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Universe with a large lepton asymmetry

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Refs. MK, Murai arXiv:2203.09713
Kasuya, MK, Murai in preparation

1. Introduction

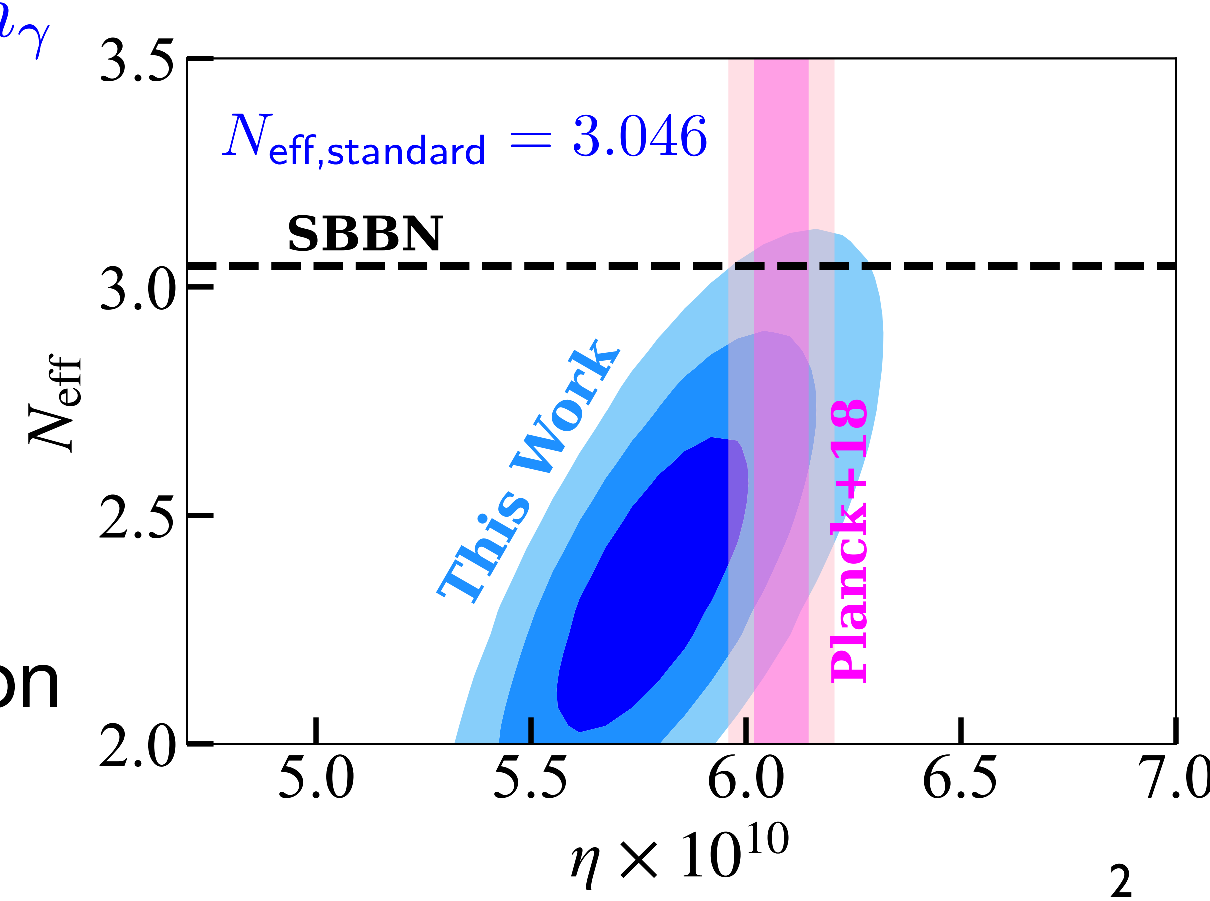
- He4 is produced in Big Bang Nucleosynthesis (BBN)
- Recent new measurements of He4 (together with previous data) determined primordial He4 abundance Matsumoto et al. arXiv: 2203.09617

$$Y_p = 0.2370^{+0.0034}_{-0.0033} \qquad Y = \rho_{^4\mathrm{He}}/\rho_B$$

- $\sim 1\sigma$ smaller than the previous results
- Constraints on the parameters of BBN (including D measurement)
  - Baryon-to-photon ratio $\eta_B = n_B/n_\gamma$
  - Effective number of ν species N_{eff}

