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Universe with a large lepton asymmetry

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Refs. MK, Murai arXiv:2203.09713, 2308.13134
Kasuya, MK, Murai arXiv:2212.13370
Kasai, MK, Murai arXiv:2402.11902

Contents

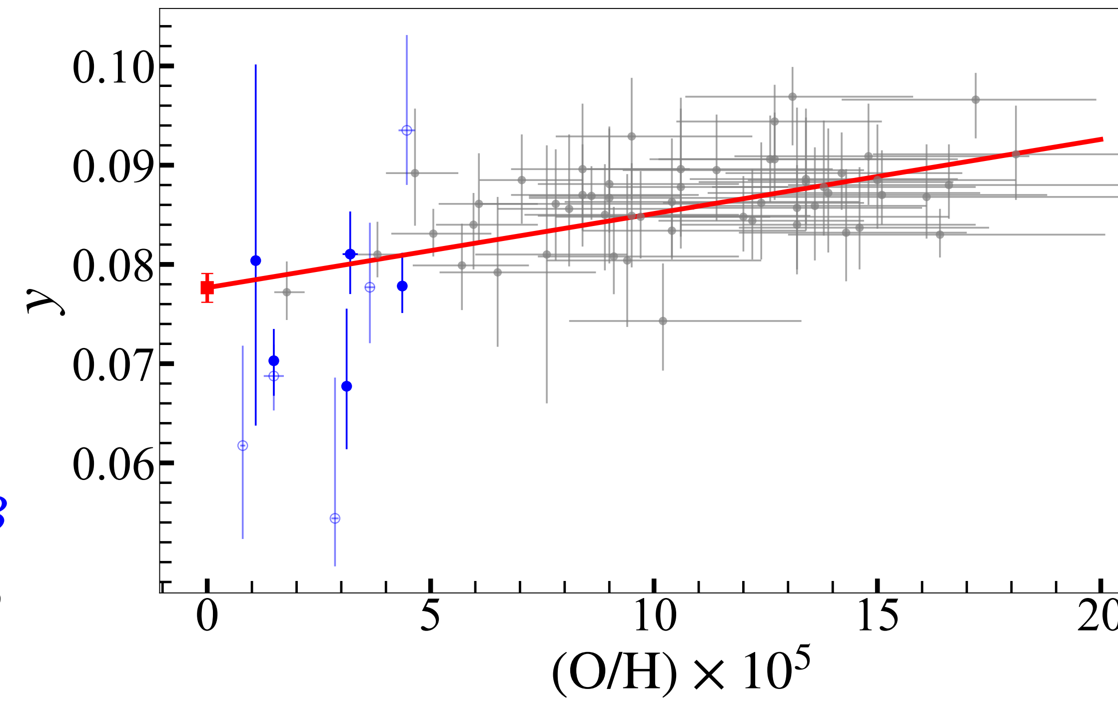
1. Introduction

- He4 is produced in Big Bang Nucleosynthesis (BBN)
- Recent new measurements of He4 (together with previous data) determined primordial He4 abundance

$$Y_p = 0.2370^{+0.0034}_{-0.0033}$$

$$Y = \rho_{^4\mathrm{He}}/\rho_B$$

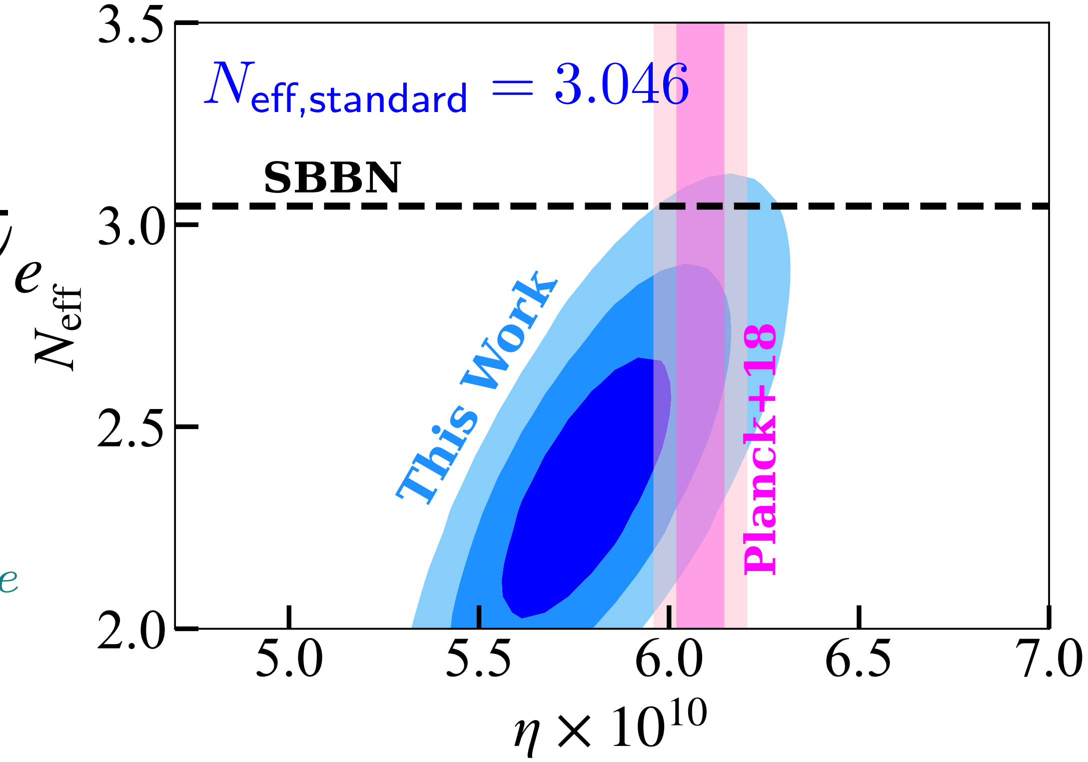
Matsumoto et al. arXiv: 2203.09617



- $\sim 1\sigma$ 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

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

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



1 Introduction

- This implies the total lepton asymmetry

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

- 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 $|\eta_B|$
- Affleck-Dine leptogenesis and Q-balls (L-balls) can produce such a large lepton asymmetry

MK Takahashi Yamaguchi (2002)

