Leptogenesis via the Relaxation of Higgs and other Scalar Fields

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Outline

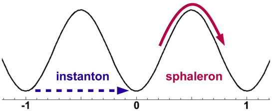
Leptogenesis via scalar field relaxation

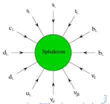
Matter-antimatter asymmetry

- Our universe contains most baryon but no anti-baryon

$$\eta_B = n_B/n_\gamma \cong 6 \times 10^{-10} \qquad \Omega_B h^2 = 0.022$$

  from both CMB observation and BBN.
- Sakharov's conditions for **Baryogenesis**
  1. B violation
  2. C and CP violations
  3. Deviation from thermal equilibrium
- Standard Model do satisfy all the conditions but the CP phase is too small to generate enough asymmetry. (And, the Higgs mass is too heavy)
- **Leptogenesis**:
  - Make L first. Then, **Sphaleron** process turns L into B

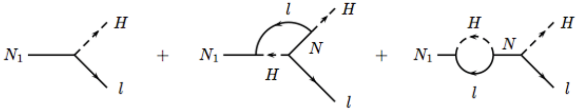




Standard Thermal Leptogenesis

Fukugita and Yanagida (1986)

- SM + Right Handed Majorana neutrino N_R



  - RH Majorana neutrino $\rightarrow$ Violates L
  - CP-violating phases in the neutrino Yukawa couplings
  - Out of equilibrium decay of RH neutrino
- Requirements:
  - The heavy RH neutrino have to be in thermal bath: $T > M_R$
  - Neutrino mass $m_\nu < 0.2\,\mathrm{eV}$
- We will look at an interesting alternative which works for $T < M_R$.

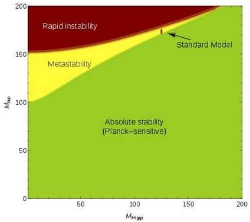
Higgs potential

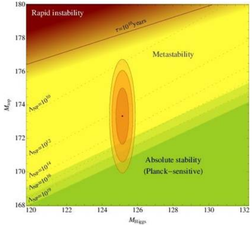
$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

- LHC has discovered the standard model Higgs boson with $m_h = 125.09 \pm 0.21 \pm 0.11\,\mathrm{GeV}$.

  $\Rightarrow$ λ is smaller than was expected.
- Due to quantum correction, the λ can be **very small** or even be negative at scale $\phi \gtrsim 10^{12}\,\mathrm{GeV}$.
- With such small λ, Higgs field can obtain **large VEV** during inflation.
- The **relaxation** of such large VEV after inflation can lead to interesting consequence in cosmology.

  $\Rightarrow$ **Leptogenesis**





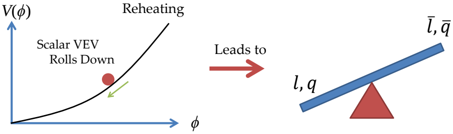
Leptogenesis via Scalar Field Relaxation

Basic Ingredients:

1. Large initial VEV of a scalar field $\phi_0 = \sqrt{\langle \phi^2 \rangle}$
2. Relaxation of the scalar field
3. Coupling between L current and derivative of ϕ

$$\mathcal{O} \propto \left(\partial_t \phi^2\right) j_L^0$$

4. L-violating process



1. Quantum Fluctuations during Inflation

- During inflation, scalar fields can obtain vacuum expectation values (VEVs) through **quantum fluctuation**.
- The field can also **roll down classically** toward its equilibrium minimum

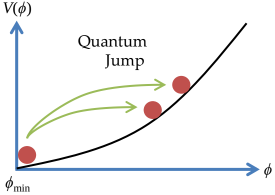
$$\ddot{\phi} + 3H\dot{\phi} = -\frac{dV(\phi)}{d\phi}$$

with relaxation time scale

$$\tau_{\rm roll} \sim \left[\frac{d^2V(\phi)}{d\phi^2}\right]^{-1/2} = \frac{1}{m_{\rm eff}}$$

- If $m_{\rm eff} \ll H_I$, there is insufficient time for the field to roll down.

