Post-Inflationary Higgs Relaxation and Leptogenesis

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Outline

- **Motivation: the Higgs potential**
- **Quantum fluctuation during inflation**
- **Post-inflationary Higgs relaxation**
- **Leptogenesis via Higgs field relaxation**
- **Cosmic Infrared Background (CIB) excess**
- **Isocurvature perturbation**

Based on:

[1] A. Kusenko, L. Pearce, LY, Phys. Rev. Lett. 114, 061302 (2015).
[2] L. Pearce, LY, A. Kusenko, M. Peloso, Phys. Rev. D 92, 023509 (2015).
[3] LY, L. Pearce, A. Kusenko, Phys. Rev. D 92, 043506 (2015).
[4] H. Gertov, L. Pearce, F. Sannino, LY, Phys. Rev. D 93, 115042 (2016).
[5] A. Kusenko, L. Pearce, LY, Phys. Rev. D 93, 115005 (2016).
[6] M. Kawasaki, A. Kusenko, L. Pearce, LY, Phys. Rev. D 95, 103006 (2017).

The Higgs Potential

The Higgs Boson

- **In 2012, ATLAS and CMS found the Higgs boson.**

  $$V(\Phi) = -m^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2,$$

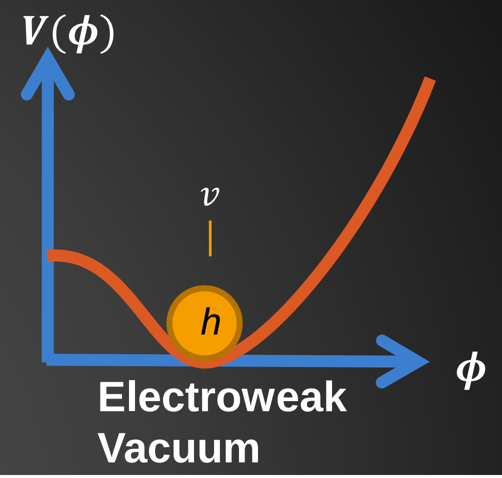
  where $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$.

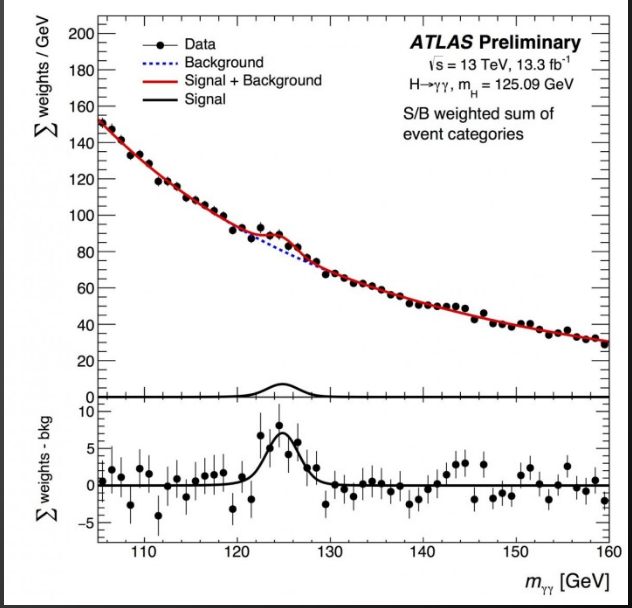
- **Higgs boson mass:**
  $M_h = 125.09 \pm 0.21 \pm 0.11$ **GeV.**

- **A mass smaller than expected!**

- **A small quartic coupling**

  $$\lambda(\bar{\mu} = M_t) \approx M_h^2/2v^2 \approx 0.129$$





C. Patrignani et al. (Particle Data Group),
Chin. Phys. C, 40, 100001 (2016).

Running of λ

J. Elias-Miro et al., Phys. Lett. B709, 222 (2012)
G. Degrassi et al., JHEP 1208, 098 (2012)
D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

- **QFT: Coupling constants changes with energy scale μ**

$$\beta_\lambda = -\frac{36}{(4\pi)^2} y_t^4 + \cdots$$

- **Due to large top mass**

$$m_t = \frac{1}{\sqrt{2}} y_t v$$

- **If no new physics, $\lambda(h)$ becomes very small and turns negative at $\mu \gtrsim 10^{10} - 10^{12}$ GeV.**