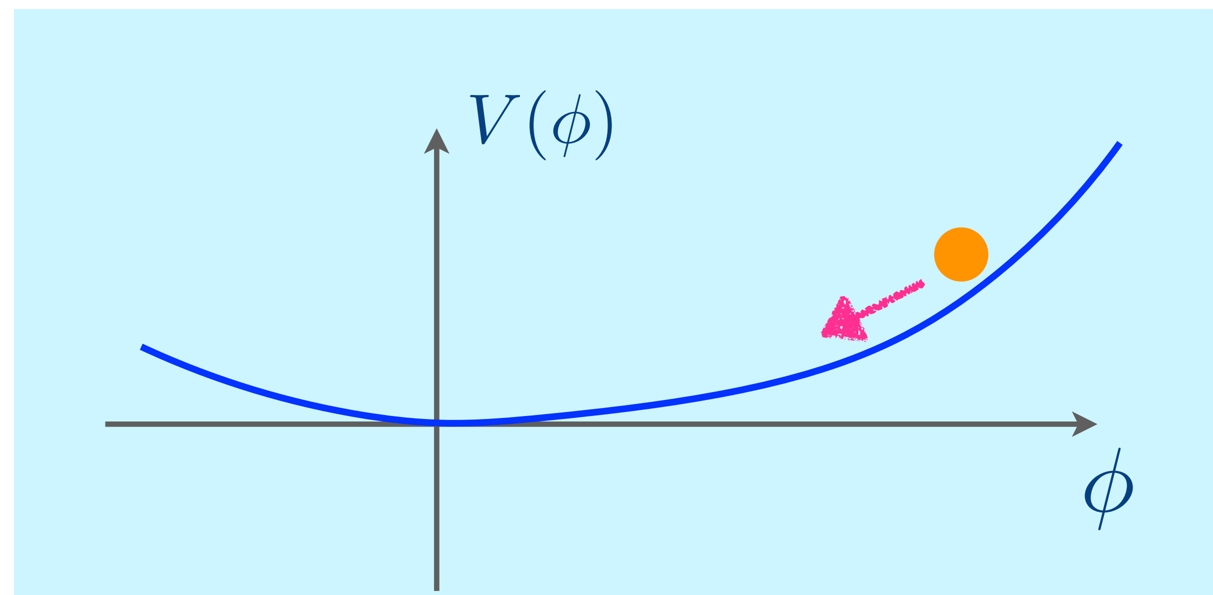
Gelmini MK Kusenko Murai Takhistov (2020)

- Produced lepton number is confined inside Q-balls and protected against the sphaleron process

2. Affleck-Dine mechanism and Q-ball formation

2.1 Affleck-Dine mechanism

- Flat directions in the scalar potential of minimal SUSY standard model (MSSM) $\ni$ (squark, slepton, Higgs)
- One of flat directions = AD field Φ
- AD field has a baryon number or/and a lepton number ← We assume here
- The flat direction is lifted by the effects of SUSY breaking and the existence of the cutoff scale



- Potential

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

V_{susy} : SUSY breaking mass term

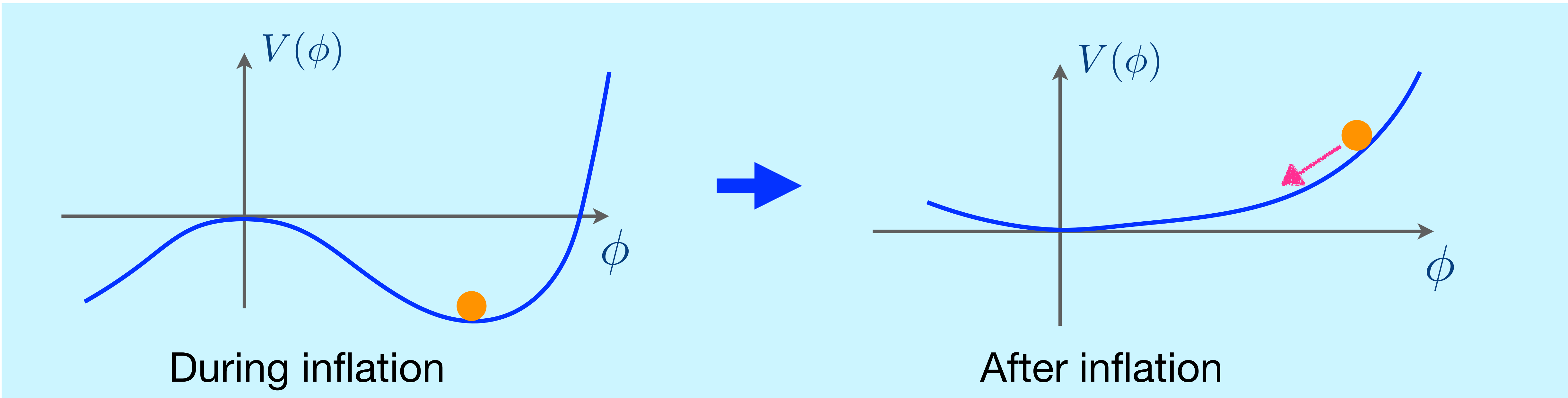
Hubble induced mass term

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

V_A : A-term $(A \sim m_{3/2})$

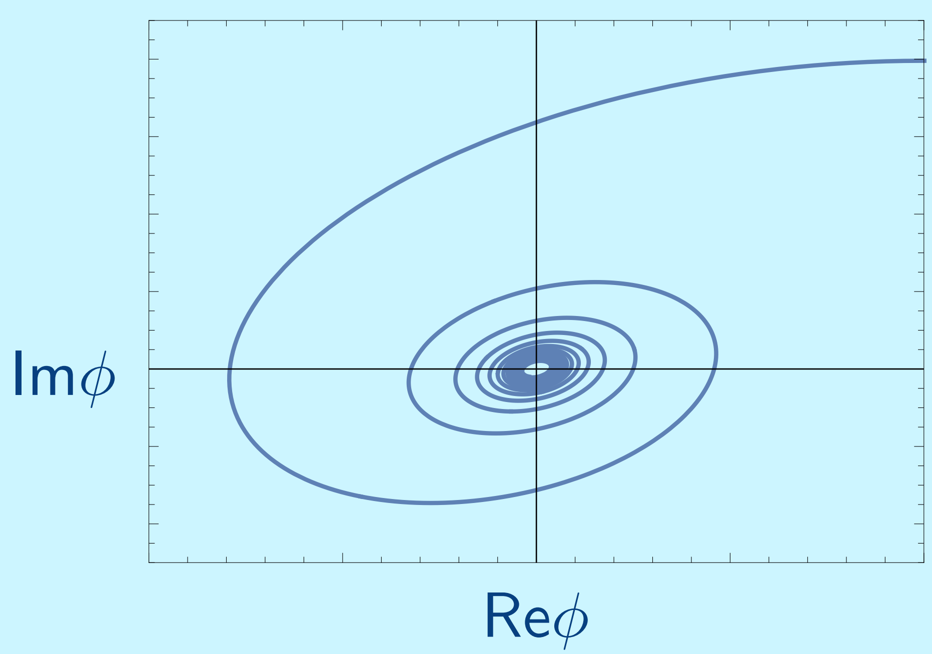
2.1 Affleck-Dine mechanism

- During inflation AD field has a large field value (if $c_H < 0$)
- After inflation AD field starts to oscillate when $H \sim m_\Phi$