  $\Rightarrow$A **large field value** $\phi_0 = \sqrt{\langle\phi^2\rangle}$.
- Quantum fluctuation makes perturbation for all the wavelengths within the horizon: $p = k/a > H_I$.
- Once those fluctuations are pushed outside the horizon, they become classical and are frozen.



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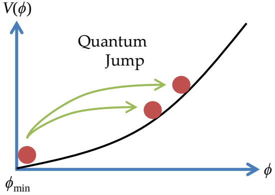

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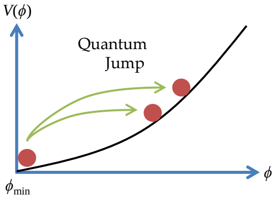

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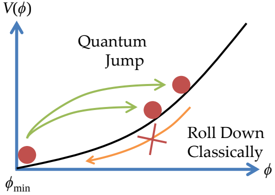

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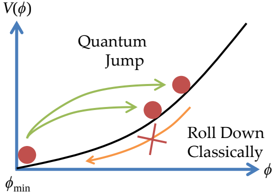

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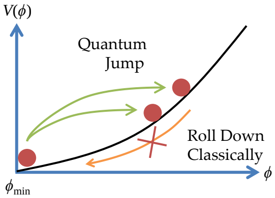

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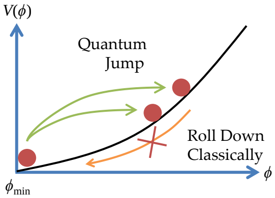


1. Large Initial VEV for Scalar Fields

- The average equilibrium VEV $\phi_0 = \sqrt{\langle\phi^2\rangle}$ is such that

$$V(\phi_0) \sim H_I^4$$

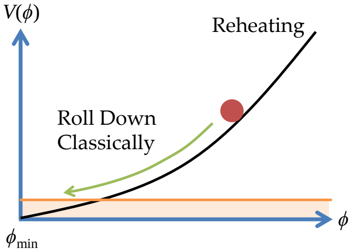
- This is

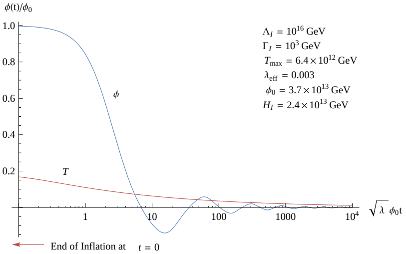
$$\phi_0 \simeq 0.19 H_I^2/m \qquad \text{for } V \sim m^2\phi^2/2$$
$$\phi_0 \simeq 0.36\lambda^{-1/4} H_I \qquad \text{for } V \sim \lambda\phi^4/4$$

- For inflation scale $\Lambda_I \sim 10^{16}\,\text{GeV}$, $H_I = \Lambda_I^2/\sqrt{3}M_{pl} \sim 10^{13}\,\text{GeV}$,with $\lambda \sim 0.01$, the VEV is $\phi_0 \sim 10^{13}\,\text{GeV}$.
- For such a large VEV, the scalar field can be sensitive to higher dimensional operators.

2. Scalar Field Relaxation after Inflation

- After inflation, H decreases. When $H < m_\phi$, the scalar field can relax.
- ϕ rolls down and oscillate with decreasing amplitude due to the Hubble friction H.
- For $\lambda\phi^4$ potential, the typical relaxation time is $t_{\rm rlx} \approx 7\lambda^{-1/2}\phi_0^{-1}$.





3. Effective Chemical Potential

Dine et. al. (1991)
Cohen, Kaplan, Nelson (1991)

- During the relaxation, the scalar field can be sensitive to **higher dimensional operators**.
- We consider the couplings between the **derivative** of ϕ and j^{μ}_{B+L} like

$$\mathcal{L}_6 = -\frac{1}{M_n^2}\left(\partial_\mu |\phi|^2\right) j^{\mu}_{B+L} \quad \text{or} \quad \mathcal{L}_5 = -\frac{1}{M_n}\left(\partial_\mu \phi\right) j^{\mu}_{B+L}$$

j^{μ}_{B+L}: the $B+L$ ferimion current
M_n: new energy scale when the operator is relevant.