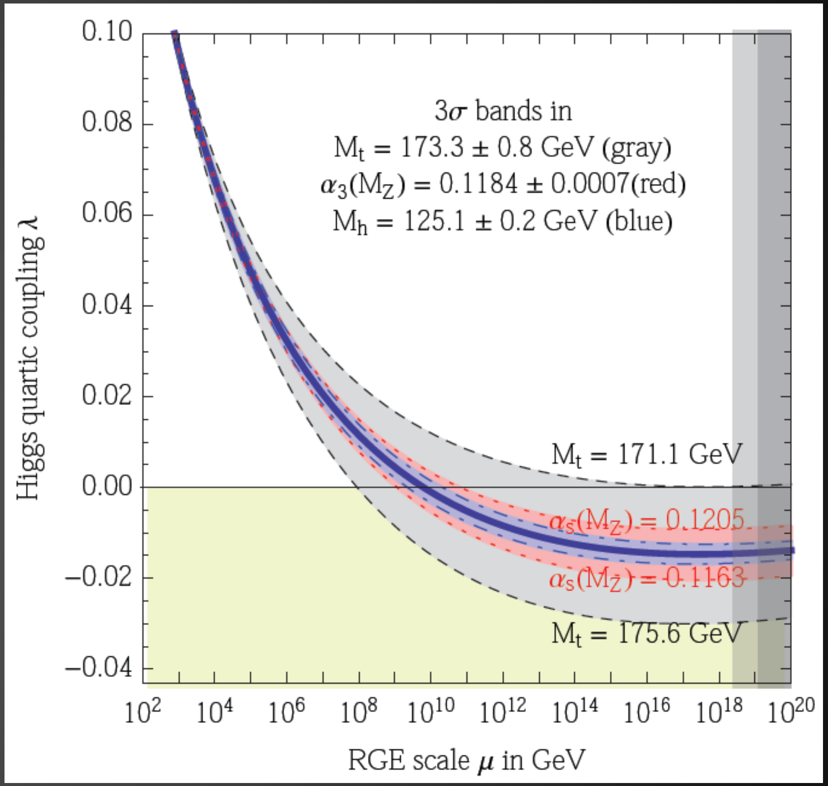
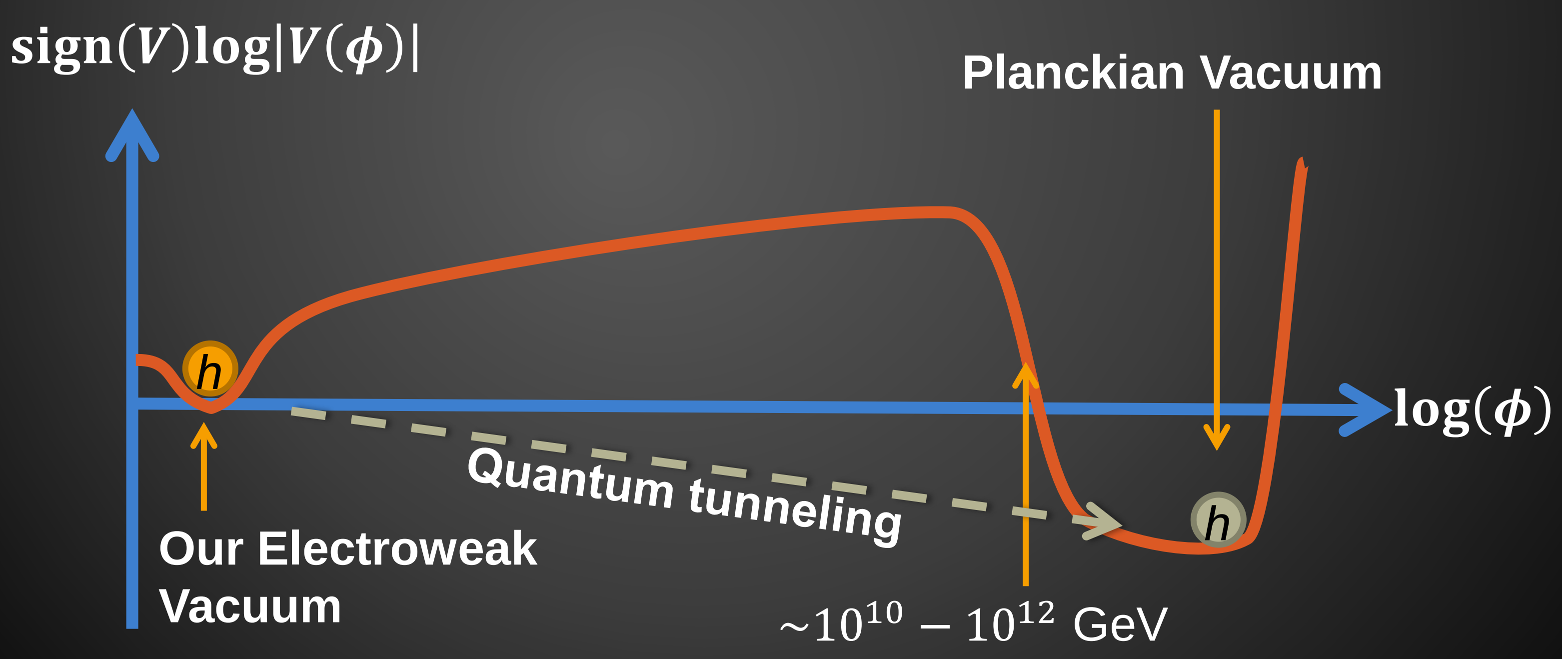


Figure from D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

The Higgs Effective Potential

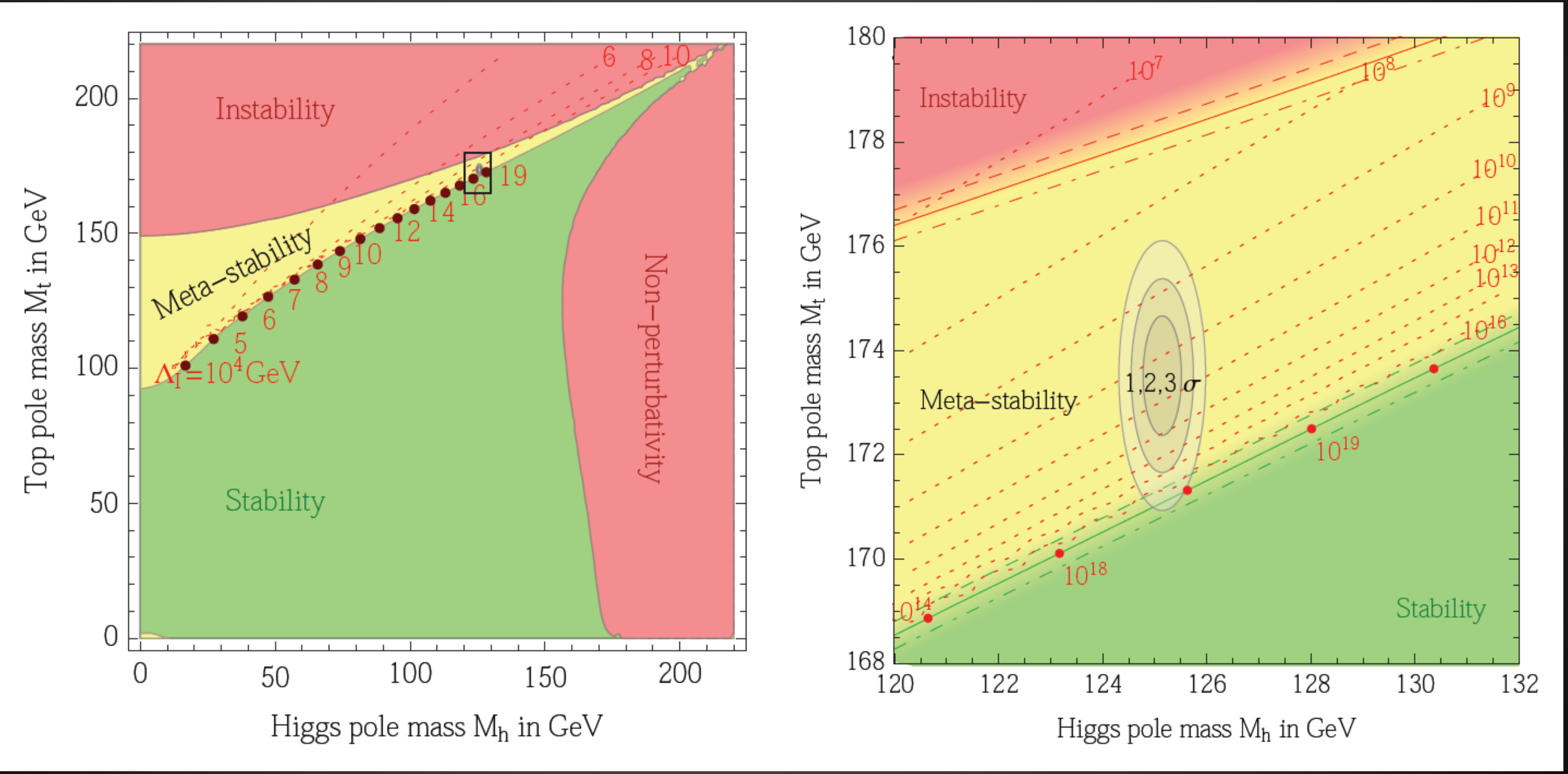
- **Another minimum in the potential: Planckain vacuum!!**
  - **Much lower than the electroweak vacuum.**
- **Our universe can tunnel into the Planckain vacuum and end in a big crunch!**



