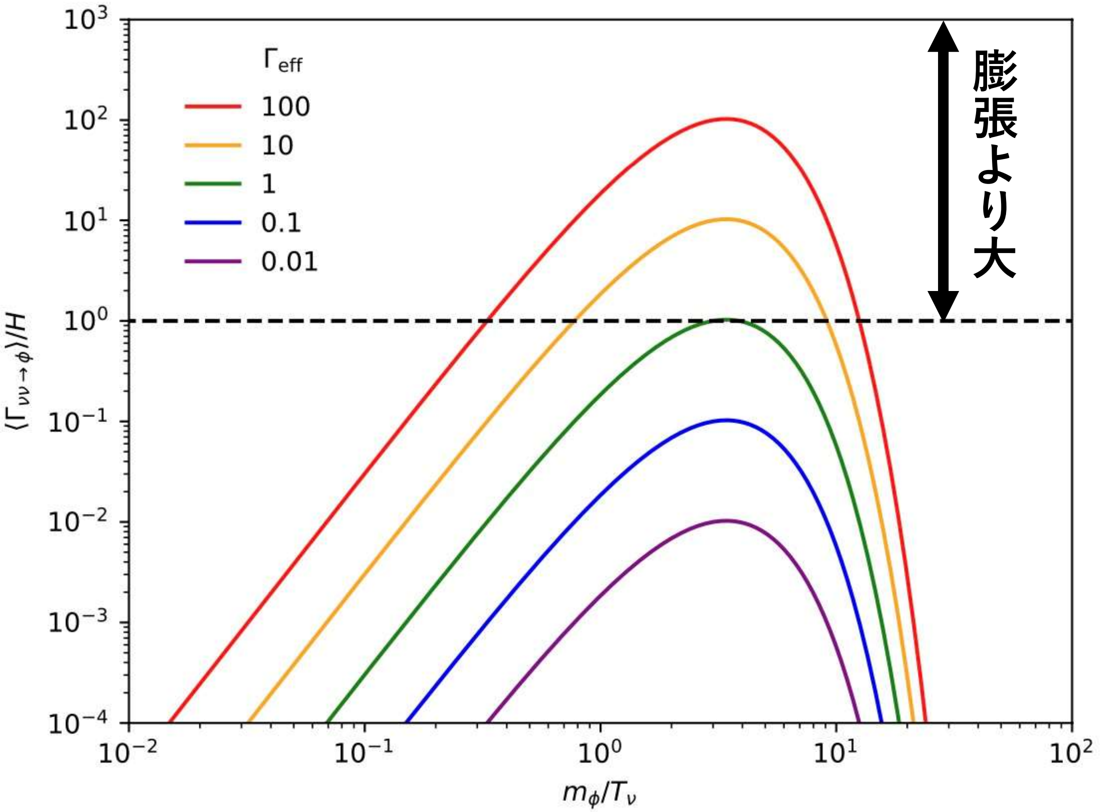
Divergent at $\epsilon \to 0$ = contribution from on-shell

α_0 physical off-shell contribution！

3. Time Evolution

Contribution from inverse decay $\nu\nu \to \phi$





effective reaction rate

$$\Gamma_{\text{eff}} \equiv \left. \frac{\langle \Gamma_{\nu\nu\to\phi} \rangle}{H} \right|_{T_\nu = m_\phi/3}$$

$$\Gamma_{\text{eff}} \cong \left(\frac{\lambda}{4 \times 10^{-12}} \right)^2 \left(\frac{\text{keV}}{m_\phi} \right)$$

$$\lambda^2 = \text{tr}(h^\dagger h)$$

Instead of λ^2 we use Γ_{eff}

4. Result

Parameter

Initial：$T_\gamma = T_\nu = 50\ \mathrm{MeV},\ \ T_\phi = 1.0\ \mathrm{MeV}$

To check $Z' - \phi$ scattering

- $m_\phi = 0.05,\ 0.1,\ 0.5,\ 1.0,\ 5.0,\ 10.0\ \mathrm{MeV}$
- $\Gamma_{\mathrm{eff}} = 0.01,\ 0.1,\ 1.0,\ 10,\ 100$

$$\Gamma_{\mathrm{eff}} \cong \left(\frac{\lambda}{4\times 10^{-1}}\right)^2 \left(\frac{\mathrm{keV}}{m_\phi}\right)$$

$$\lambda^2 = \mathrm{tr}(h^\dagger h)$$

Z'

