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Lepton asymmetry from Q-balls and enhancement of second order gravitational waves

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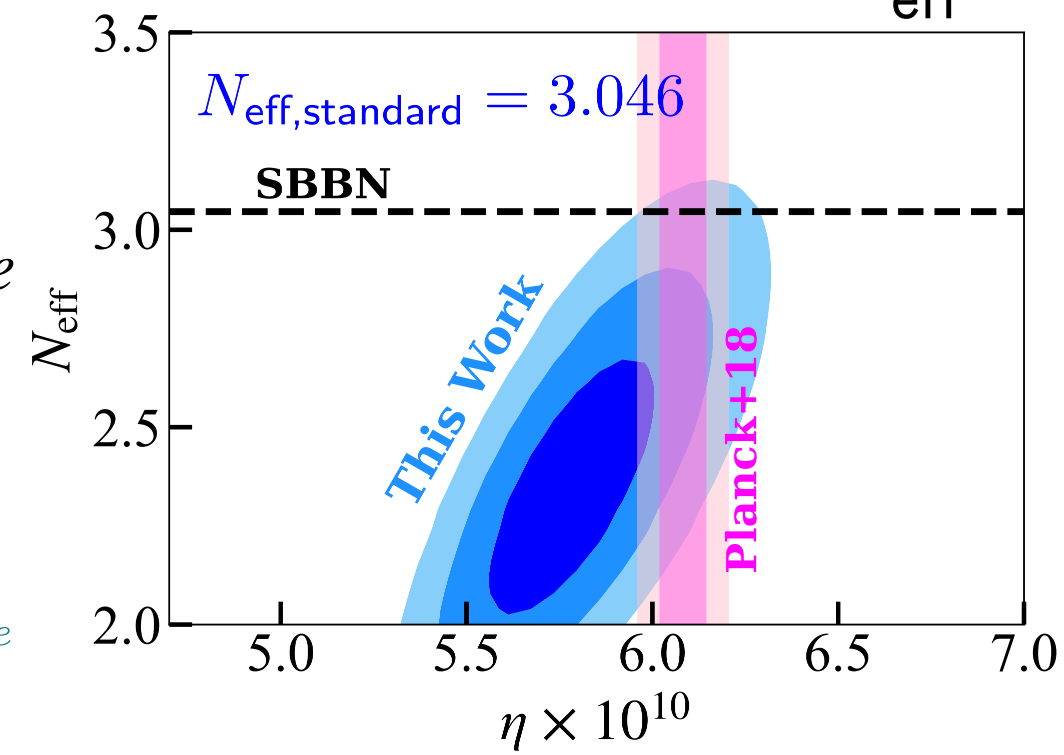
Refs. MK, Murai arXiv:2203.09713
Kasuya, MK, Murai arXiv:2212.13370

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
- New Y_p (+D obs.) causes $> 2\sigma$ tension between constraint on N_{eff} and the standard value



- Suggests asymmetry between ν_e and $\bar{\nu}_e$
- Chemical potential parameter

$$\xi_e = 0.05^{+0.03}_{-0.02}$$
$$N_{\mathrm{eff}} = 3.11^{+0.34}_{-0.31}$$

$$n_{\nu_e} - n_{\bar{\nu}_e} \simeq \frac{T^3}{6}\xi_e$$

- This implies the total lepton asymmetry

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

1. Introduction

- Lepton asymmetry is much larger than the 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

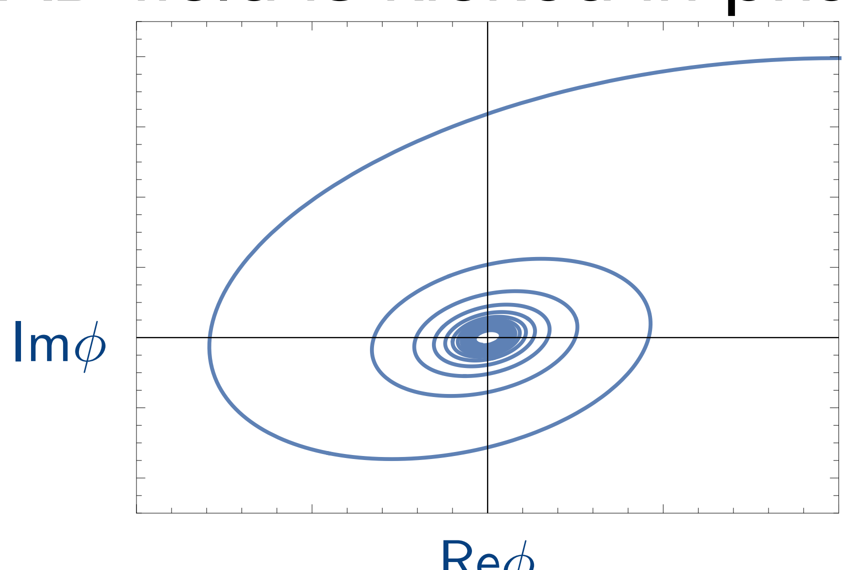
$$\rightarrow \quad \eta_B \simeq -\frac{8}{23}\eta_L$$