Meta-stability of our Vacuum

J. Elias-Miro et al., Phys. Lett. B709, 222 (2012)
G. Degrassi et al., JHEP 1208, 098 (2012)
D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

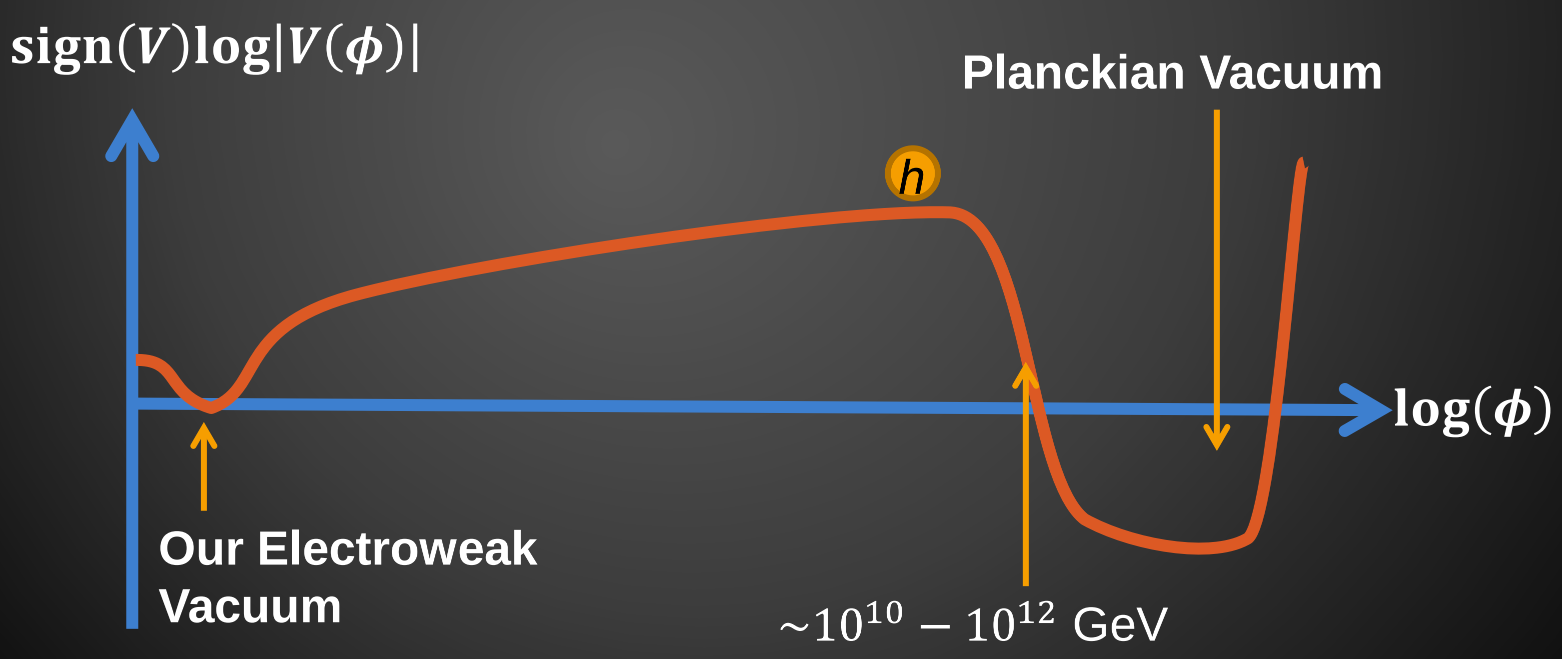
Our universe seems to be right on the meta-stable region.



The Higgs Effective Potential

What does it imply?

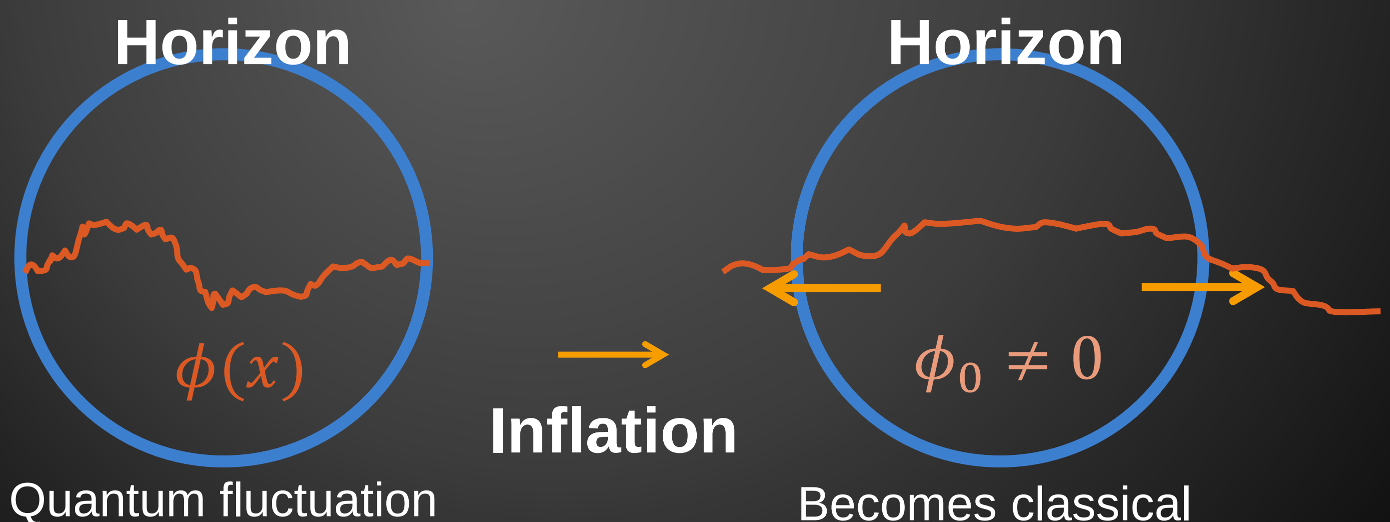
- **A shallow Higgs potential at large scale**
- **A large Higgs VEV during inflation**