- $m_{Z'} = 13\ \mathrm{MeV},\ \ g_{\mu-\tau} = 5.0\times 10^{-4}\ (N_{\mathrm{eff}}^{Z'} \cong 3.4)$
- $m_{Z'} = 18\ \mathrm{MeV},\ \ g_{\mu-\tau} = 4.0\times 10^{-4}\ (N_{\mathrm{eff}}^{Z'} \cong 3.2)$

4. Result

w/w.o $Z' - \phi$ scattering for N_{eff}

$m_{Z'} = 13$ MeV, $g_{\mu-\tau} = 5.0 \times 10^{-4}$

m_ϕ [MeV]	Γ_{eff}	N_{eff} (no scat.)	N_{eff} (scat.)	diff
0.1	0.01	3.45419	3.45381	-3.8×10^{-4}
0.1	10	3.61269	3.61275	$+0.6 \times 10^{-4}$
1.0	0.01	3.46957	3.46911	-4.6×10^{-4}
1.0	10	3.87105	3.87057	-4.8×10^{-4}
10.0	0.01	3.39982	3.39927	-5.5×10^{-4}
10.0	10	3.39945	3.39893	-5.2×10^{-4}

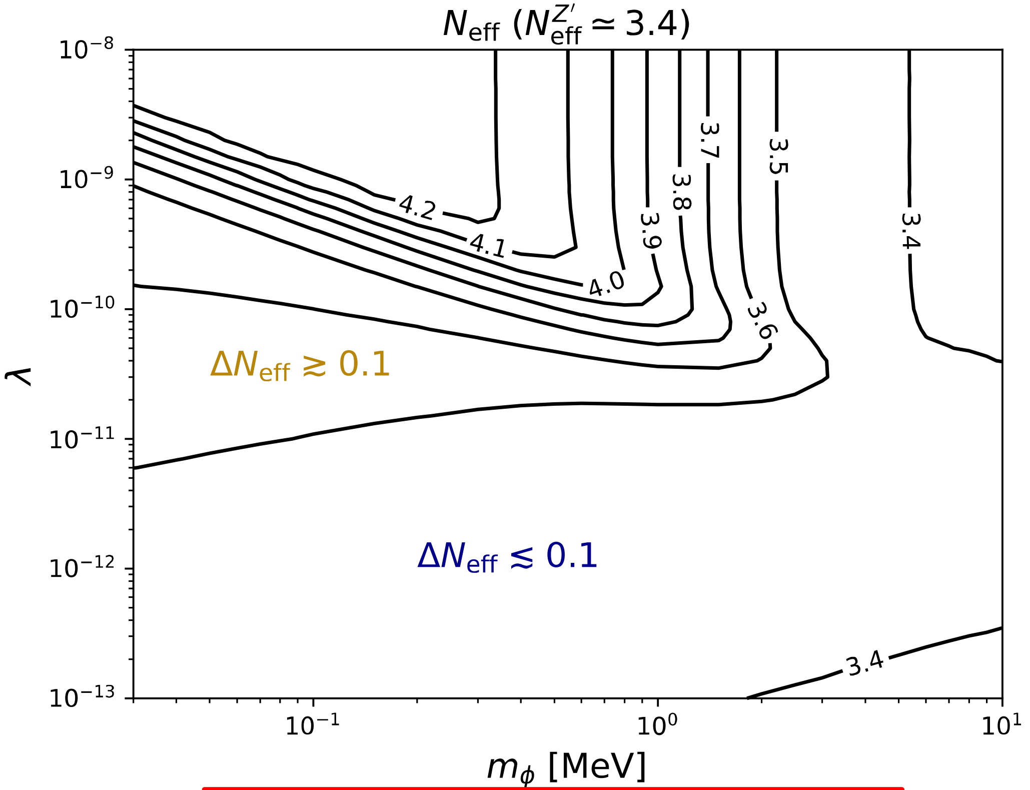
- Scattering slightly reduces though
- Contribution of $Z' - \phi$ scattering $\sim \mathcal{O}(10^{-4})$ $\rightarrow$ negligible