- Difficult to produce lepton asymmetry much larger than $|\eta_B|$
- We consider Q-ball (L-ball) formation
  - Q-ball is a non-topological soliton in a scalar theory with $U(1)$
  - Q-balls are produced in the Affleck-Dine leptogenesis
  - Produced lepton number is confined inside Q-balls and protected against the sphaleron process
- Subsequent Q-ball decay enhances GWs produced by the second order effect of curvature perturbations

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 which has a B or L number
- Potential of AD field is lifted by SUSY breaking effect
- During inflation ($H \gg m_\phi$) ϕ has a large value by $-H^2|\phi|^2$ term
- After inflation, when $m_\phi \simeq H$ ϕ starts to oscillate

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



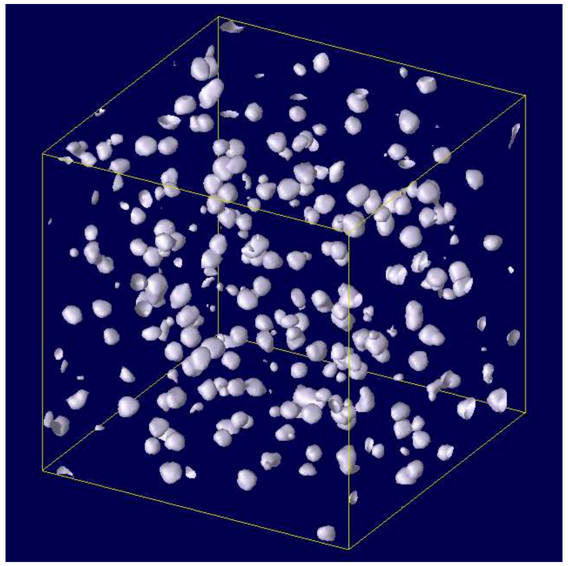
$n_L \sim |\phi|^2 \dot{\theta}$

Lepton number generation

AD leptogenesis

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



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

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

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

3.1 L-ball formation

- AD field starts oscillation with amplitude $\varphi_{\rm osc} > \varphi_{\rm eq}$ at $H \sim m_{3/2}$
- For $K > 0$ L-balls do not form until $\varphi < \varphi_{\rm eq}$ $\quad \Rightarrow \; n_L \simeq m_{3/2}\varphi_{\rm osc}^2$
  - L-ball formation is delayed [delayed-type L-ball]
  - Lepton charge is confined inside L-balls
- Properties of delayed-type L-ball

Hisano Nojiri Okada (2001)