Quantum Fluctuation during Inflation

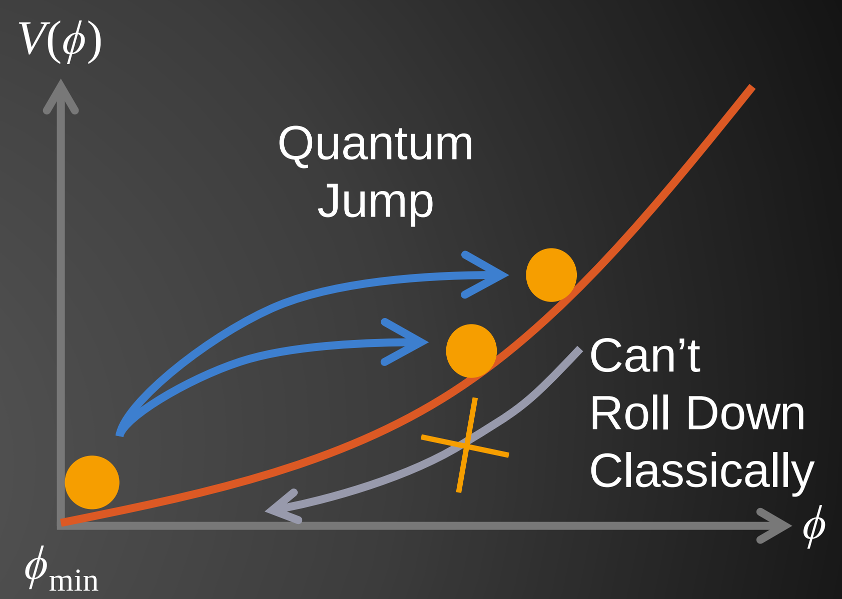
Quantum Fluctuation during Inflation

- During inflation, quantum fluctuations of scalar field get amplified and pulled to over the horizon size.
- They becomes classical when the wavelength exits the horizon.
- $\phi(t)$ jumps randomly like Brownian motion.



Quantum Fluctuation during Inflation

- **Quantum fluctuation brings the field to non-zero value.**
- **Classical rolling down follows**
  $$\ddot{\phi} + 3H_I\dot{\phi} = -V'(\phi),$$
  which requires
  $$t_{\mathrm{rlx}} \sim \left[\frac{d^2V(\phi)}{d\phi^2}\right]^{-1/2} = \frac{1}{m_\phi}$$
- **If $m_\phi \ll H_I$, insufficient time to relax (slow-rolling).**
- **A non-zero VEV of the scalar field is building up.**



Bunch, Davies (1978);
Linde (1982);
Hawking, Moss (1982);
Starobinsky (1982);
Vilenkin, Ford (1982);
Starobinsky, Yokoyama (1994).

Stochastic Approach

A. A. Starobinsky (1982)
A. Vilenkin (1982)

- **Fokker-Planck equation:**

$$\frac{\partial P_c(\phi,t)}{\partial t} = -\frac{\partial j_c}{\partial \phi} \quad \text{where } -j_c = \frac{\partial}{\partial \phi}\left(\frac{H^3 P_c}{8\pi^2}\right) + \frac{P_c}{H}\frac{dV}{d\phi}$$

$P_c(\phi, t)$**: probability distribution of** ϕ

- **Massless scalar, the field undergoes random walks**

$$\phi_0 \equiv \sqrt{\langle \phi^2 \rangle} \simeq \frac{H_I^{3/2}}{2\pi}\sqrt{t} = \frac{H_I}{2\pi}\sqrt{N}, \qquad N\text{: number of e-folds}$$

- **Massive case** $V(\phi) = \frac{1}{2}m^2\phi^2$**:**

$$\phi_0 \simeq \sqrt{\frac{3}{8\pi^2}\frac{H_I^2}{m}}$$

- **For** $V(\phi) = \frac{\lambda}{4}\phi^4$**:** $\quad \phi_0 \simeq 0.36 H_I/\lambda^{1/4}$
- **In general,** $\quad \boxed{V(\phi_0) \sim H_I^4}$

Large Higgs VEV During Inflation

- Higgs has a shallow potential at large scale (small λ).
- Large Higgs vacuum expectation value (VEV) during inflation.
- For inflationary scale $\Lambda_\mathrm{I} = 10^{16}$ GeV, the Hubble rate $H_I = \frac{\Lambda_\mathrm{I}^2}{\sqrt{3}M_{pl}} \sim 10^{13}$ GeV, and $\lambda \sim 0.01$, the Higgs VEV after inflation is

$$\phi_0 \simeq 0.36 H_I/\lambda^{1/4} \sim 10^{13}\ \mathrm{GeV}.$$

- For such a large VEV, the Higgs field can be sensitive to higher scale physics.

Post-Inflationary Higgs Field Relaxation

Post-inflationary Higgs Relaxation

- As the inflation end, the H drops.
- When $H < m_{\phi,\mathrm{eff}}$, the Higgs field can relax classically

$$\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + \frac{\partial V_{\mathrm{eff}}\big(\phi, T(t)\big)}{\partial \phi} = 0$$

- $V_{\mathrm{eff}}(\phi, T)$ is the finite temperature effective potential.
- Higgs field oscillates with decreasing amplitude due to the Hubble friction $3H\dot{\phi}(t)$.
- Relaxation time (depending on T_{RH} and Λ_I)

$t_{\mathrm{rlx}} = t_{RH}\left(\frac{2.5}{a_T T_{RH} t_{RH}}\right)^{4/3}$ if thermal mass dominates $V \approx \frac{1}{2}\alpha_T^2 T^2 \phi^2$

$t_{\mathrm{rlx}} = 6.9/\sqrt{\lambda}\phi_0$ if the zero T dominates $V \approx \lambda\phi^4/4$

- Typically during reheating or right after reheating.