$$N_{\mathrm{eff}} = 2.37^{+0.19}_{-0.24}$$

$$\eta_B = 5.80^{+0.13}_{-0.16} \times 10^{-10}$$



- $> 2\sigma$ tension between constraint on N_{eff} and the standard value

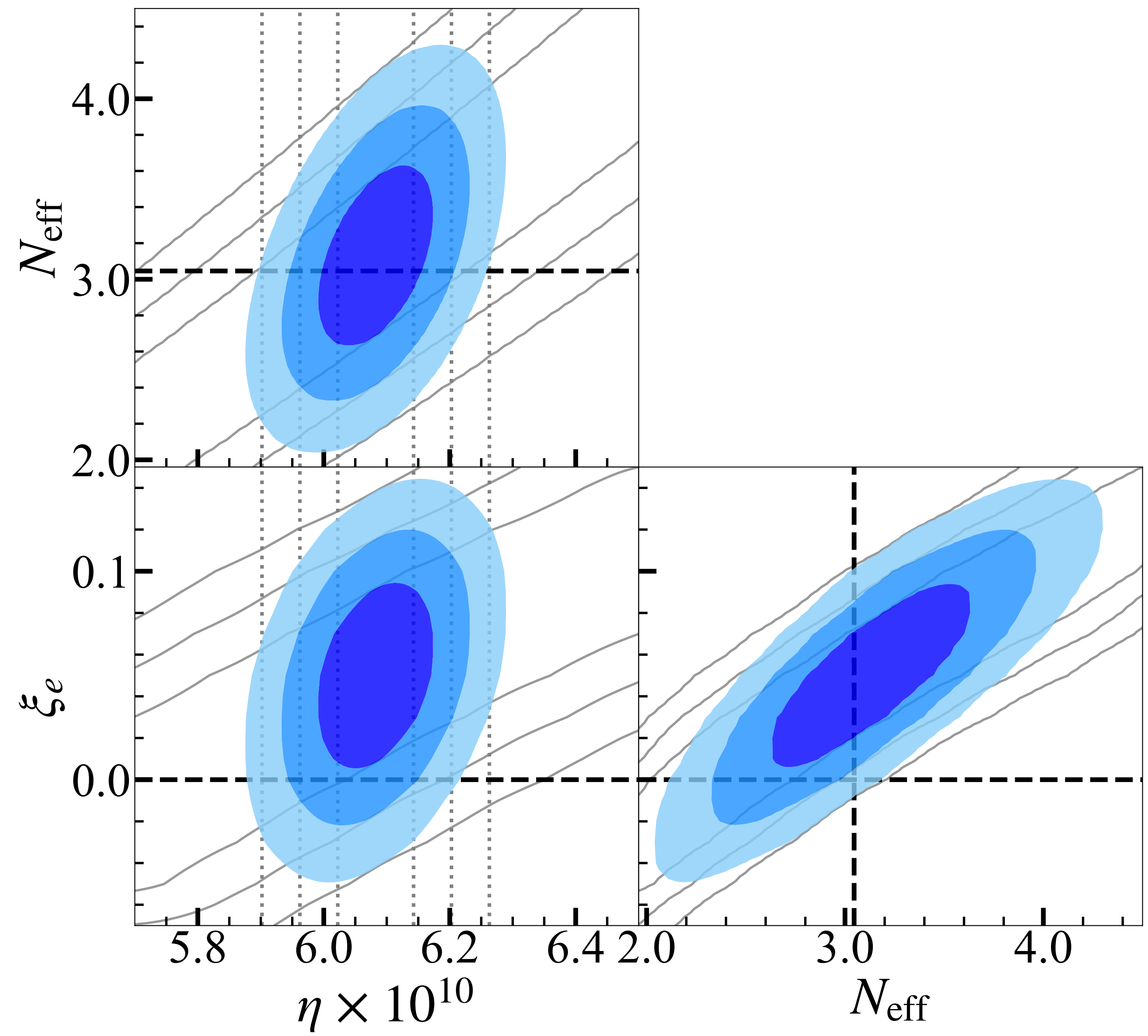
1. Introduction

- Introducing asymmetry between ν_e and $\bar{\nu}_e$
- Chemical potential parameter $\xi_e = \mu_{\nu_e}/T_{\nu_e}$ $\quad n_{\nu_e} - n_{\bar{\nu}_e} \simeq \frac{T^3}{6}\xi_e$

$$\xi_e = 0.05^{+0.03}_{-0.02}$$

$$N_{\rm eff} = 3.11^{+0.34}_{-0.31}$$

$$\eta_B = 6.08^{+0.06}_{-0.06} \times 10^{-10}$$



- Large lepton asymmetry
  - All 3 flavors share asymmetry due to oscillation

$$n_L = 3(n_{\nu_e} - n_{\bar{\nu}_e})$$

  - Lepton asymmetry

$$\eta_L = \frac{n_L}{s} \simeq 5.3 \times 10^{-3}$$

1. Introduction

- Lepton asymmetry is much larger than the observed baryon asymmetry

$$\eta_{B,\text{obs}} \sim 10^{-10}$$

- If a lepton number is produced at $T \gtrsim 100$ GeV, it is partially converted to a baryon number through the sphaleron process

$$\rightarrow \quad \eta_B \simeq -\frac{8}{23}\eta_L$$

- To produce lepton asymmetry much larger than $|\eta_B|$
  - Lepton asymmetry is produced below the EW scale
  - Produced asymmetry is protected against the sphaleron process
- We consider Q-ball (L-ball) formation to realize the latter
  - Q-ball is a non-topological soliton in a scalar theory with $U(1)$
  - Q-balls are produced in the Affleck-Dine leptogenesis
- Large lepton asymmetry is successfully produced by L-ball formation

2. Affleck-Dine mechanism

- Flat directions in the scalar potential of MSSM $\ni (\tilde{q},\ \tilde{\ell},\ H)$