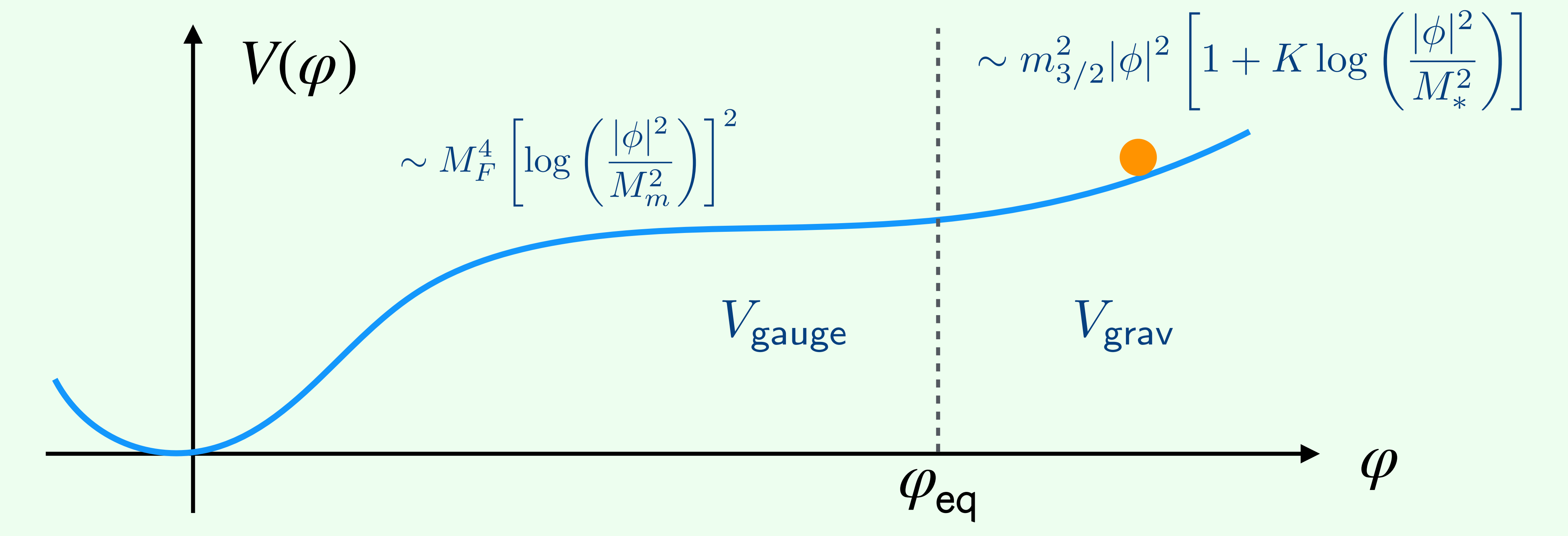
$$M_Q = \frac{4\sqrt{2}\pi}{3}\zeta M_F Q^{3/4} \qquad Q\,:\ \text{L-charge}$$

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

$$\zeta \sim 2.5$$

$$Q = \beta\left(\varphi_{\rm eq}/M_F\right)^4$$

$$\beta \simeq 6\times 10^{-4}$$



3.2 L-ball evolution

- We assume that L-balls dominate the Universe
- L-balls decay emitting neutrinos with decay rate $\Gamma_Q \simeq \frac{1}{Q}\frac{\omega_Q^3}{4\pi^2}4\pi R_Q^2$

→ Lepton asymmetry is released

- Decay temperature

$$T_{\rm dec} \simeq 2.69\ {\rm MeV}\left(\frac{m_{3/2}}{0.5\ {\rm GeV}}\right)^{5/2}\left(\frac{M_F}{5\times 10^6\ {\rm GeV}}\right)^{-2}$$