Post-inflationary Higgs Relaxation

M. Kawasaki, A. Kusenko, L. Pearce, LY, Phys. Rev. D 95, 103006 (2017).

- **If the thermal mass dominates,**

$$V(\phi, T) \approx \frac{1}{2}\alpha_T^2 T^2 \phi^2$$

where $\alpha_T \approx \sqrt{\left(\lambda + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 3y_t^2\right)/12} \approx 0.33$ **at** $\mu = 10^{13}$ **GeV.**

- **The equation of motion is approximately (assuming MD)**

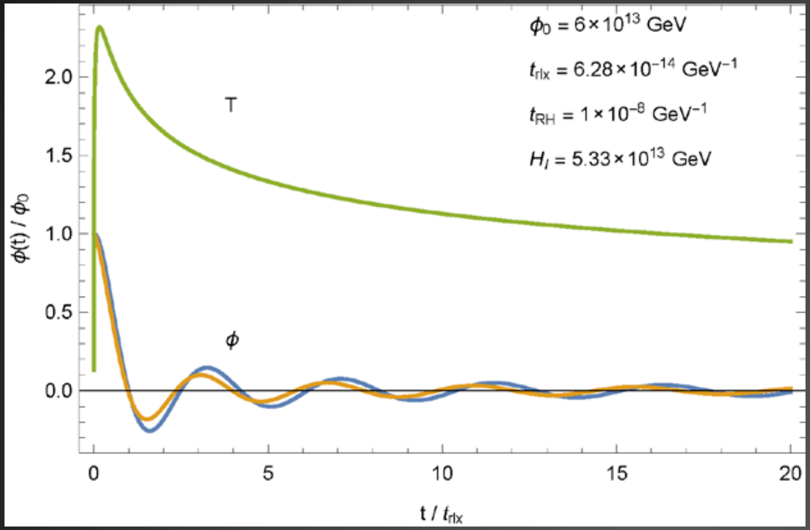
$$\ddot{\phi}(t) + \frac{2}{t}\dot{\phi}(t) + \alpha_T^2 \frac{T_{RH}^2\sqrt{t_{RH}}}{\sqrt{t}}\phi(t) = 0$$

- **A solution:**

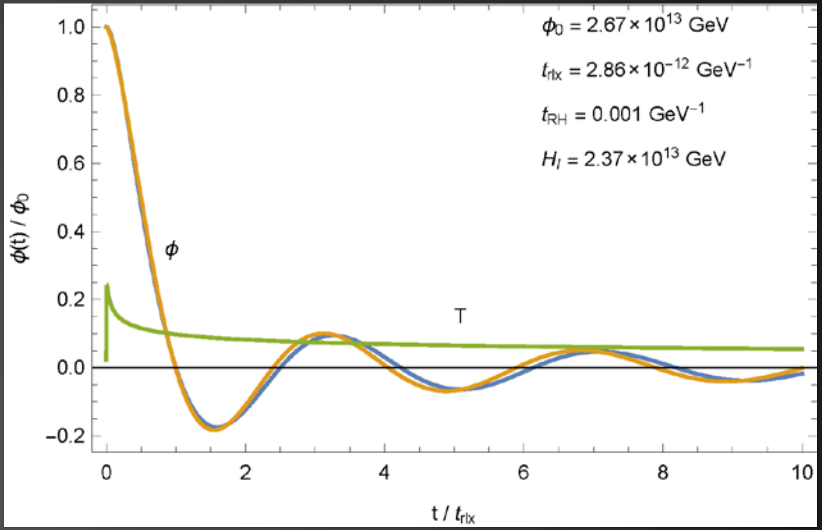
$$\phi(t) = \phi_0 \left(\frac{3}{2}\right)^{2/3} \Gamma\left(\frac{5}{3}\right) J_{2/3}\left(\frac{4\alpha_T\beta}{3}x^{3/4}\right)\frac{1}{(\alpha_T\beta)^{2/3}\sqrt{x}}$$

where $\beta = T_{RH}t_{RH}$**,** $x = t/t_{RH}$**, and** $J_n(z)$ **is the Bessel function of the first kind.**

Post-inflationary Higgs Relaxation



Thermal mass dominated

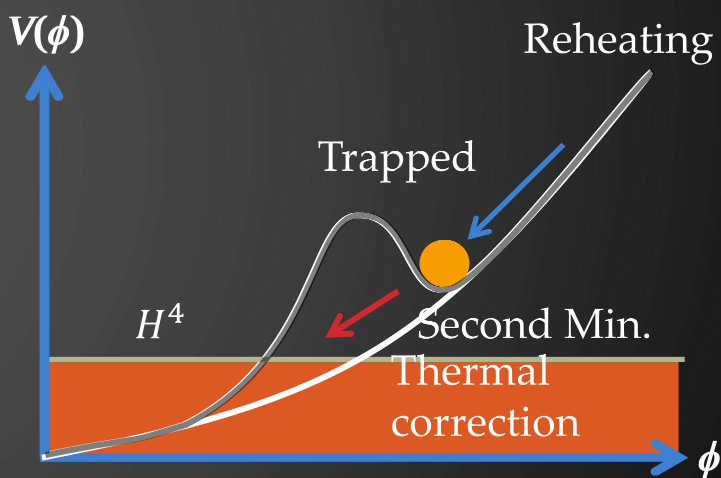


Zero T potential dominated

- **What can this do for us?**
  - Breaks time reversal symmetry,
    and provides the out of thermal equilibrium condition.
  - An important epoch for the matter-antimatter asymmetry!

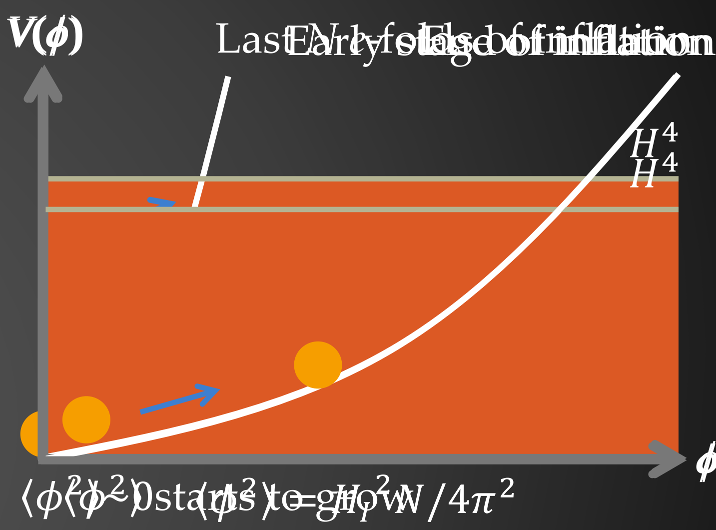
Initial Conditions for the Higgs field

- **Initial Condition 1 (IC-1):**
  - **A metastable Planckian vacuum due to higher dimensional operators**
    $$\mathcal{O} \sim \frac{1}{M^2}\phi^6, \frac{1}{M^4}\phi^8, \frac{1}{M^6}\phi^{10}$$
  - **Higgs field trapped in a metastable vacuum during inflation**
  - **Reheating destabilize the metastable vacuum via**
    $$\delta V \sim T^2 \phi^2$$
    and the Higgs VEV relaxes