  Minimal SUSY standard model

- One of flat directions = AD field ϕ
- AD field has a baryon number or a lepton number

$$V(\phi) = (m_\phi^2 + c_H H^2)|\phi|^2 + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + A\frac{\phi^n}{M_p^{(n-3)}} + h.c.$$

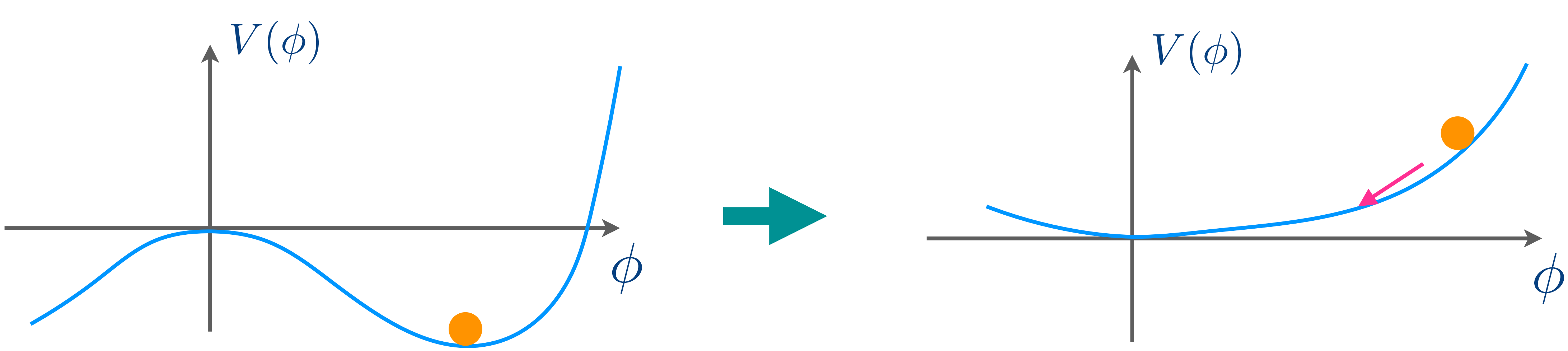
V_{susy} : SUSY breaking mass term

Hubble induced mass term

V_{NR} : Non-renormalizable term (n≥4)

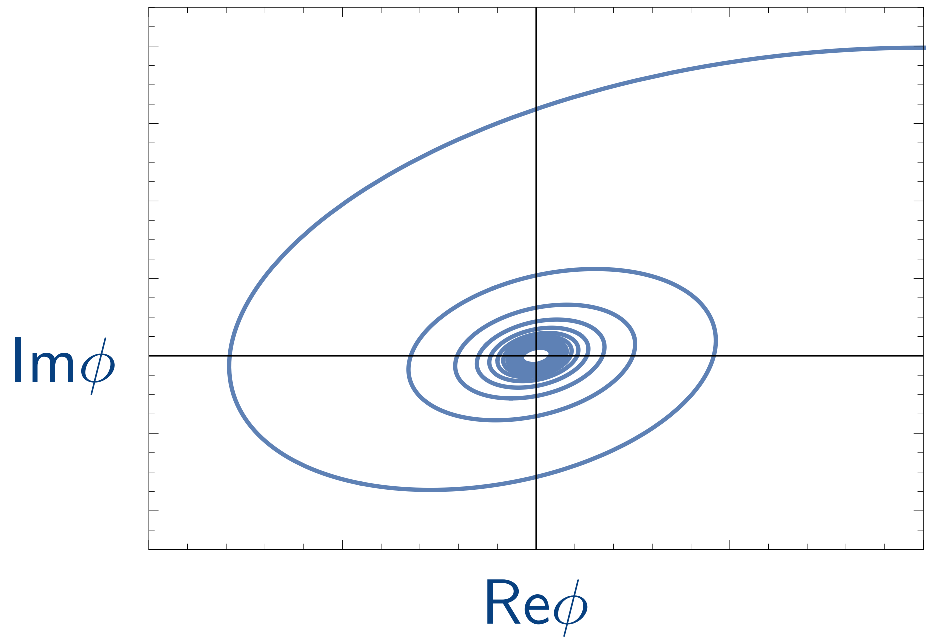
V_A : A-term

- During inflation ($H \gg m_\phi$) ϕ has a large value if $c_H < 0$
- After inflation, when $m_\phi \simeq H$ ϕ starts to oscillate



2. Affleck-Dine mechanism

- AD field is kicked in phase direction due to A-term



$n_L \sim |\phi|^2 \dot{\theta}$

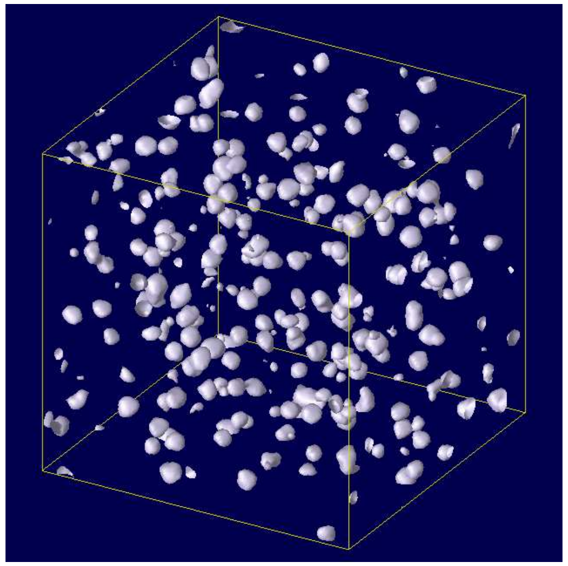
Lepton number generation

AD leptogenesis

- AD mechanism can generate lepton number efficiently
- Large lepton asymmetry is realized