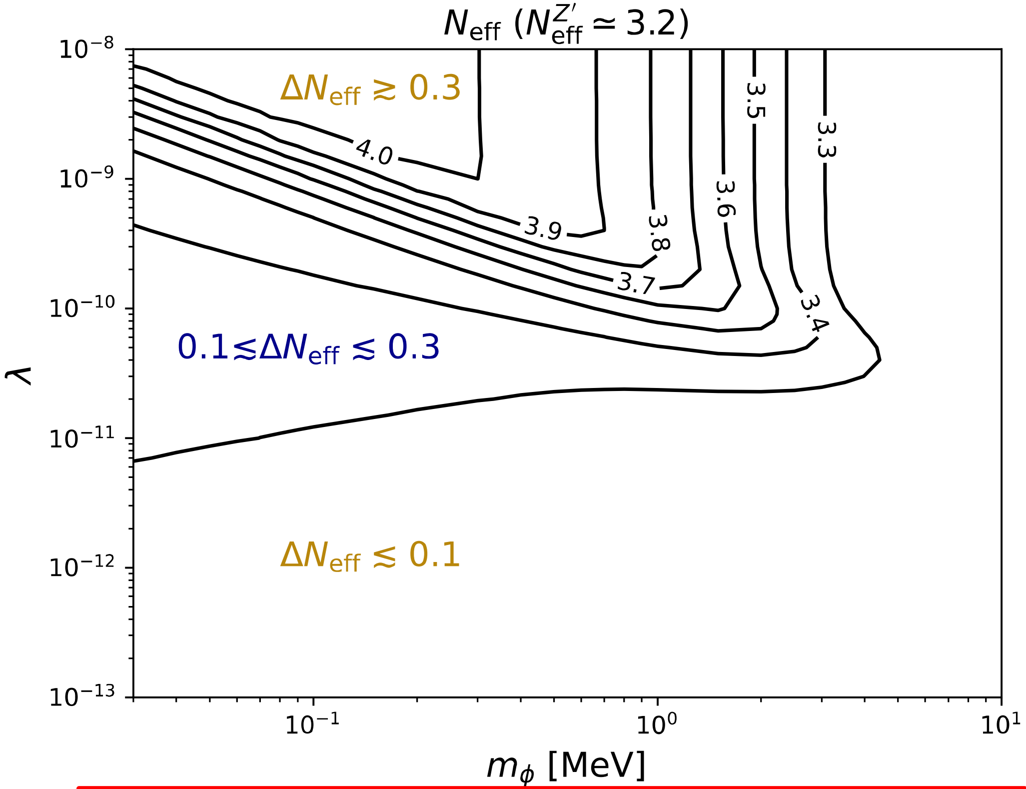
4. Result

Majoron mass and Coupling

$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{Z'}$$

Blue：alleviate Hubble Tension





- $m_\phi \lesssim 3.0$ MeV , $\lambda \lesssim \mathcal{O}(10^{-12})$
- $m_\phi \gtrsim 3.0$ MeV

- $m_\phi \lesssim 2.0$ MeV , $\lambda \cong \mathcal{O}(10^{-11} - 10^{-10})$
- 2.0 MeV $\lesssim m_\phi \lesssim 3.0$ MeV , $\lambda \gtrsim \mathcal{O}(10^{-11})$

5. Summary

- $m_{Z'} = 13\ \mathrm{MeV},\ \ g_{\mu-\tau} = 5.0 \times 10^{-4}$ then
  - $m_\phi \leq 1.0\ \mathrm{MeV},\ \ \Gamma_{\mathrm{eff}} \leq 0.01 - 0.1$
  - $m_\phi \sim \mathcal{O}(1\ \mathrm{MeV}),\ \ \Gamma_{\mathrm{eff}} \leq 0.01$
  - Not a naïve summation of two contribution

  No contributionto toは N_{eff} for $m_\phi \geq 10.0\ \mathrm{MeV}$

- Scattering process for N_{eff} is $\mathcal{O}(10^{-4})$ → negligible