Initial Conditions for the Higgs field

- **Initial Condition 2 (IC-2):**
  - **Inflaton VEV induced mass term to the Higgs via**
    $$\mathcal{O} = I^n \phi^m / \Lambda^{n+m-4}$$
  - **Large $\langle I \rangle$ during early stage of inflation**
  - **Large Higgs mass and suppressing quantum fluctuation**
  - **In the last N_{last} e-fold of inflation, $\langle I \rangle$ decreases and Higgs becomes massless with**
    $$\phi_0 = \frac{H\sqrt{N_{\mathrm{last}}}}{2\pi}$$



II

Leptogenesis via the Relaxation of the Higgs Field

Sakharov Conditions

Andrei D. Sakharov (1967)

Successfully Leptogenesis requires:

1. **Deviation from thermal equilibrium**
   - **Post-inflationary Higgs relaxation**
2. **C and CP violations**
   - **CP phase in the quark sector (not enough), higher dimensional operator, …**
3. **Lepton number violation**
   - **Right-handed Majorana neutrino, others …**

Effective Operator

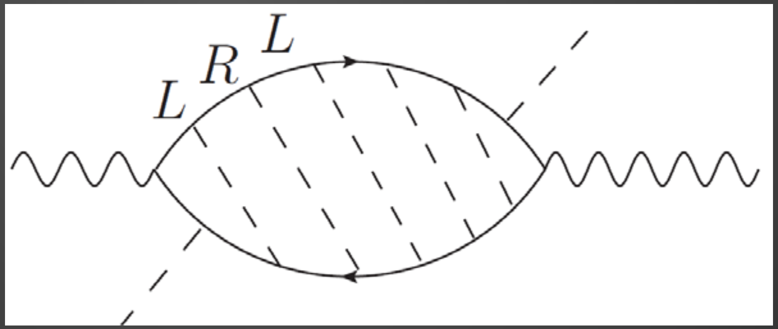
M. E. Shaposhnikov (1987),
M. E. Shaposhnikov (1988)

- CP violation: Consider the effective operator:

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right),$$

W and B: $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ gauge fields
$\widetilde{W}$: dual tensor of W
Λ_n: energy scale when the operator is relevant

- In standard model, integrating out a loop with all 6 quarks:

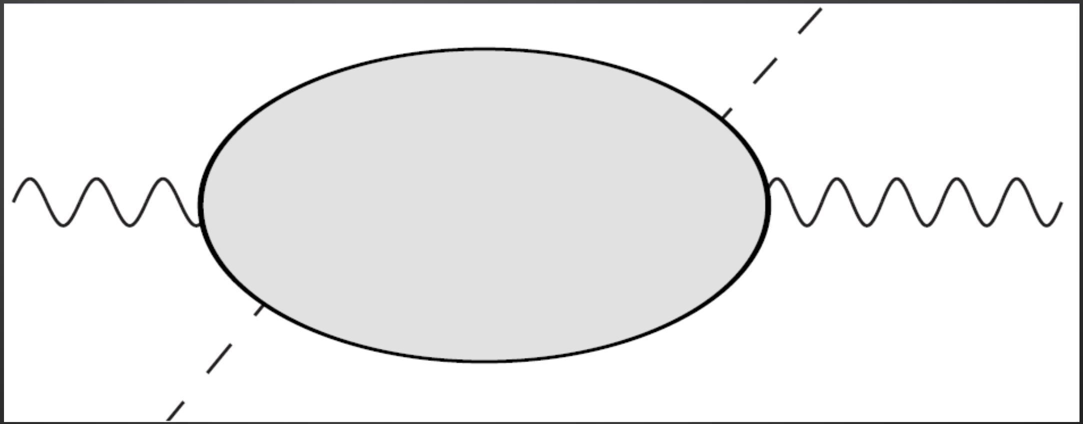


- Also used by baryogenesis
- But suppressed by small Yukawa and small CP phase

Effective Operator

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$$

- Replace the SM fermions by heavy states that carry $SU(2)$ charge.
- Scale: $\Lambda_n = M_n$ mass (must not from the SM Higgs) or
  $\Lambda_n = T$ temperature



Effective Chemical Potential

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

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$$

- **Using electroweak anomaly equation, we have**

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}|\phi|^2\partial_\mu j^\mu_{B+L},$$

where j^μ_{B+L} is the $B+L$ fermion current.

- **Integration by part:**

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

- **Similar to the one use by spontaneous baryogenesis.**
- **Breaks CPT spontaneously while ϕ is changing!**
- **Sakharov's conditions doesn't have to be satisfied explicitly in this form.**

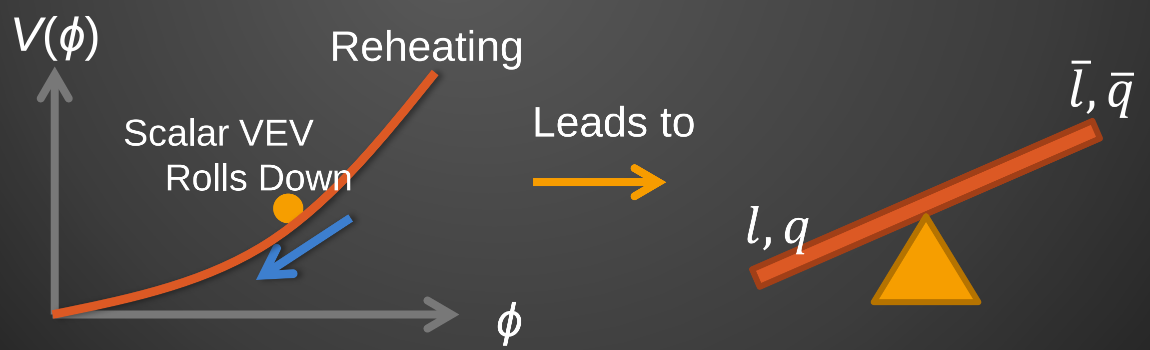
Effective Chemical Potential

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

- **Effective chemical potential for baryon and lepton number:**

$$\mu_{\text{eff}} = \frac{1}{\Lambda_n^2}\partial_t |\phi|^2$$

- **Shifts the energy levels between fermions and anti-fermions while Higgs is rolling down ($\dot{\phi} \neq 0$).**