- AD field is kicked into phase direction due to θ-dependent potential

V_A : A-term



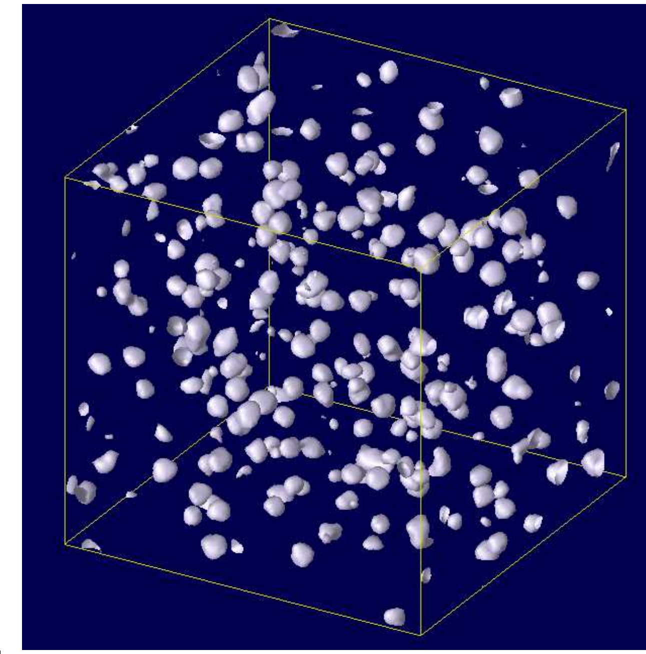
$n_L \sim \dot{\theta}|\phi|^2$

Lepton number generation

$$\eta_L = \frac{n_L}{s} \sim \frac{T_R}{m_{3/2}} \left(\frac{\phi_{\rm ocs}}{M_p} \right)^2$$

2.2 Q-balls formation

Kusenko Shaposhnikov (1998)
Kasuya MK (1999)



Hiramatsu MK Takahashi (2010)

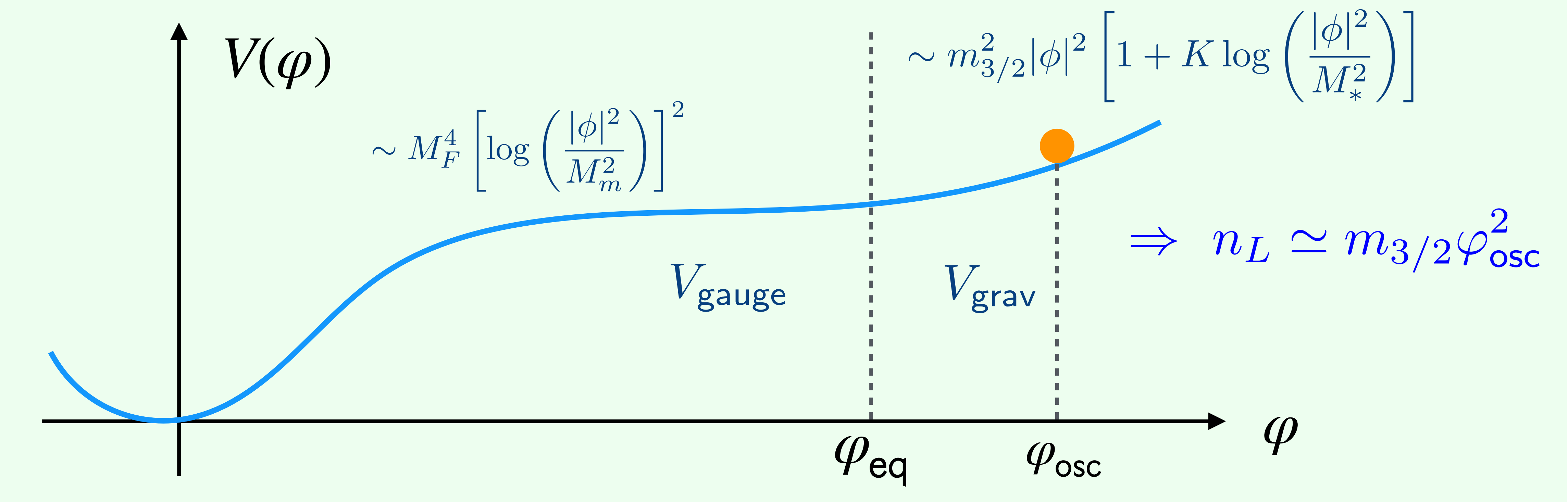
- AD field oscillation has spatial instabilities if the potential is flatter than ϕ^2
- AD field fragments into spherical lumps (Q-balls)
  - Q-balls have lepton charge (= L-balls)
- Q-ball properties depend on SUSY breaking models
- We consider gauge-mediated SUSY breaking models

$$V(\Phi) = \underbrace{M_F^4 \left[\log\left(1 + \frac{|\Phi|^2}{M_{\rm mess}^2}\right)\right]^2}_{V_{\rm gauge}} + \underbrace{m_{3/2}^2 |\Phi|^2 \left[1 + K \log\left(\frac{|\Phi|^2}{M_*^2}\right)\right]}_{V_{\rm grav}}$$

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

- Q-balls are always formed when $V_{\rm gauge}$ dominates the potential
- Q-balls are formed if $K < 0$ when $V_{\rm grav}$ dominates the potential

2.3 Q-ball formation



- AD field starts oscillation with amplitude $\varphi_{\rm osc} > \varphi_{\rm eq}$ at $H \sim m_{3/2}$
- We assume $K > 0\ \Rightarrow$ Q-balls do not form until $\varphi < \varphi_{\rm eq}$
  - Q-ball formation is delayed [delayed-type L-ball]
- Q-ball mass, radius and energy per lepton number

$$M_Q = \frac{2\sqrt{2}\pi}{3}\zeta M_F Q^{3/4} \qquad R_Q = \frac{1}{\sqrt{2}}\zeta^{-1}M_F Q^{-1/4}$$

$$\omega = dM_Q/dQ = \sqrt{2}\zeta M_F Q^{-1/4} \qquad \zeta \sim 3.6$$

Hisano Nojiri Okada (2001)

$$Q = \beta\left(\varphi_{\rm eq}/M_F\right)^4 \qquad \beta \simeq 6\times10^{-4}$$

2.4 Q-ball evolution

- We assume that Q-balls dominate the Universe
- Q-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