$\gtrsim 1{\rm MeV}$ for successful BBN

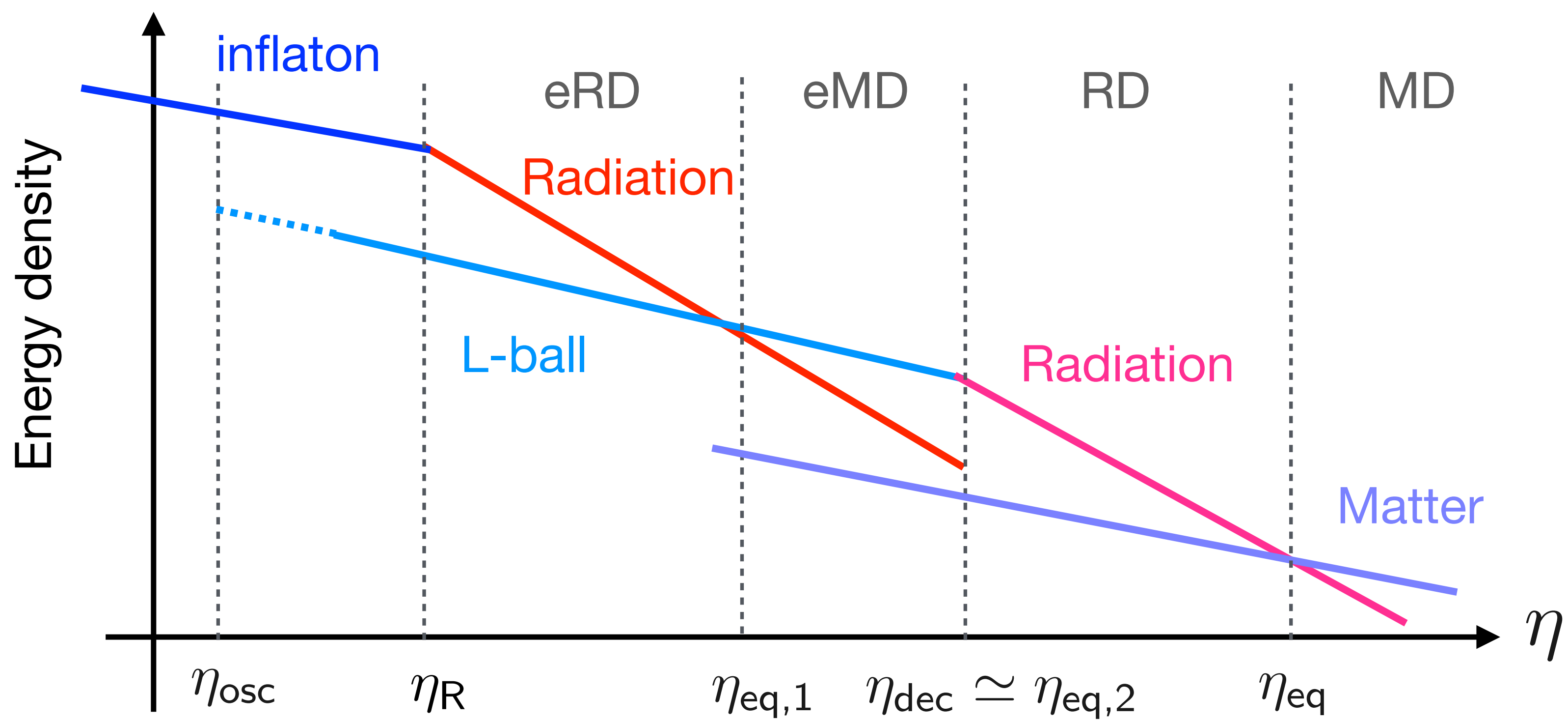
- Lepton asymmetry

$$\eta_L \simeq \frac{3T_{\rm dec}}{4m_{3/2}}$$

- A fraction of L-charge is emitted by evaporation and converted into B-number

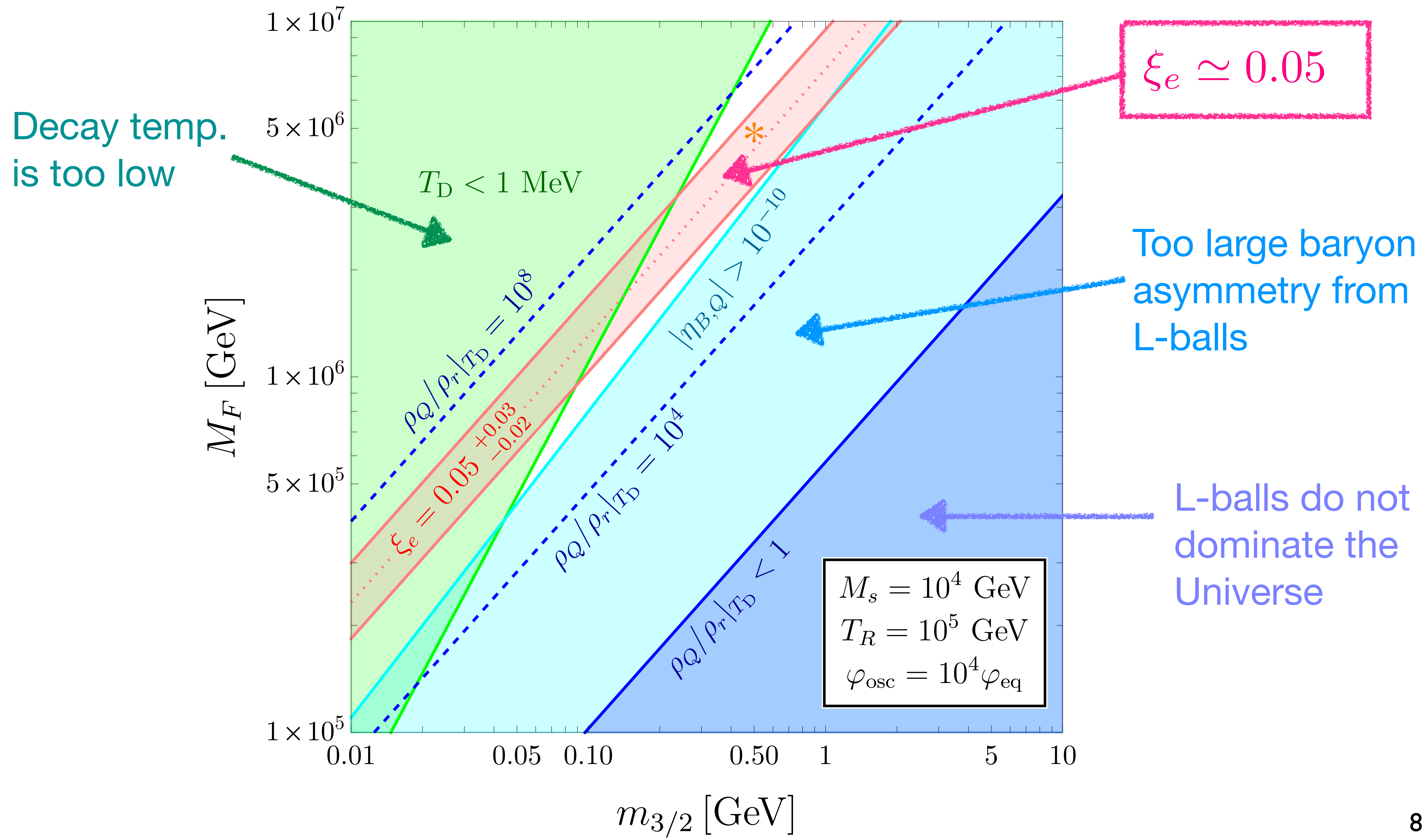
$$\eta_{B,Q} = -\frac{8}{23}\frac{\Delta Q_{\rm EW}}{Q}\eta_L$$