3.1 Formation of L-balls

- AD field oscillation has spatial instabilities if the potential is flatter than the quadratic one
- AD field fragments into spherical lumps (non-topological solitons) called Q-balls
  - For $U(1) = U(1)_L$, formed Q-balls are called L-balls
- L-ball formation depends on SUSY breaking
- We consider gauge-mediated SUSY breaking models



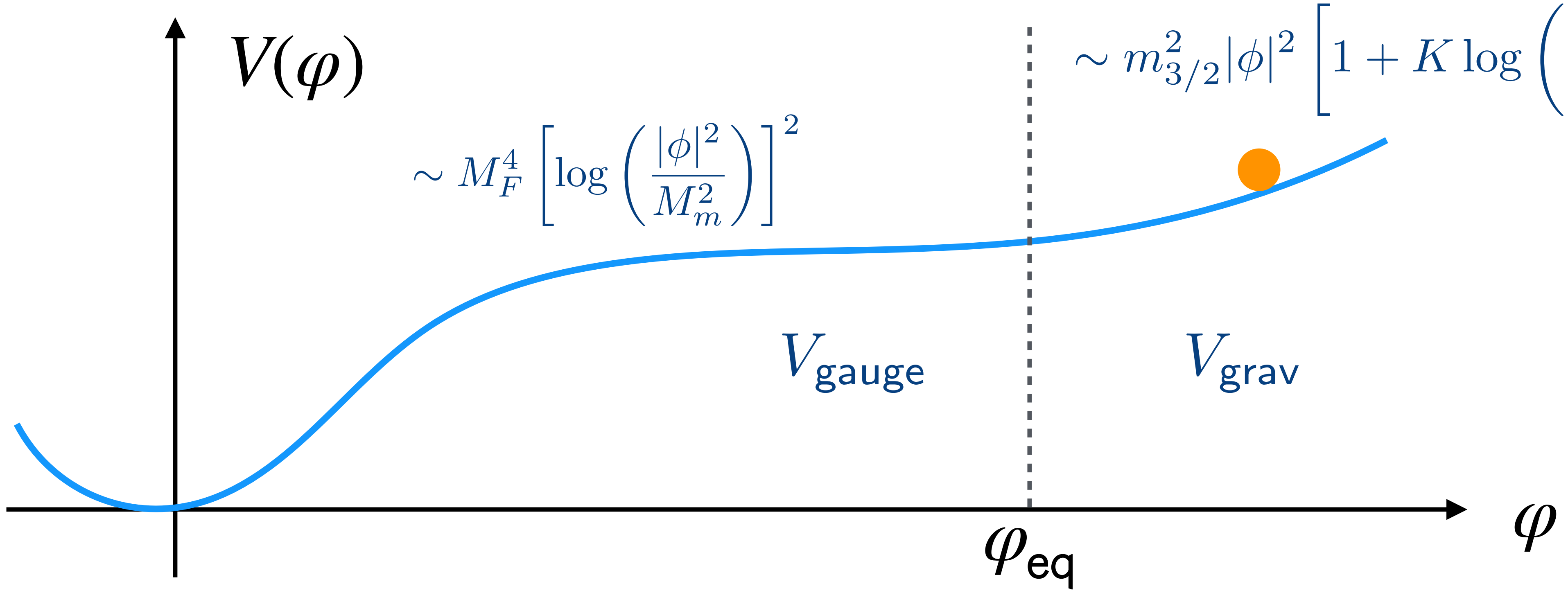
$$V_{\text{susy}} = V_{\text{gauge}} + V_{\text{grav}} = M_F^4 \left[\log\left(\frac{|\phi|^2}{M_m^2}\right)\right]^2 + m_{3/2}^2|\phi|^2\left[1 + K\log\left(\frac{|\phi|^2}{M_*^2}\right)\right]$$

$m_{3/2} < 1\text{GeV}$

  - L-balls are formed if $K < 0$ when V_{grav} dominates the potential
  - L-balls are always formed when V_{gauge} dominates the potential
- We assume $K > 0$, so L-balls are formed when V_{gauge} dominates the potential

3.1 L-ball formation

- AD field starts oscillation with amplitude $\varphi_{\rm osc} > \varphi_{\rm eq}$ at $H \sim m_{3/2}$
- Lepton asymmetry $n_L \simeq m_{3/2}\,\varphi_{\rm osc}^2$
- For $K > 0$ L-balls do not form until $\varphi < \varphi_{\rm eq}$
  - L-ball formation is delayed [delayed-type L-ball]
  - Lepton charge is confined inside L-balls
    (Produced asymmetry is protected against the sphaleron process)