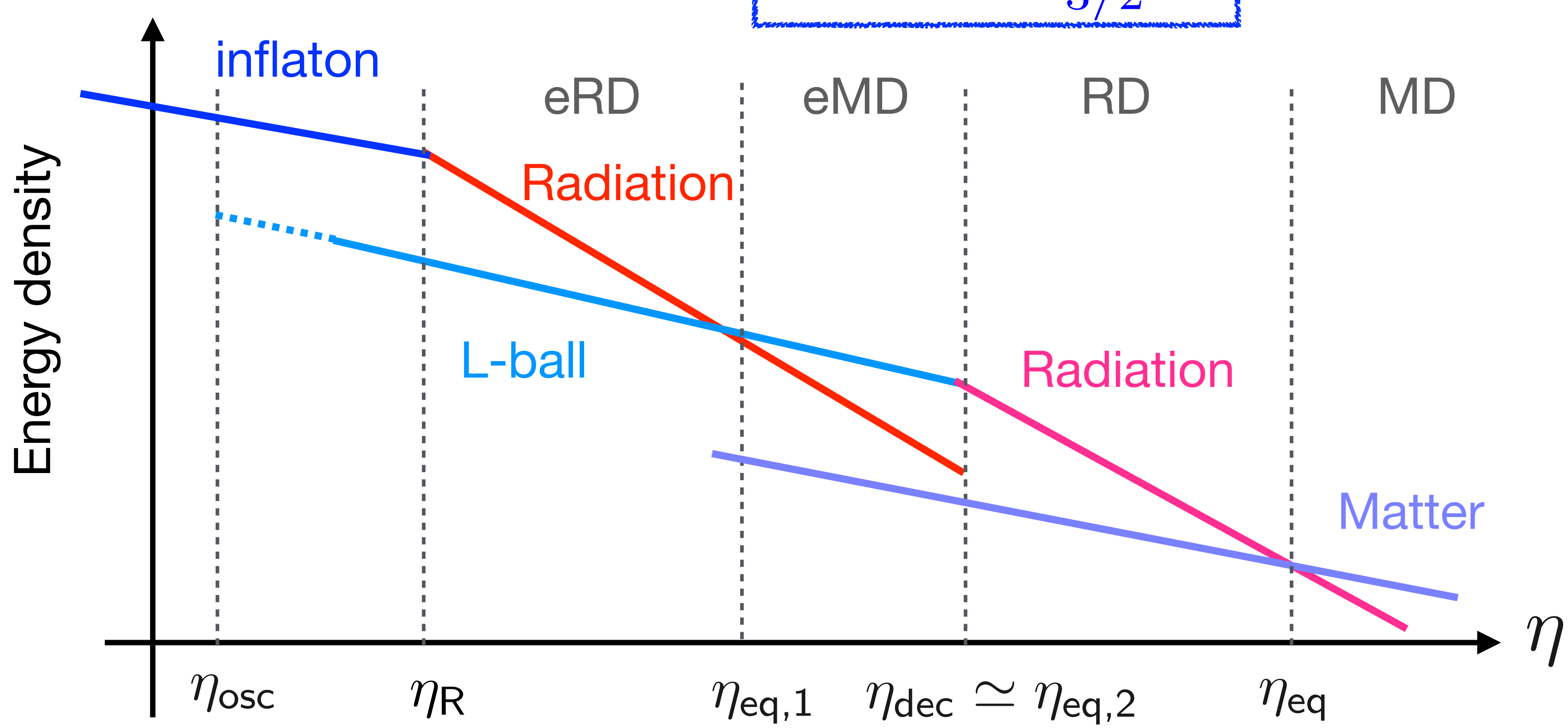
- Decay temperature

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

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

- Lepton asymmetry

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

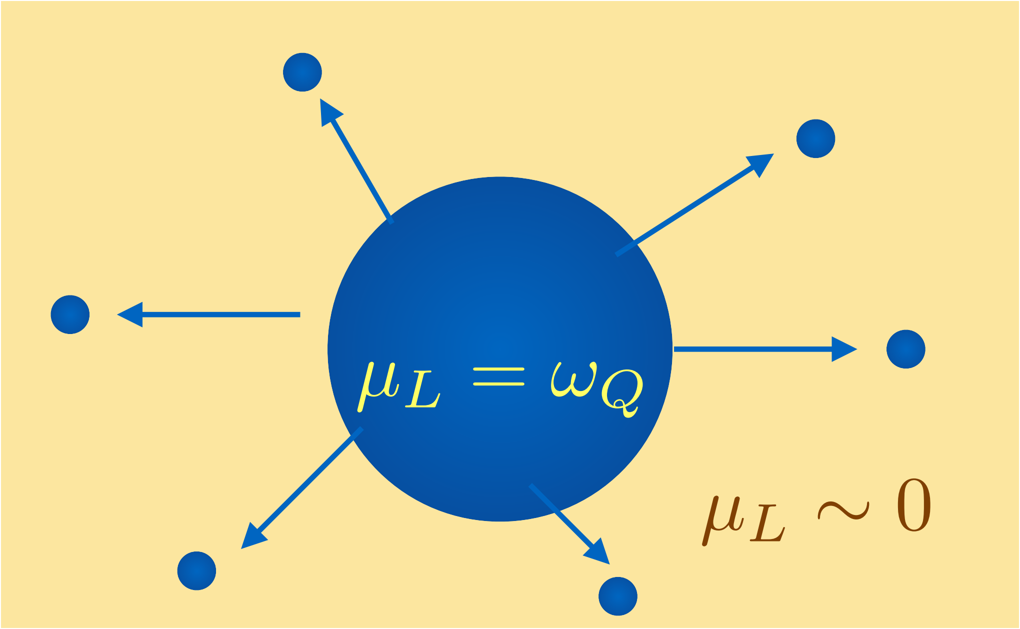


2.5 Q-ball evaporation

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

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

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

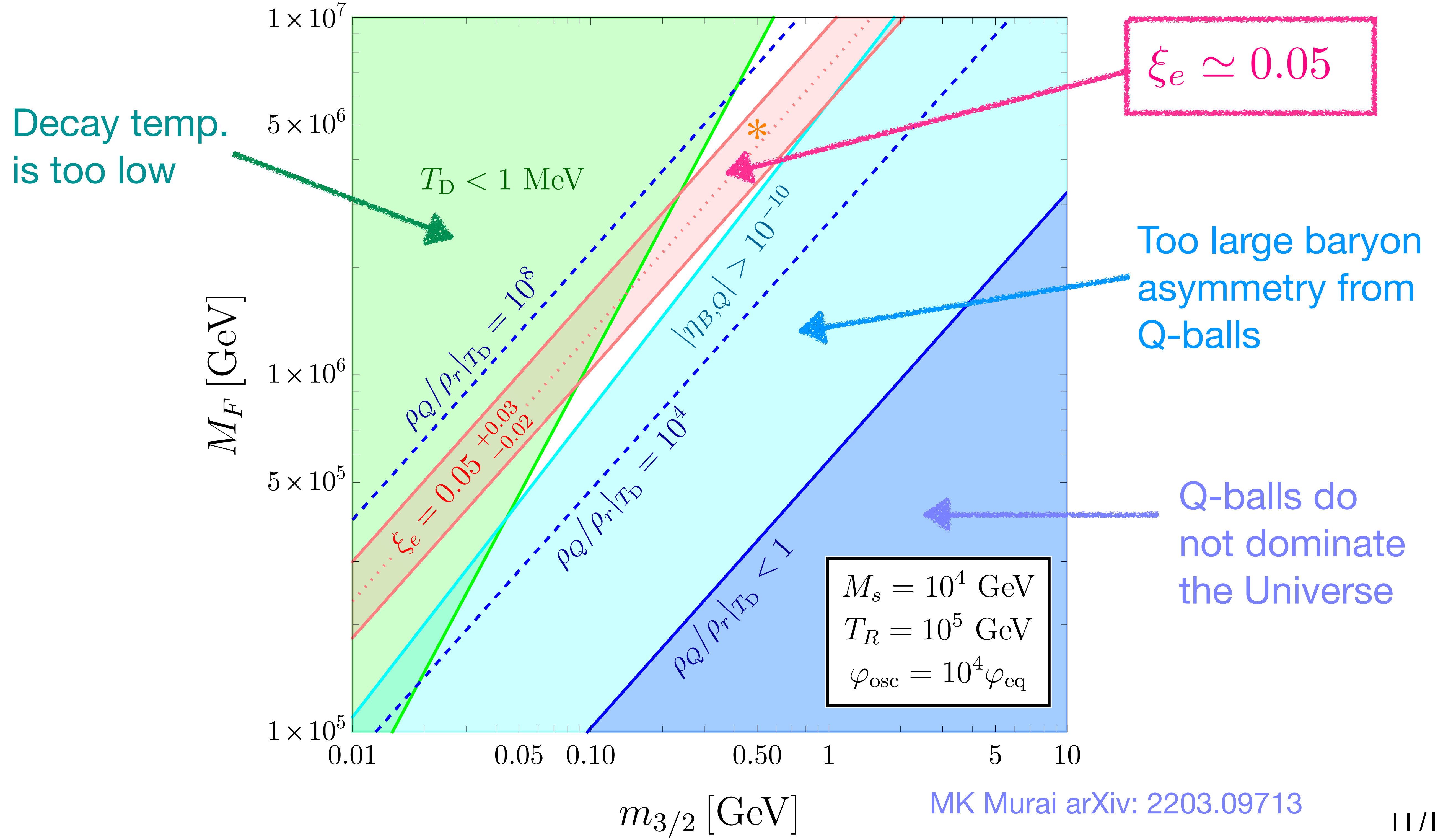


- The produced baryon asymmetry should be smaller than the observed one so as not to spoil the success of BBN