- These operators are similar to those used in **spontaneous baryogenesis** scenarios.
- **Break** CPT spontaneouslly!
- So the Sakharov's conditions doesn't has to be satisfied exactly.

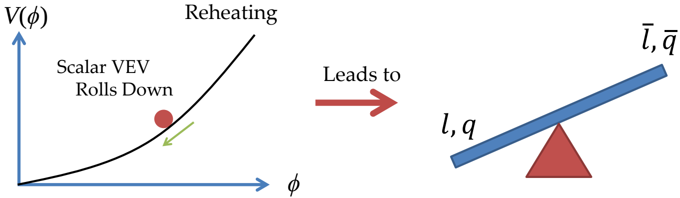
3. Effective Chemical Potential

$$\mathcal{L}_6 = -\frac{1}{M_n^2}\left(\partial_\mu |\phi|^2\right) j^\mu_{B+L} \quad \text{or} \quad \mathcal{L}_5 = -\frac{1}{M_n}\left(\partial_\mu \phi\right) j^\mu_{B+L}$$

- These give **effective chemical potentials** to baryons and leptons

$$\mu_6 = \frac{1}{M_n^2}\partial_t |\phi|^2 \quad \text{or} \quad \mu_5 = \frac{1}{M_n}\partial_t \phi$$

- When ϕ rolls down, this **shifts the energy levels** between fermions and anti-fermions.



3. Derivative coupling?

M. E. Shaposhnikov (1987),
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- Integration by part

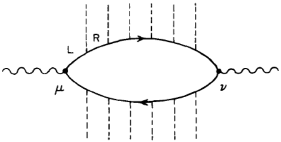
$$\mathcal{L}_6 = -\frac{1}{M_n^2}\left(\partial_\mu |\phi|^2\right) j^\mu_{B+L} \to \frac{1}{M_n^2} |\phi|^2 \, \partial_\mu j^\mu_{B+L}$$

- The operator is equivalent to

$$\mathcal{L}_6 \propto \frac{1}{M_n^2} |\phi|^2 \left(g^2 W\tilde{W} - \frac{1}{2} g'^2 B\tilde{B} \right)$$

through the **electroweak anomaly equation**, where W and B are $SU(2)_L$ and $U(1)_Y$ gauge fields.

- For the case that ϕ is the Higgs field, this can be generated by
  1. Heavy fermion in the loops: $M_n = M_f$
  2. Thermal loops: $M_n = T$



3. More derivative couplings

- $\mathcal{L}_6$ operators
  - Higgs fields h [A. Kusenko, L. Pearce, LY, arXiv:1410.0722]
  - Elementary Goldstone boson Higgs [H. Gertov, F. Sannino, L. Pearce, LY, arXiv:1601.07753.]
- $\mathcal{L}_5$ operators
  - Axion $a(t)$ [A. Kusenko, K. Schmitz, T.T. Yanagida, arXiv:1412.2043.]

$$\mathcal{L}_{\text{eff}} \supset \frac{g_2^2}{32\pi^2}\frac{a(t)}{f_a}F\tilde{F} = -\frac{a(t)}{N_f f_a}\partial_\mu\left(\overline{\psi}\gamma^\mu\psi\right)$$

  - Majoron $\chi(t)$ [M. Ibe, and K. Kaneta, arXiv:1504.04125.]

$$\mathcal{L}_{\text{eff}} \supset -\frac{\partial_\mu\chi}{\sqrt{2}M_R}j_L^\mu$$

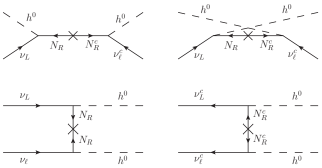
  - 750 GeV pseudoscalar S [A. Kusenko, L. Pearce, LY, arXiv:1604.02382.]

$$\mathcal{L} \supset \tilde{\lambda}_g\frac{\alpha_s}{12\pi v_{\text{EW}}}SG^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + \tilde{\lambda}_\gamma\frac{\alpha}{\pi v_{\text{EW}}}SF_{\mu\nu}\tilde{F}^{\mu\nu}$$

4. Right-handed Majorana neutrino

- Even though the energy levels for leptons and anti-leptons are different, we still need a lepton-number-violating process to produce net lepton asymmetry.
- Last ingredient: **Right-handed neutrino** N_R with Majorana mass term M_R.