3.1 L-ball formation

- Properties of delayed-type L-ball

Hisano Nojiri Okada (2001)

$$M_Q = \frac{4\sqrt{2}\pi}{3}\zeta M_F Q^{3/4}$$

$$R_Q = \frac{1}{\sqrt{2}\zeta} M_F^{-1} Q^{1/4} \qquad \omega_Q = dM_Q/dQ \simeq \sqrt{2}\pi\zeta M_F Q^{-1/4}$$

Q : L-charge

$\zeta \sim 2.5$

- L-ball charge $\quad Q = \beta\,(\varphi_{\rm eq}/M_F)^4 \qquad \beta \simeq 6\times 10^{-4}$

- L-balls decay emitting neutrinos with decay rate

$$\Gamma_Q \simeq \frac{N_\ell}{Q}\frac{\omega_Q^3}{12\pi^2}4\pi R_Q^2$$

N_ℓ :# of decay channel $\simeq 3$

→ lepton asymmetry is released

- Decay temperature

$$T_{\rm D} \simeq \left(\frac{90}{\pi^2 g_*(T_{\rm D})}\right)^{1/4}\sqrt{M_{\rm Pl}\Gamma_Q}$$

$$\simeq 2.69\ {\rm MeV}\left(\frac{g_*}{10.75}\right)^{-1/4}\left(\frac{m_{3/2}}{0.5\ {\rm GeV}}\right)^{5/2}\left(\frac{M_F}{5\times 10^6\ {\rm GeV}}\right)^{-2}$$

▷ $T_{\rm D}$ should be higher than ~ 1MeV for successful BBN

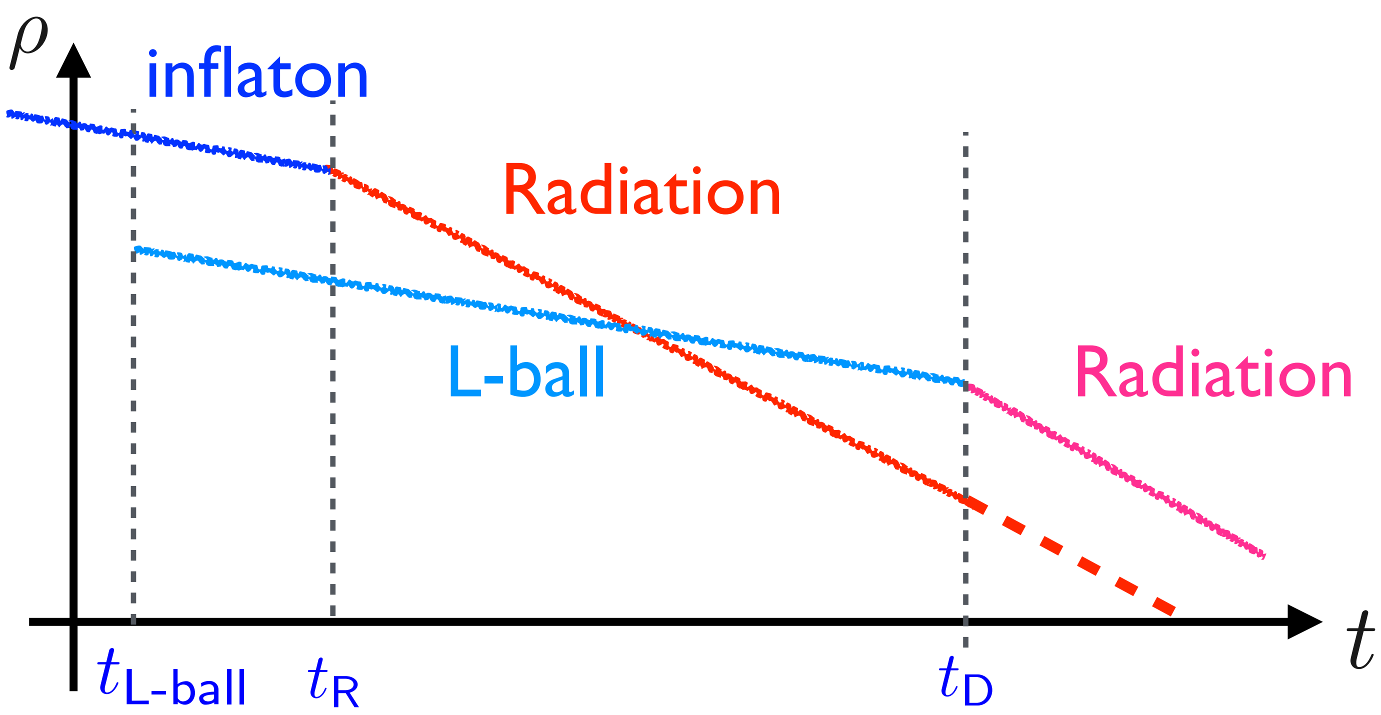
3.3 L-ball evolution

- We assume that L-balls dominate the Universe
- Lepton asymmetry

$$\eta_L \simeq \frac{n_L}{4\rho_\phi/3T_{\rm D}} \simeq \frac{m_{3/2}\varphi_{\rm osc}^2}{4m_{3/2}^2\varphi_{\rm osc}^2/(3T_D)} = \frac{3T_{\rm D}}{4m_{3/2}}$$