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



3.3 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 scalar 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

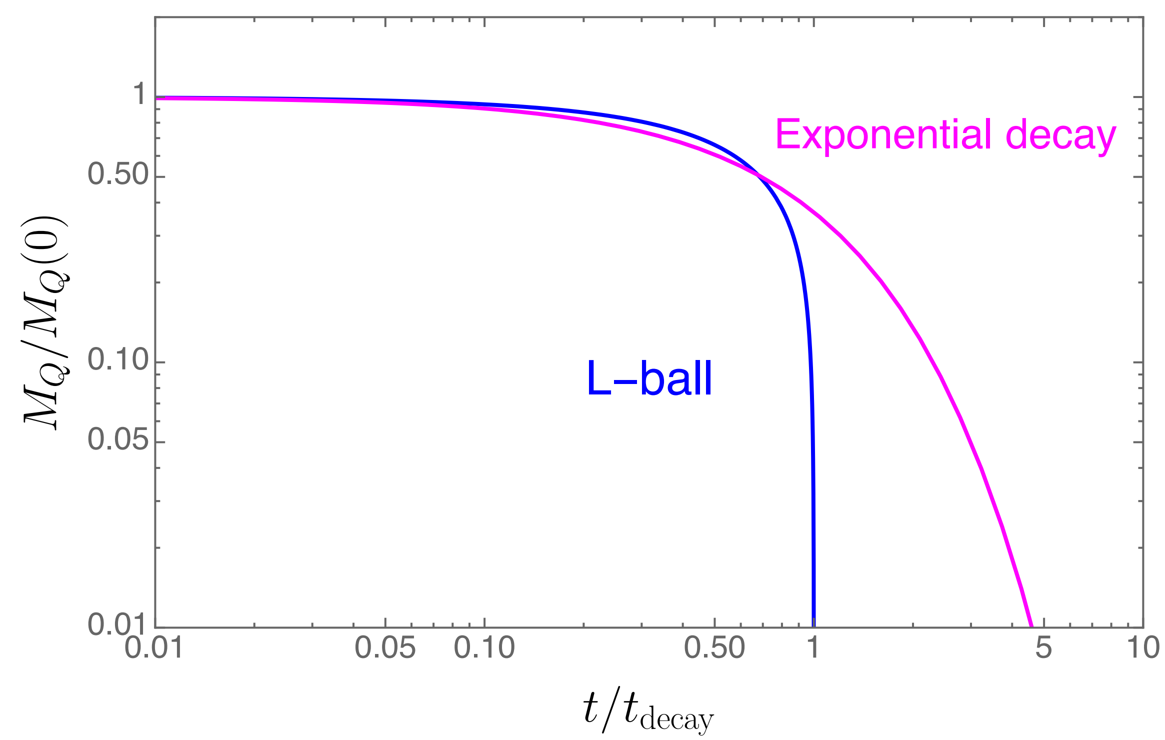
- GW production is enhanced when there exists an early MD era with a sharp transition to the RD era

Inomata et al. (2020)