- The processes for $\Delta L = 2$ are
  - $\nu_L h^0 \leftrightarrow \overline{\nu}_L h^0$
  - $\nu_L \nu_L \leftrightarrow h^0 h^0$ & $\overline{\nu}_L \overline{\nu}_L \leftrightarrow h^0 h^0$
- For $m_\nu \sim 0.1$ eV, $\sigma_R \sim m_\nu^2 / 16\pi v_{\rm EW}^4 \sim 10^{-31}$ GeV^{-2}.



- Different from thermal leptogenesis: N_R don't need to be in thermal bath. $T < M_R$

The Boltzmann transport equation

- If the system was in equilibrium, the lepton asymmetry would reach a value

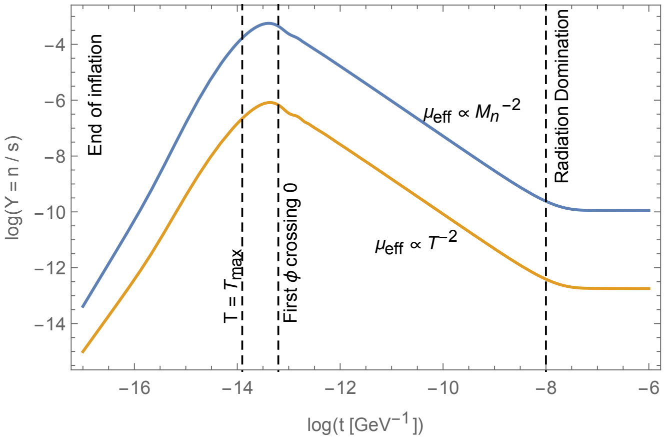
$$n_{L,eq} = \frac{-2}{\pi^2}\mu_{\text{eff}}T^2.$$

- However, the interactions are **not fast enough** for the system to reach the equilibrium because $T < M_R$.
- The system still make some L asymmetry. Describes by the **Boltzmann transport equation**

$$\frac{d}{dt}n_L + 3Hn_L \approx -\frac{2}{\pi^2}T^3\sigma_R\left(n_L + \frac{2}{\pi^2}\mu_{\text{eff}}T^2\right)$$

where n_L is the lepton number density.
- **Washout**: To suppressed the washout, the lepton-number-violating interaction $T^3\sigma_R$ turns off before the scalar field stop oscillating!

Sample plots of lepton asymmetry evolution



- $\Lambda_I = 1.5 \times 10^{16}\,\text{GeV}$, $\Gamma_I = 10^8\,\text{GeV}$, and $T_{RH} = 5 \times 10^{12}\,\text{GeV}$.
- For $\mu_{\text{eff}} \propto M_n^{-2}$ case, choose $M_n = 5 \times 10^{12}\,\text{GeV}$.

Resulting asymmetry

- Approximate analytical formula for final lepton asymmetry (lepton to entropy density ratio)

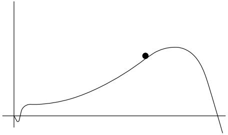
$$Y \approx \frac{90\sigma_R}{\pi^6 g_{*S}} \left(\frac{\phi_0}{M_n}\right)^n T_{\rm rlx}^2 \begin{cases} \frac{T_{\rm rlx}^3 t_{\rm rlx}^2}{T_{RH}^3 t_{RH}^2} \exp\left(-\frac{8+\sqrt{15}}{\pi^2}\frac{\sigma_R T_{RH}^3}{\Gamma_I}\right) & \text{for } t_{\rm rlx} < t_{RH} \\ \exp\left(-\frac{\sqrt{15}}{\pi^2}\frac{\sigma_R T_{RH}^2 T_{\rm rlx}}{\Gamma_I}\right) & \text{for } t_{\rm rlx} > t_{RH} \end{cases}$$

where $n = 2$ for $\mu_{\rm eff} \propto \partial_t |\phi|^2 / M_n^2$, and $n = 1$ for $\mu_{\rm eff} \propto \partial_t |\phi| / M_n$. Accurate to within an order of magnitude.