- L-ball domination at L-ball decay

$$\left.\frac{\rho_Q}{\rho_R}\right|_{T_{\rm D}} \simeq 9.66\times10^6 \left(\frac{g_*}{10.75}\right)^{1/4}\left(\frac{m_{3/2}}{0.5\ {\rm GeV}}\right)^{-9/2}\left(\frac{M_F}{5\times10^6\ {\rm GeV}}\right)^6\left(\frac{T_R}{10^5\ {\rm GeV}}\right)\left(\frac{\varphi_{\rm osc}}{10^4\varphi_{\rm eq}}\right)^2$$

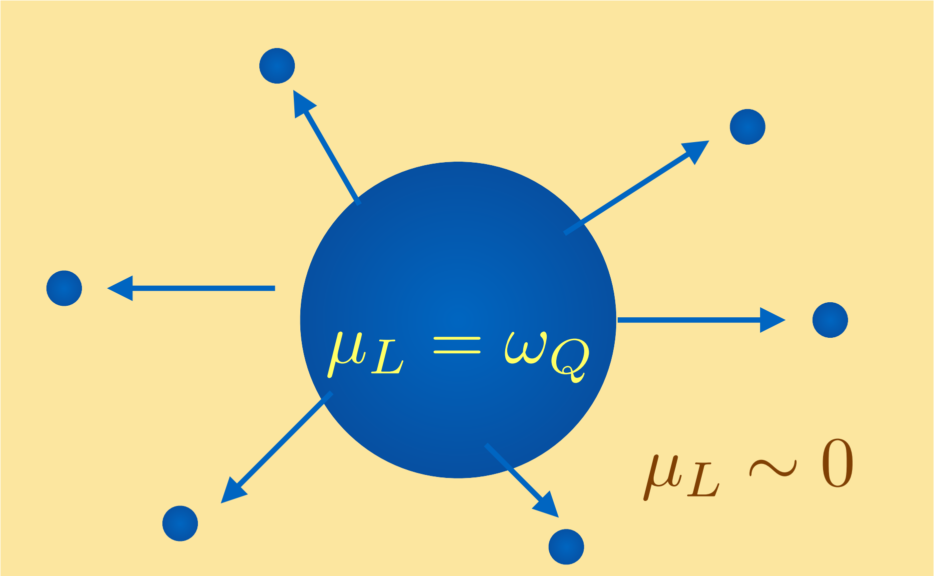


3.4 L-ball evaporation

- L-balls in thermal plasma emit their charge by evaporation
- A part of lepton number emitted above EW scale is converted into baryon number
- Produced baryon asymmetry

$$\Rightarrow \quad \eta_{B,Q} = -\frac{8}{23}\frac{\Delta Q_{\rm EW}}{Q}\eta_L$$