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

2.6 Constraints on model parameters

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



MK Murai arXiv: 2203.09713

3. Production of 2nd-order GWs in Q-ball scenario

3.1 Gravitational wave production

- Inflation produces curvature perturbations $\zeta \sim 10^{-5}$ at large scales, which are in good agreement with CMB observations
- Curvature perturbations at small scales are not known and could be much larger
- Curvature and tensor perturbations do not couple in the linear order but they do in the second order

Ananda Clarkson Wands (2007)
Baumann Steinhardt Takahashi Ichiki (2007)
Saito Yokoyama (2009) Bugaev Kulimai (2010)

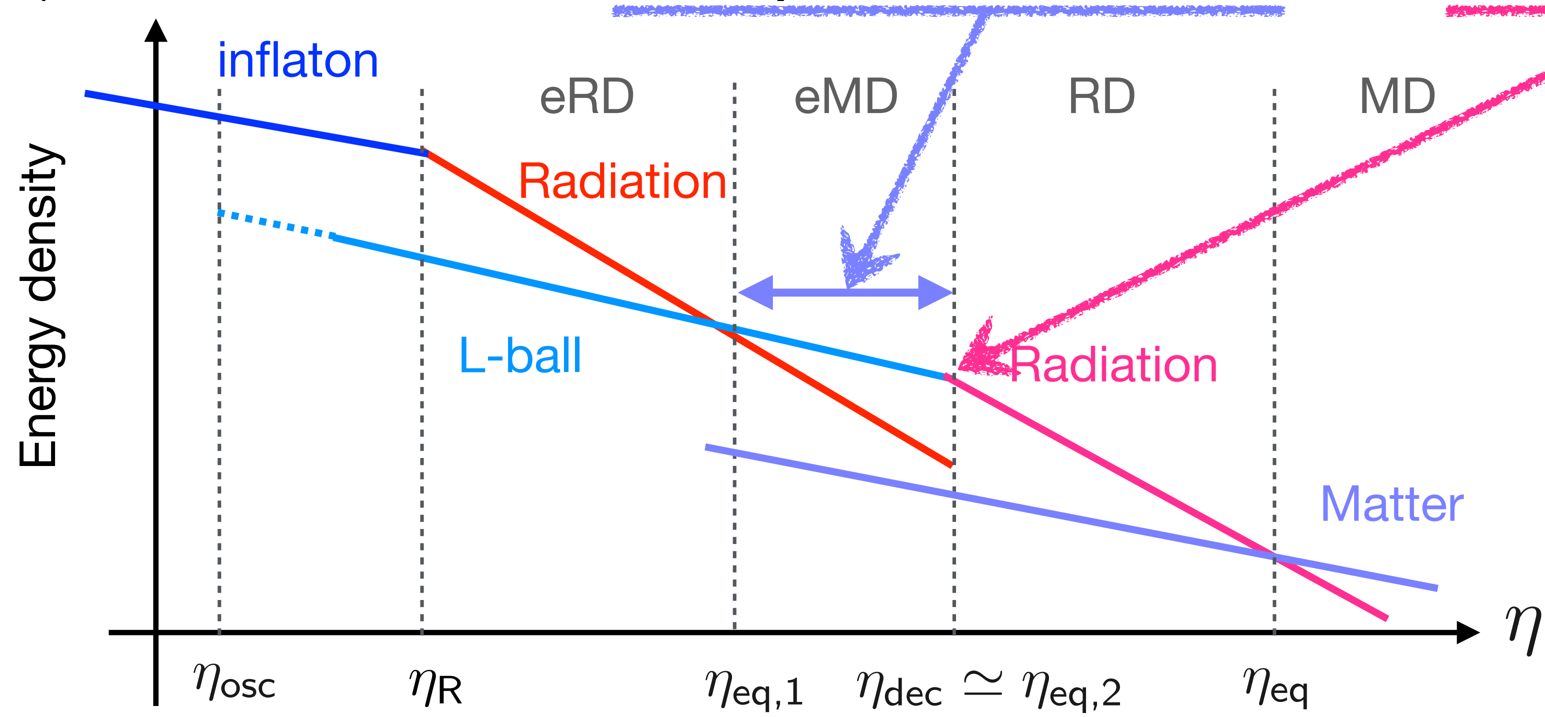
$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\zeta^2)$$

- GWs are produced by the 2nd order effect of scalar perturbations
- Furthermore, GW production is enhanced when there exists an early MD era with a sharp transition to the RD era (Poltergeist mechanism)

Inomata Kohri Nakama Terada (2019) Inomata MK Mukaida Terada Yanagida (2020)