Inomata Kohri Nakama Terada (2019)

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

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



- L-balls enhance the GW production
  - We estimate GW production taking into account the time evolution of L-ball energy

see also White Pearce Vagie Kusenko (2021)

4.2 Enhancement of GWs at L-ball decay

- Power spectrum of curvature perturbations
  - $A_s \simeq 2 \times 10^{-9}$
    (amplitude at CMB scale)

$$\mathscr{P}_\zeta(k) = C^2 A_s \theta(k_{\rm NL} - k)$$

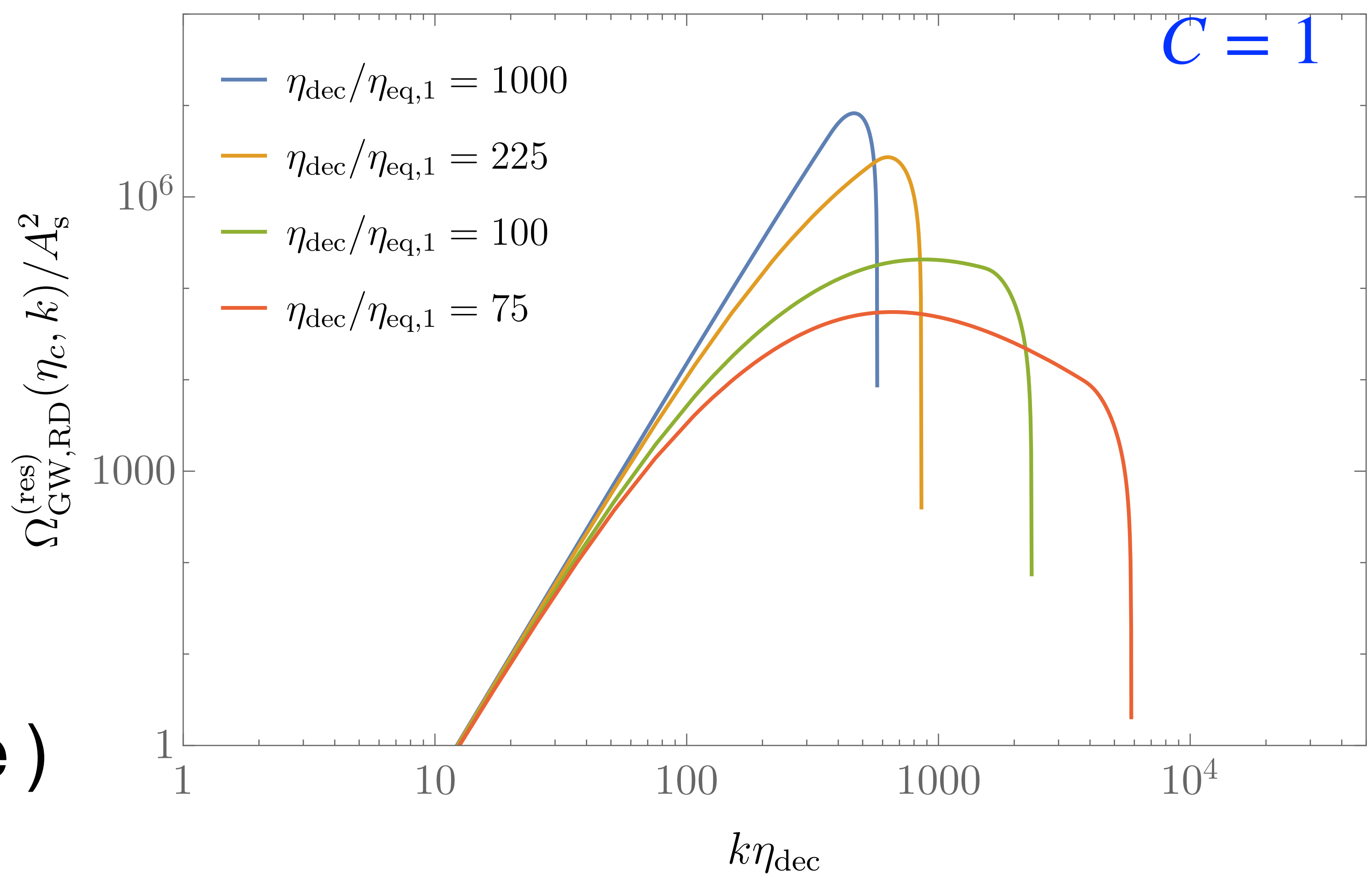
  - $k_{\rm NL}$: cut-off scale where matter perturbations become non-linear at L-ball decay (introduced to avoid considering non-linear evolution)