$\Delta Q_{\rm EW}$: evaporated charge above EW scale

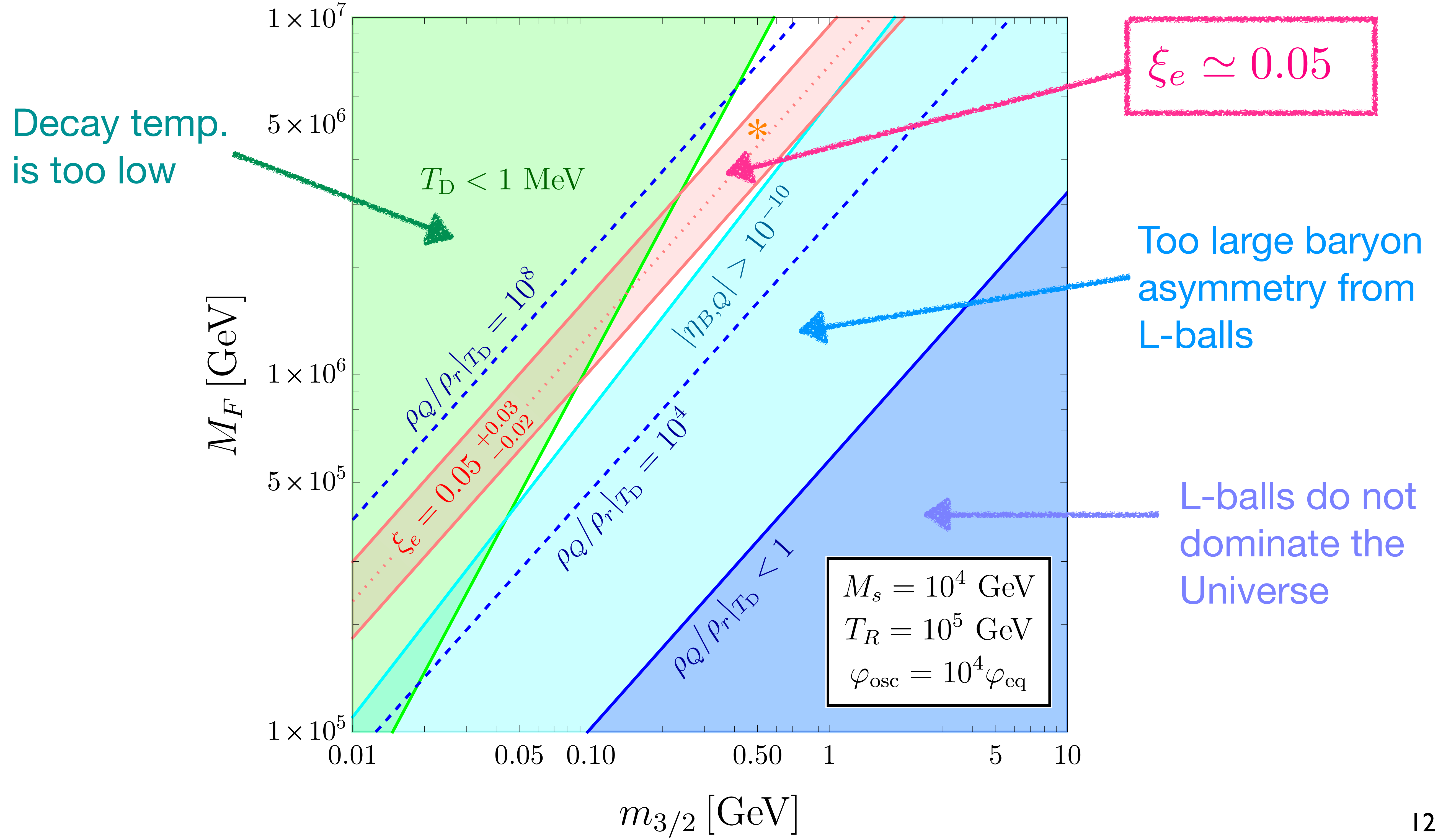


- Baryon asymmetry from L-balls is negative since we need positive lepton asymmetry
- The produced baryon asymmetry should be small not to spoil the success of BBN

$$|\eta_{B,Q}| \lesssim \eta_{B,\rm obs} \sim 10^{-10}$$

3.5 Constraints on model parameters

- Large lepton asymmetry suggested by the recent He4 observation is realized in L-ball scenario



4.1 Gravitational wave production

- GWs are produced by the 2nd order effect of curvature perturbations Ananda Clarkson Wands (2007) Baumann Steinhardt Takahashi Ichiki (2007) Saito Yokoyama (2009) Bugaev Kulimai (2010)

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\zeta^2)$$

$\mathcal{H} = a'/a$

h_{ij} : tensor perturbation = GW

ζ : curvature perturbation

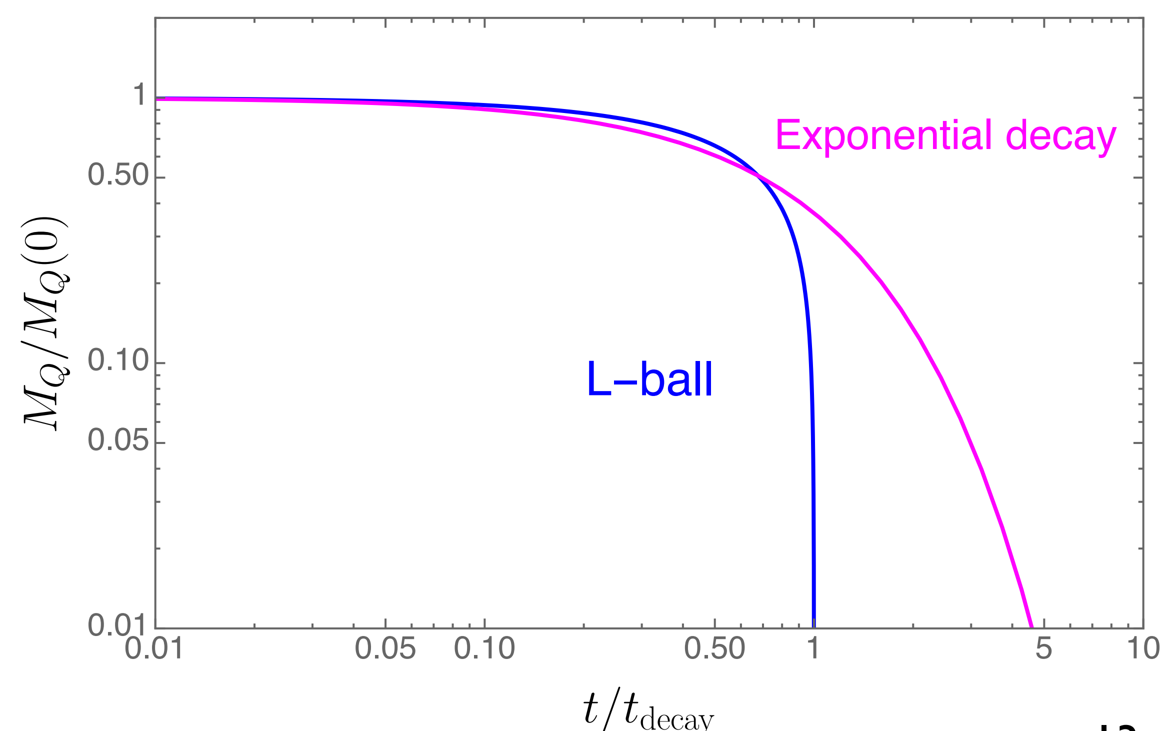
- Moreover, GW production is much enhanced when there exists an early matter-dominated era with a sharp transition to the radiation-dominated era Inomata Kohri Nakama Terada (2019) Inomata et al. (2020)