3.2 Enhancement of GWs at Q-ball decay

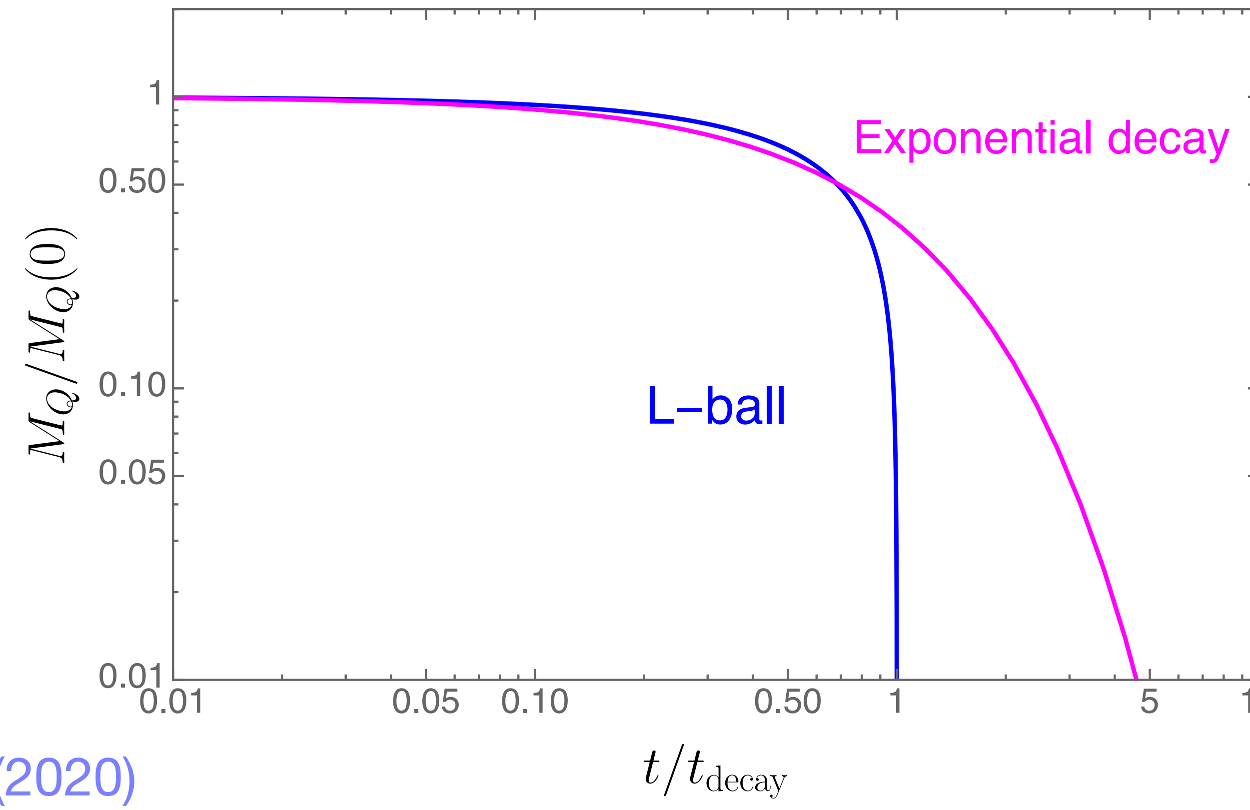
- Q-balls realize an early MD universe and decay rapidly



- Q-balls decay rapidly

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

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



- Q-balls enhance GW production

White Pearce Vagie Kusenko (2020)

- We estimate GW production taking into account the time evolution of Q-ball energy

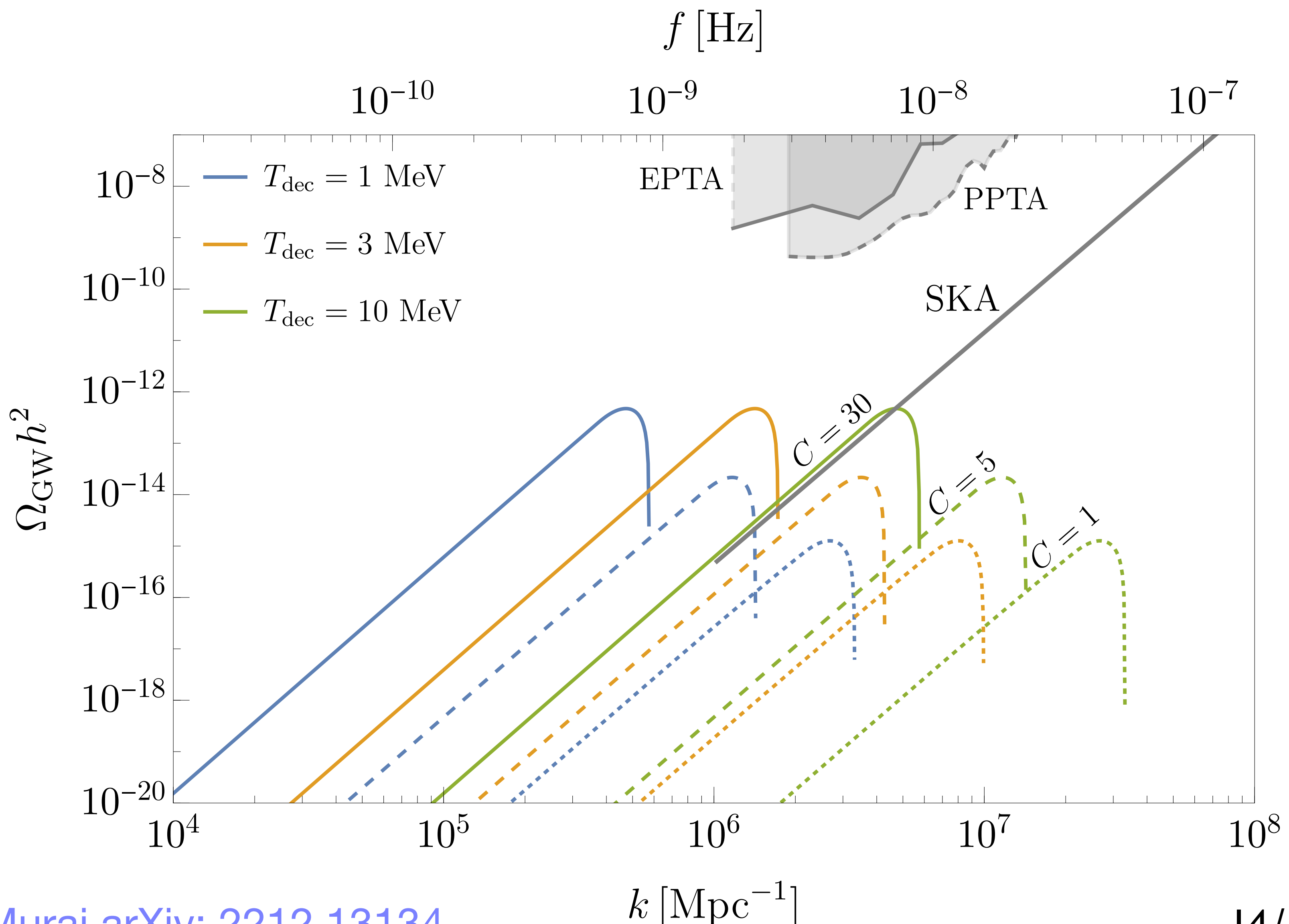
3.2 Enhancement of GWs at Q-ball decay

- Scale-invariant 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
  - Peak is determined by the cutoff $k_{\rm NL}$
  - Need to understand non-linear evolution