Isocurvature perturbations

Isocurvature perturbations

- One issue with the CMB observations
- $\phi_0 = \sqrt{\langle \phi^2 \rangle}$ is the **average** over several Hubble volumes.
- Different patch of the universe has different initial VEV due to fluctuation $\delta\phi_0$.
- The fluctuation for massless field is
  $$\delta\phi_0/\phi_0 \simeq 1/\sqrt{N}$$
  where N is the number of e-folds of inflation.
- Since the final asymmetry
  $$Y \propto \phi_0^n \qquad \text{with } n \sim 1, 2$$
  $\Rightarrow$ Different baryon asymmetry in each Hubble volume $\delta Y_B / Y_B \simeq n/\sqrt{N}$.



[Figure from Lauren Pearce]

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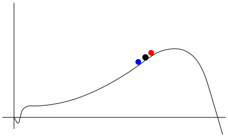

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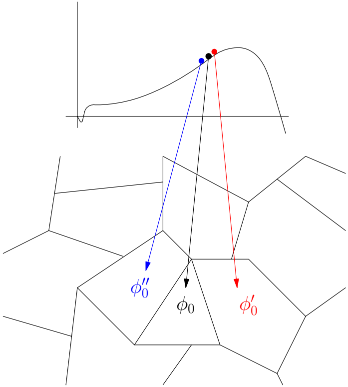

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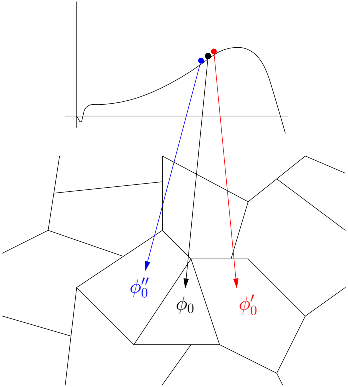

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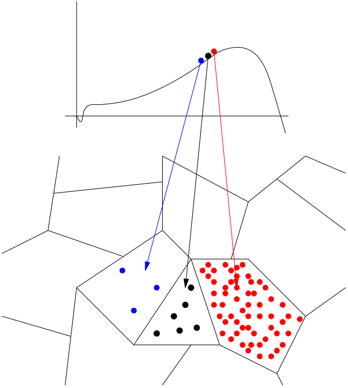


[Figure from Lauren Pearce]

Isocurvature perturbations

- Since ϕ is not inflaton, the fluctuation in Y_B is independent from the curvature perturbation coming from inflation.
- For $N_{\text{last}} \sim 50$, this produces **large isocurvature perturbations**

$$\frac{\delta Y_B}{Y_B} \approx \frac{n}{\sqrt{N_{\text{last}}}} \sim 0.1 - 0.3 \qquad \text{with } n = 1, \text{ or } 2$$

- This is constrainted by CMB observations.

Isocurvature perturbations: Constraints from Planck

- CMB observation by Planck satellite (2015) constrains the isocurvature perturbation by

$$\beta_{\text{iso}}(k_*) = \frac{\mathcal{P}_{II}(k_*)}{\mathcal{P}_{RR}(k_*) + \mathcal{P}_{II}(k_*)} < 0.033 \text{ and } 0.038,$$

  at comoving wavenumbers $k_* = 0.002\,\text{Mpc}^{-1}$ and $0.1\,\text{Mpc}^{-1}$.

- These can be translated into a limit on baryonic isocurvature perturbations

$$\left|\frac{\delta Y_B}{Y_B}\right|_{k_*} \lesssim 5 \times 10^{-5}.$$

- However, the constraint is only for large scales $l \gtrsim 60\,\text{Mpc}$ ($k \lesssim 0.1\,\text{Mpc}^{-1}$).