- L-balls realize an early MD universe and decay rapidly

$$\Gamma = \frac{1}{Q}\frac{dQ}{dt} = \frac{4}{5}\frac{1}{t_{\rm decay} - t}$$

$$\Rightarrow \quad M_Q = M_Q(0)\left(1 - \frac{t}{t_{\rm decay}}\right)^{3/5}$$

- L-balls enhance the GW production

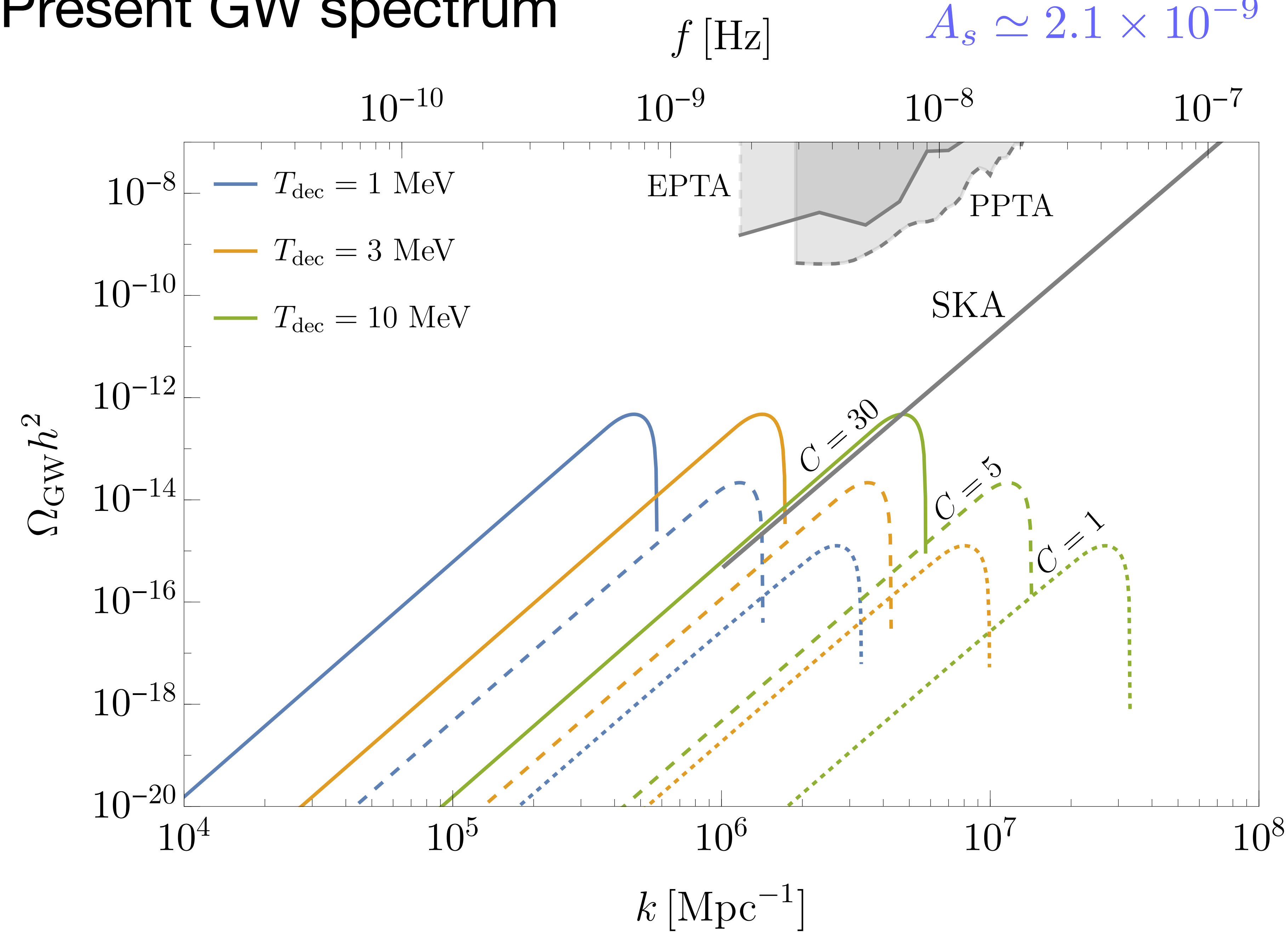


4.2 Enhancement of GWs by L-balls

- Power spectrum of curvature perturbation $\mathcal{P}_\zeta = C^2 A_s\, \theta(k_{\mathrm{NL}} - k)$

  $A_s \simeq 2.1 \times 10^{-9}$ [amp. at CMB scale]

- Present GW spectrum



- GWs can be detected by the future Pulsar timing array experiment (SKA) for $T_{\rm dec} \sim$ a few MeV and $C \gtrsim$ several

5. Summary

- Recent He4 measurement suggests that our universe has a large lepton asymmetry
- L-ball scenario successfully realizes a large lepton asymmetry suggested by the He4 measurement
- L-balls also dominate the universe and decay rapidly, which significantly enhances gravitational wave production from curvature perturbations.