- GW spectrum

$\eta_{\rm dec}$: decay time

$\eta_{\rm eq,1}$: early matter-radiation equality

→ $\eta_{\rm dec}/\eta_{\rm eq,1}$ = duration of early MD



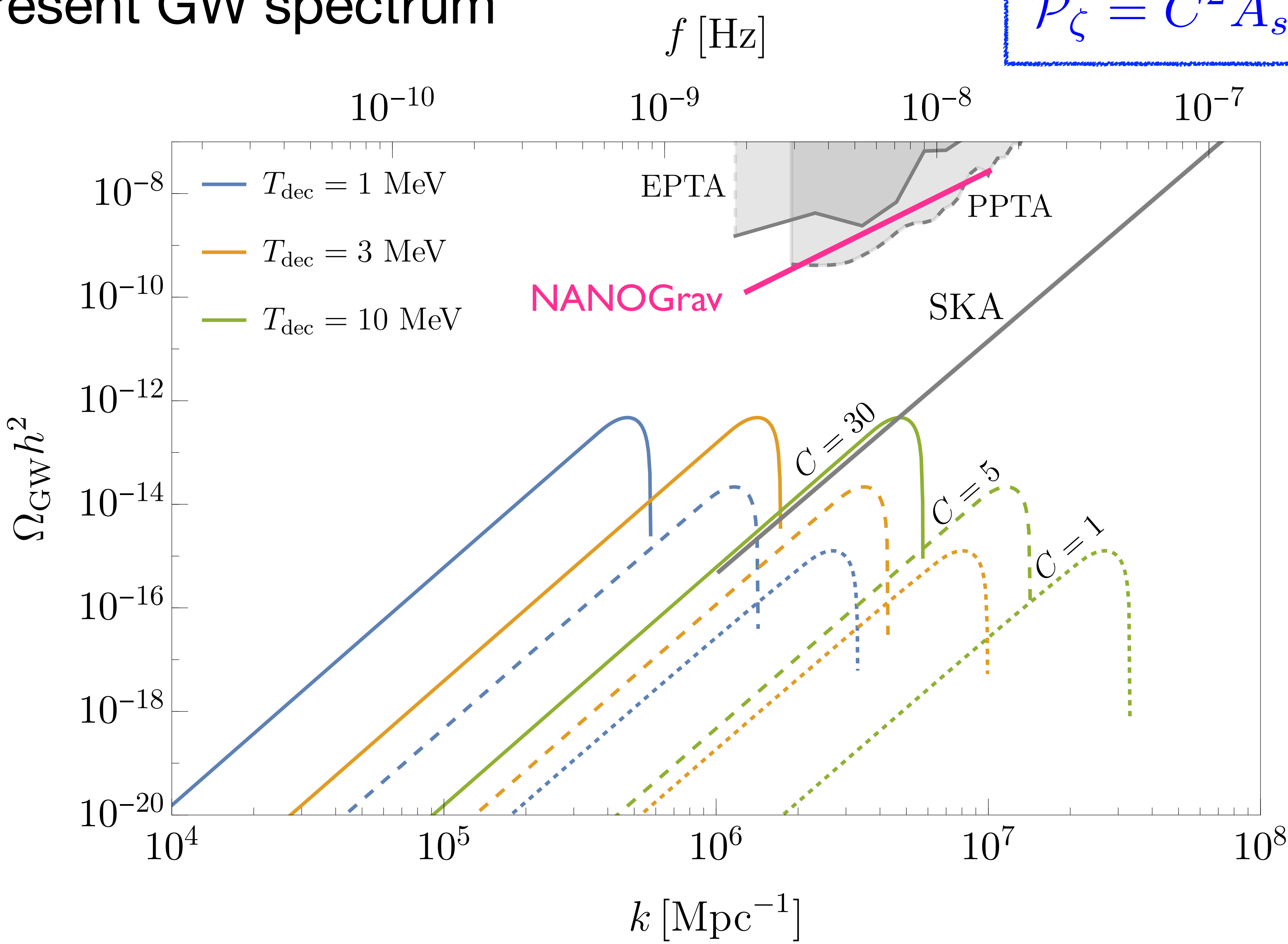
- GW amplitude is large for sufficiently long early MD (which applies to L-ball case)