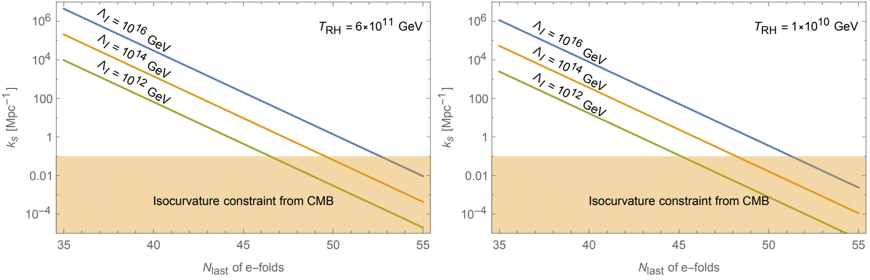
Isocurvature perturbations only in small scales

- For small scales ($k \gtrsim 0.1\,\mathrm{Mpc}^{-1}$), CMB is limited by **Silk damping** (**photon diffusion damping**).
- Isocurvature perturbation in small scales ($k \gtrsim 0.1\,\mathrm{Mpc}^{-1}$) is allowed.
- If the scalar field ϕ is massive ($m_\phi \gg H_I$) at the beginning of the inflation, but becomes light ($m_\phi < H_I$) later, then the quantum fluctuation can only grow in the late time.
- And, the produced perturbation will only be in small scales

$$k \gtrsim e^{-N_{\mathrm{last}}} H_I \left(\frac{T_{RH}}{\Lambda_I}\right)^{4/3} \frac{g_{*S}^{1/3}(T_{\mathrm{CMB}})}{g_{*S}^{1/3}(T_{RH})} \frac{T_{\mathrm{CMB}}}{T_{RH}}$$

where N_{last} is the number of e-folds of inflation that the fluctuation of ϕ has grow.

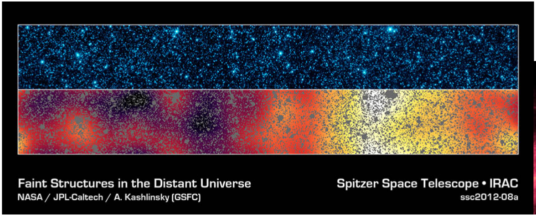
Isocurvature perturbations only in small scales

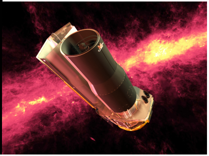


- The wavenumber of the produced perturbation vs. the number of e-folds that the fluctuation has grow at different inflation energy scales Λ_I and reheat termperatures T_{RH}.
- For $\Lambda_I = 10^{16}$ GeV, $T_{RH} = 10^{12}$ GeV, the fluctuation for $N_{\text{last}} \lesssim 50$ only appear in scale smaller than $0.1\,\text{Mpc}^{-1}$.
- This affect the structure formation and help on resolving the excess found in CIB fluctuation.

Cosmic Infrared Background fluctuation excess

Cosmic Infrared Background (CIB) anisotropies





- CIB is the infrared part of extragalactic backgound, which contains radiation from galaxies at all redshifts through out the entire cosmic history.
- The absolute intensity of CIB is difficult to be determined due to the large uncertainty associated with the foreground signal, Galactic components, and zodiacal light.
- Therefore, recent measurements focus on the anisotropies (spatial fluctuation) of CIB.

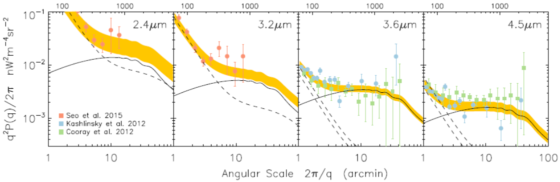
Excess in CIB fluctuation

A. Kashlinsky, astro-ph/0412235
A. Cooray et. al., 1205.2316
K. Helgason et. al., 1505.07226

- *Akari* and *Spitzer*: Excess in fluctuation at few arcmin scale in the near-IR (2-5 μm).

$$\delta F_{2-5\mu\mathrm{m}}\left(5'\right) \simeq 0.09\,\mathrm{nWm^{-2}sr^{-1}}$$

- Not from known galaxy populations.
- Might come from first star forming at $z \gtrsim 10$, but have difficulty with pure adiabatic spectrum from inflation.
- Due to the insufficient perturbation in the small scale at high redshift ($z \gtrsim 8$) for structure to form. [Helgason et. al. (2016) and Kashlinsky (2016)]