- **Produce more lepton than antilepton in the present of L violating process.**

Lepton Number Violation

Last ingredient:

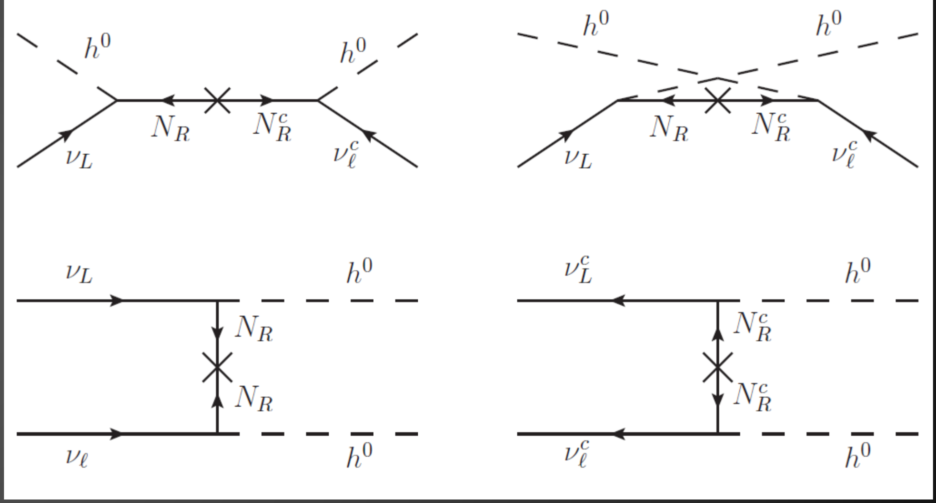
- **Right-handed neutrino N_R with Majorana mass term M_R.**

The processes for $\Delta L = 2$:

- $\nu_L h^0 \leftrightarrow \overline{\nu_L} h^0$
- $\nu_L \nu_L \leftrightarrow h^0 h^0$
- $\overline{\nu_L \nu_L} \leftrightarrow h^0 h^0$

For $m_\nu \sim 0.1$ eV,

$$\sigma_R \sim \frac{\Sigma_i m_{\nu,i}^2}{16\pi v_{EW}^2} \sim 10^{-31}\ \text{GeV}^{-2}.$$

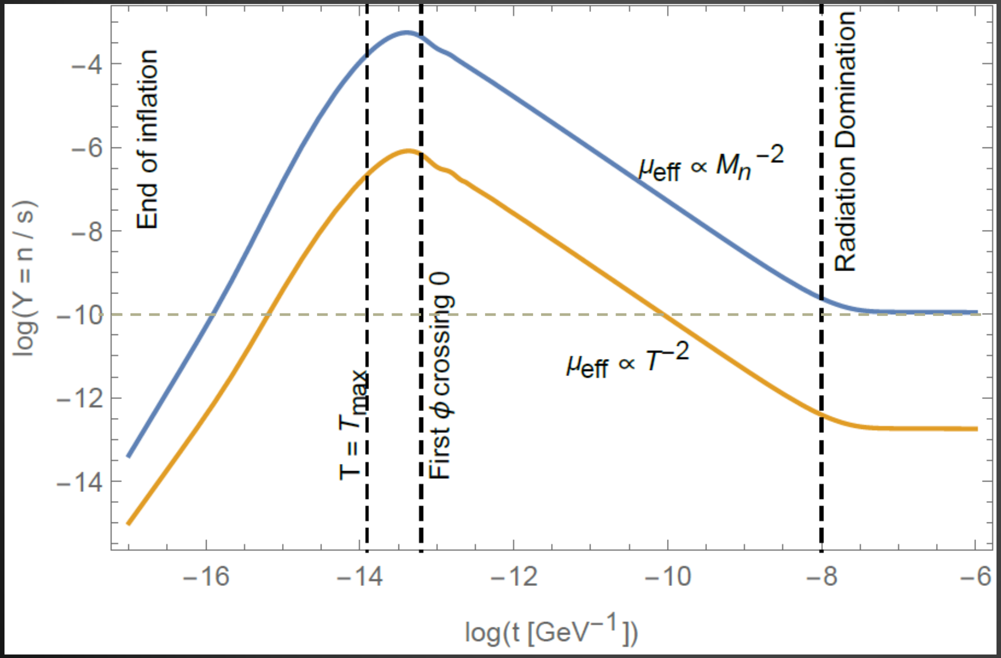


LY, L. Pearce, A. Kusenko, Phys. Rev. D 92, 043506 (2015).

Evolution of Lepton Asymmetry

Boltzman equation: $\dot{n}_L + 3Hn_L \approx -\frac{2}{\pi^2}T^3\sigma_R\left(n_L - \frac{2}{\pi^2}\mu_{\rm eff}T^2\right)$

Final lepton asymmetry: $Y = \frac{n_L}{s} \approx \frac{90\sigma_R}{\pi^6 g_{*S}}\left(\frac{\phi_0}{\Lambda_{\rm n}}\right)^2 \frac{3z_0 T_{RH}}{4\alpha_T t_{RH}} \exp\left(-\frac{8+\sqrt{15}}{\pi^2}\sigma_R T_{RH}^3 t_{RH}\right)$



$\Lambda_{\rm I} = 1.5 \times 10^{16}$ GeV,

$\Gamma_I = 10^8$ GeV,

$T_{RH} = 5 \times 10^{12}$ GeV,

$\phi_0 = 6 \times 10^{13}$ GeV.

For $\mu_{\rm eff} \propto M_n^{-2}$ case,

$M_n = 5 \times 10^{12}$ GeV.