4.2 Enhancement of GWs by L-balls

- Present GW spectrum

$$\mathcal{P}_\zeta = C^2 A_s\, \theta(k_{\rm NL} - k)$$

$A_s \simeq 2 \times 10^{-9}$



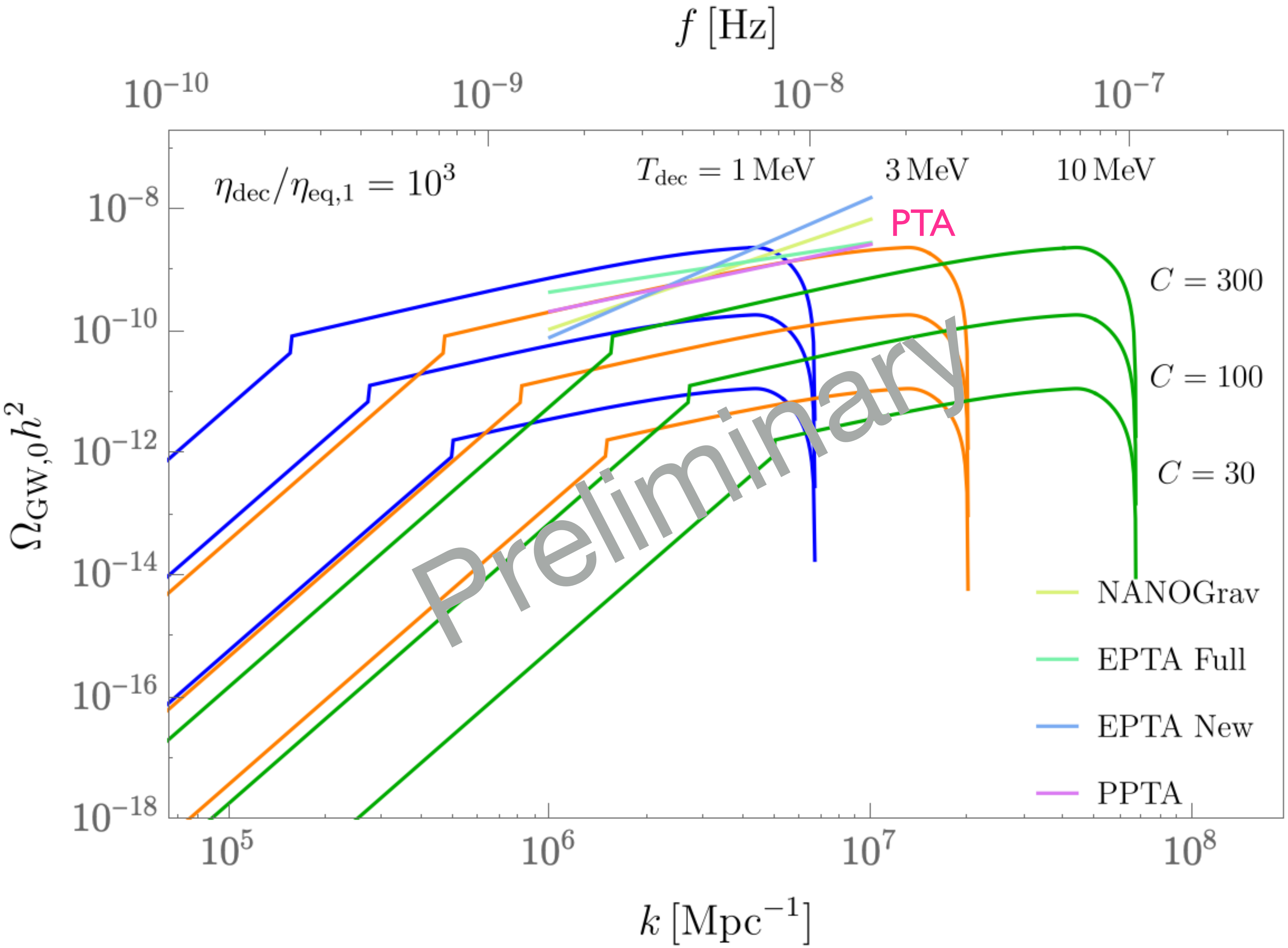
- Enhanced GW could give a significant contribution to the recent NANOGrav and other PTA signals for larger C

4.2 Enhancement of GWs by L-balls

- We include the contribution beyond the cutoff scale

  Bagla Padmanabhan astro-ph/9503077

- Enhanced GWs could account for the recent PTA signals for $T_{\rm dec} \sim 3$ MeV and $C \sim 300$



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.