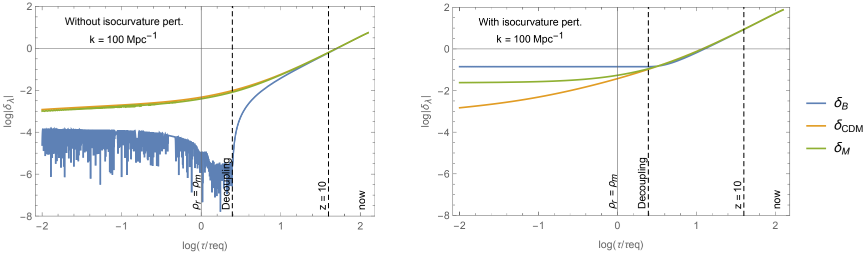


Large perturbations in small scales

A possible solution from Leptogenesis via scalar field relaxation:

1. Produces **large** baryon perturbation ($\delta_B = \delta\rho_B/\rho_B \sim 0.1$) in **small** scales at the early universe if the fluctuation in ϕ only grows in the late time of inflation.
2. The large fluctuation in baryon density induces the corresponding perturbation in CDM δ_{CDM} after recombination.
3. Total matter perturbations δ_m in small scale are much larger than that from standard adiabatic perturbation from inflation.
4. Small structures ($M_{\rm halo} \sim 10^6 M_\odot$) form eariler
5. Produce more CIB fluctuation at $z > 10$.

Growth of the perturbation

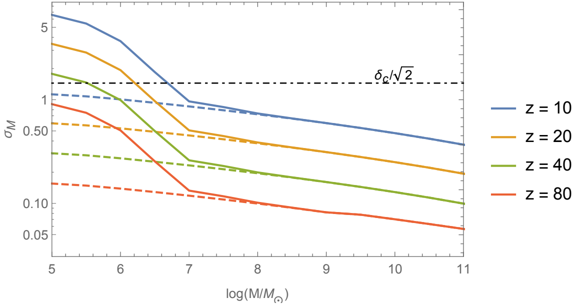


Only adiabatic perturbation from inflation with $\mathcal{R} = 5 \times 10^{-5}$

With isocurvature perturbation from leptogenesis with $\delta_B = 0.14$

- For $N_{\text{last}} = 45.7$, $\Lambda_I = 10^{16}$ GeV, $T_{RH} = 6 \times 10^{11}$ GeV, the isocurvature starts at $k_s = 100\,\text{Mpc}^{-1}$.
- The matter density perturbation exceed linear regime before $z = 10$ for the isocurvature perturbation $\Rightarrow$Structures form earlier.

Halo collapses before



- The rms density constrast $\sigma_M = \left[\int \delta_M^2(k,z)\, W_{TH}(kr_M)\, dk/k\right]^{1/2}$ over the halo mass M at various z assuming isocurvature perturbation for scale $k > 100\,\mathrm{Mpc}^{-1}$.
- Solid line: With isocurvature perturbation. Dashed line: With only adiabatic perturbation from inflation.
- Halo collapses by z when $\sigma_M(z) > \delta_c = 1.68$.
- For $k_s = 100\,\mathrm{Mpc}^{-1}$ ($N_{\mathrm{last}} = 45.7$), $M_{\mathrm{halo}} \sim 10^6 M_\odot$ collapses by $z \sim 20$, which won't happen if without isocurvature perturbation.

Summary

- During inflation, scalar fields can obtain large VEVs through quantum fluctuation.
- Relaxation of the large VEV generally happens during the reheating after inflation.
- Through the derivative coupling between the scalar field and lepton current, leptogenesis can be possible, explaining the matter-antimatter asymmetry in the universe.
- This can generate additional baryonic isocurvature perturbations, which is not constrainted in the small angular scale by CMB observation.
- Isocurvature perturbation in small scale can then lead to first star forming earlier than what is expected from ΛCDM.
- This can be the origin of the excess in CIB fluctuations.

Thank you for your attention!

Backup slide: parameter space for pseudoscalar case