Kasuya MK Murai arXiv: 2212.13134

3.3 Effect of non-linear density evolution

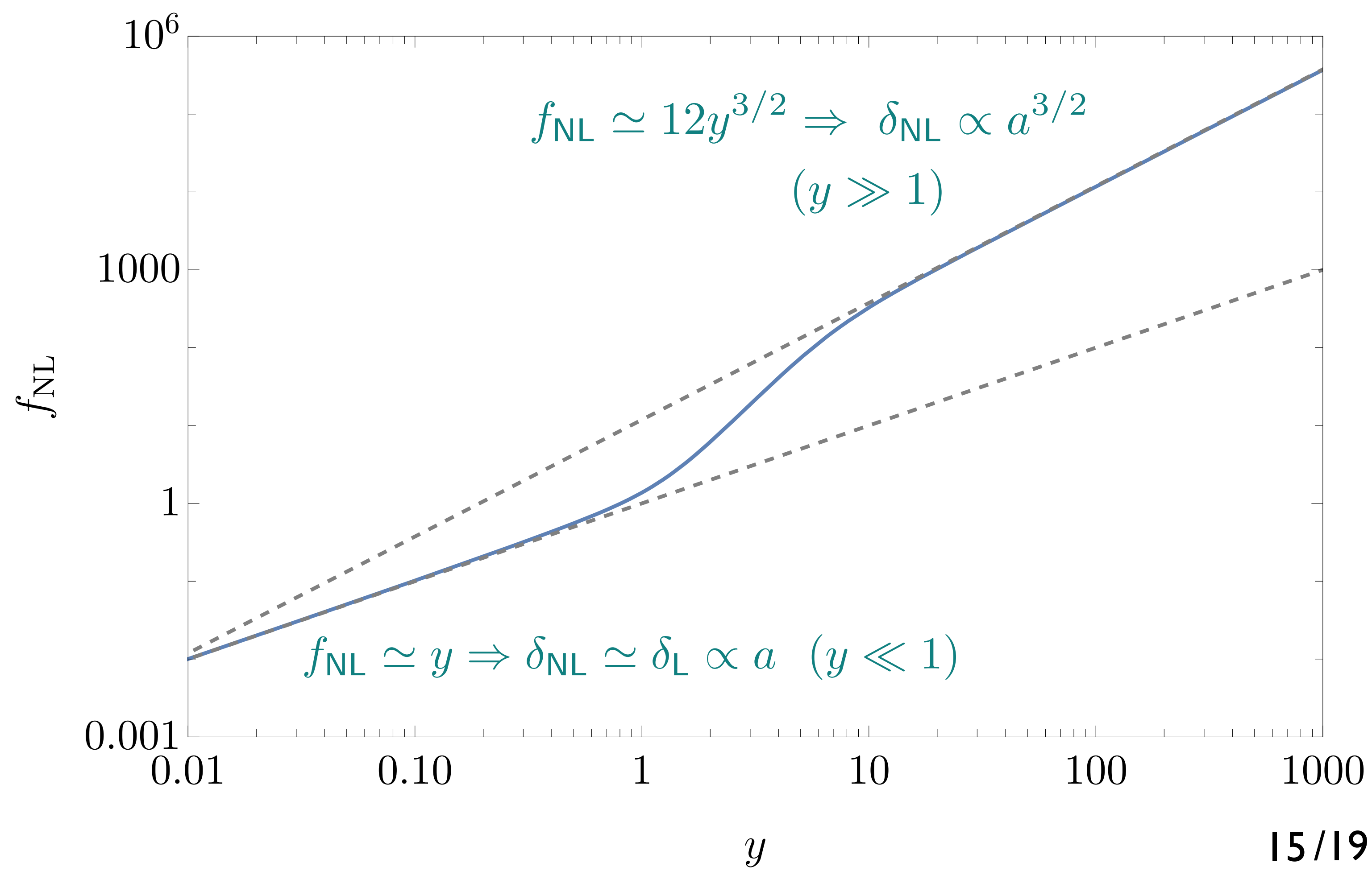
MK Murai arXiv: 2308.13134

- Estimation including the effect of non-linear density evolution
  - Gravitational potential Φ is linear
  - Φ is related to density fluctuation $\delta\rho$ through Poisson eq.
  - Anisotropic stress is neglected
- N-body simulation suggests that non-linear density fluctuation is related to linear density fluctuation

$$\delta^2_{\mathsf{m,NL}}(k_{\mathsf{NL}}) = f_{\mathsf{NL}}[\delta^2_{\mathsf{m,L}}(k_{\mathsf{L}})]$$

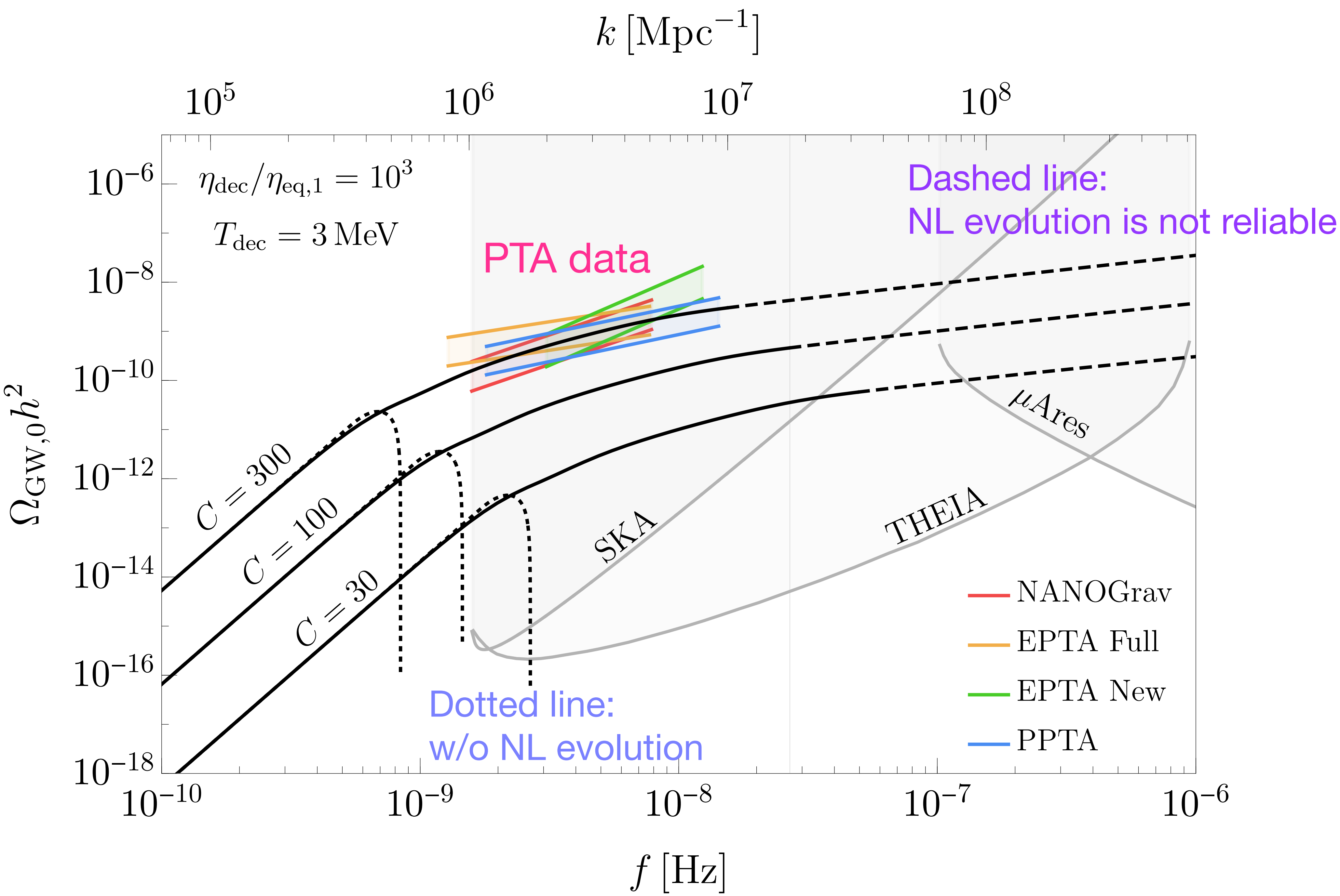
$$k_{\mathsf{L}} = \left[1 + \delta^2_{\mathsf{m,NL}}(k_{\mathsf{NL}})\right]^{-1/3} k_{\mathsf{NL}}$$

  - Estimation of $f_{\mathsf{NL}}(y)$ is reliable for $y < 10^3$



3.4 GW spectrum including NL evolution

- Power spectrum $\mathscr{P}_\zeta(k) = C^2 A_s$
- $T_{\rm dec} \simeq 3$ MeV and $C \simeq 300$ explain the recent PTA data



MK Murai arXiv: 2308.13134

4. Resonant sterile neutrino production in Q-ball scenario

Kasai MK Murai arXiv: 2403.01675

- Sterile neutrino ν_s with mass $m_s = \mathcal{O}(1)$ keV → dark matter
- Mixing with active neutrinos

$$\nu_a = \cos\theta\,\nu_1 + \sin\theta\,\nu_2$$
$$\nu_s = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2$$

$a = e, \mu, \tau$

- Finite temperature and density effects
  - Effective mixing angle

$$\theta_m^2(p,T) = \theta^2\left[\left(1 - \frac{2p}{m_s^2}\left(V_{Ta}(p,T) + V_{Da}(p,T)\right)\right)^2 + \frac{p^2\Gamma_{\nu_a}^2(p,T)}{m_s^4}\right]^{-1}$$

Finite temp. Effect $V_{Ta} \sim -G_F^2\,p\,T^4$ Density effect $V_{Da} \sim G_F T^3 \mathcal{L}_a$

  - Potential lepton asymmetry

$$\mathcal{L}_a = 2L_{\nu_a} + \sum_{a\neq b} L_{\nu_b} \qquad L_{\nu_a} = \frac{n_{\nu_a}}{s}$$

- Sterile neutrino production

$$\frac{dn_s}{dt} \propto T^5 \theta_m^2 n_a$$

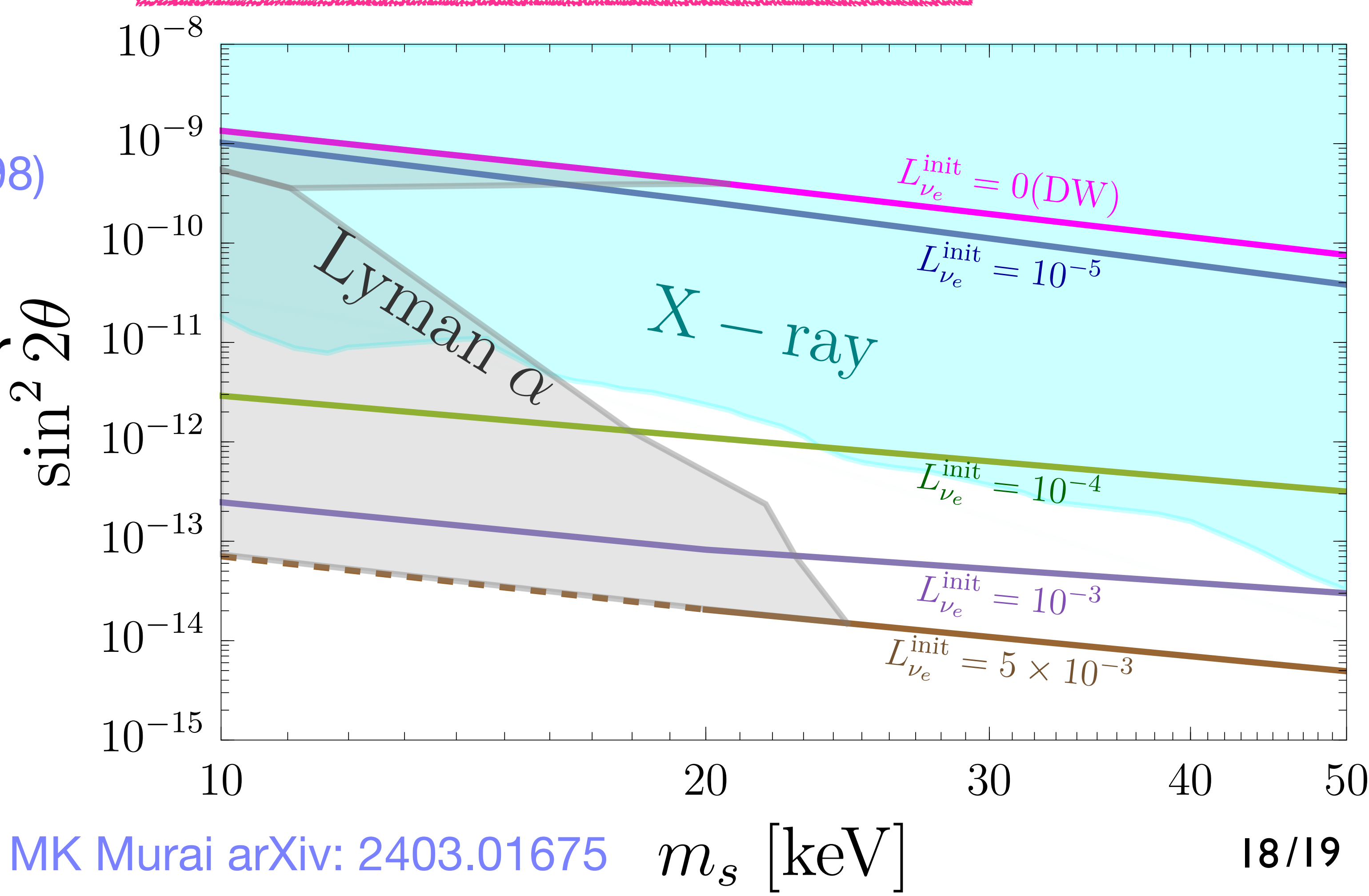
4. Resonant sterile neutrino production in Q-ball scenario

- Without large lepton asymmetry $V_{Da} \sim 0$ Dodelson Widrow (1993)
  - Sterile ν are produced via Dodelson-Widow mechanism
  - Constraint from X-ray obs. ➡ $m_s \lesssim 3$ keV ➡ Warm DM
  - Constraint from Lyman-alpha ➡ $m_s \gtrsim 20$ keV
- DW mechanism cannot account for DM
- Large lepton asymmetry ⬅ produced by Q-ball decay
  - Resonant production

    Shi and Fuller (1998)

    $$m_s^2/2p - V_{Ta} - V_{Da} \sim 0$$
  - DM density is realized for a smaller mixing angle
- Sterile ν explains all DM

$$L_{\nu_e} \gtrsim 10^{-4} \quad m_s \gtrsim 20\text{keV}$$



Kasai MK Murai arXiv: 2403.01675

4. Conclusion

- Recent He4 measurement suggests that our universe has a large lepton asymmetry
- Q-ball scenario successfully realizes a large lepton asymmetry suggested by the He4 measurement
- Q-balls also dominate the universe and decay rapidly, which significantly enhances gravitational wave production from curvature perturbations.
- For precise estimation of GW spectrum we need understand the effect of non-linear growth of density perturbations
- Sterile neutrinos are produced through resonance and can be dark matter of the universe