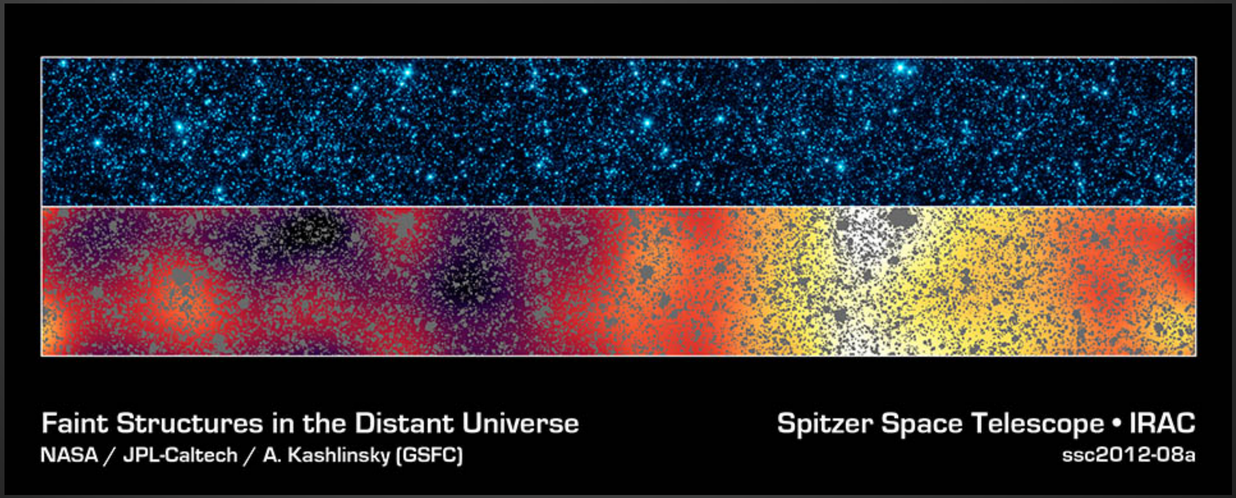
Could be one origin of the matter-antimatter asymmetry!

III

Cosmic Infrared Background Radiation Excess

Cosmic Infrared Background (CIB) Radiation

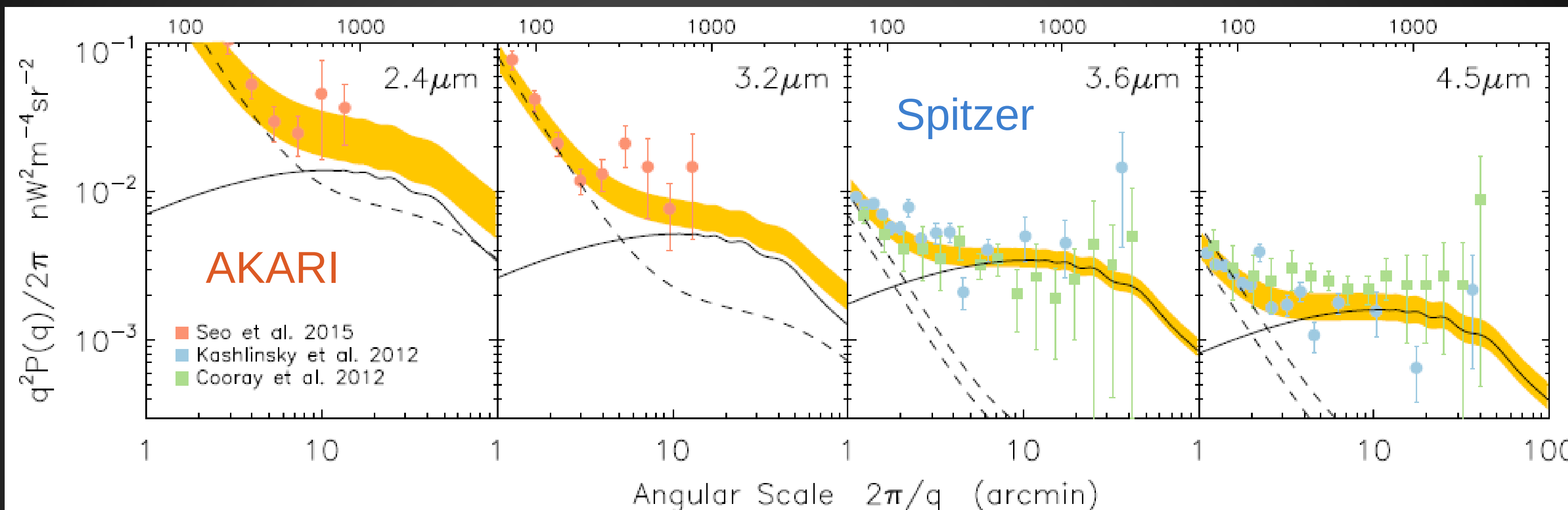
- CIB: IR part of extragalactic background light
- from galaxies at all redshifts
- Difficult to determine absolute intensity (isotropic flux) due to foreground signal, galactic components, and zodiacal light.
- More focus on the anisotropies (spatial fluctuation) of CIB



CIB (spatial) fluctuations observed by Spitzer space telescope

Excess in the CIB fluctuations

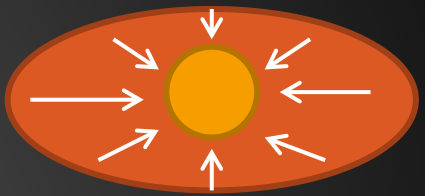
Helgason et al.,
MNRAS **455**, 282 (2015)
Kashlinsky et al.
ApJ **804**, 99 (2015)



- Excess found in near-IR ($1-10\ \mu m$) at $\theta = 3-30$ arcmins scale.
- Not from known galaxy populations at $z < 6$
- Most possible: First stars (population III stars, metal-free) at $z \gtrsim 10$ in $10^6\ M_\odot$ minihalos
- But: Needs too large star formation efficiency and/or radiation efficiency due to insufficient stars forming at $z = 10$.

CIB fluctuation from population III stars

- CIB fluctuation: $\delta F_{\mathrm{CIB}} \approx 0.09\ \mathrm{nWm^{-2}sr^{-1}}$ ($2-5\mu$m at $5'$)
- Matter density fluctuation at 5 arcmins scale: $\Delta_{5'} \approx 10\%$
- Inferred isotropic flux: $F_{\mathrm{CIB}} \approx \delta F_{\mathrm{CIB}}/\Delta_{5'} = 1\ \mathrm{nWm^{-2}sr^{-1}}$



- CIB flux from first stars (population III)

$$F_{FS} = \frac{c}{4\pi}\,\epsilon\,\rho_B\,c^2\,f_{\mathrm{halo}}\,f_*\,z_{\mathrm{eff}}^{-1}$$

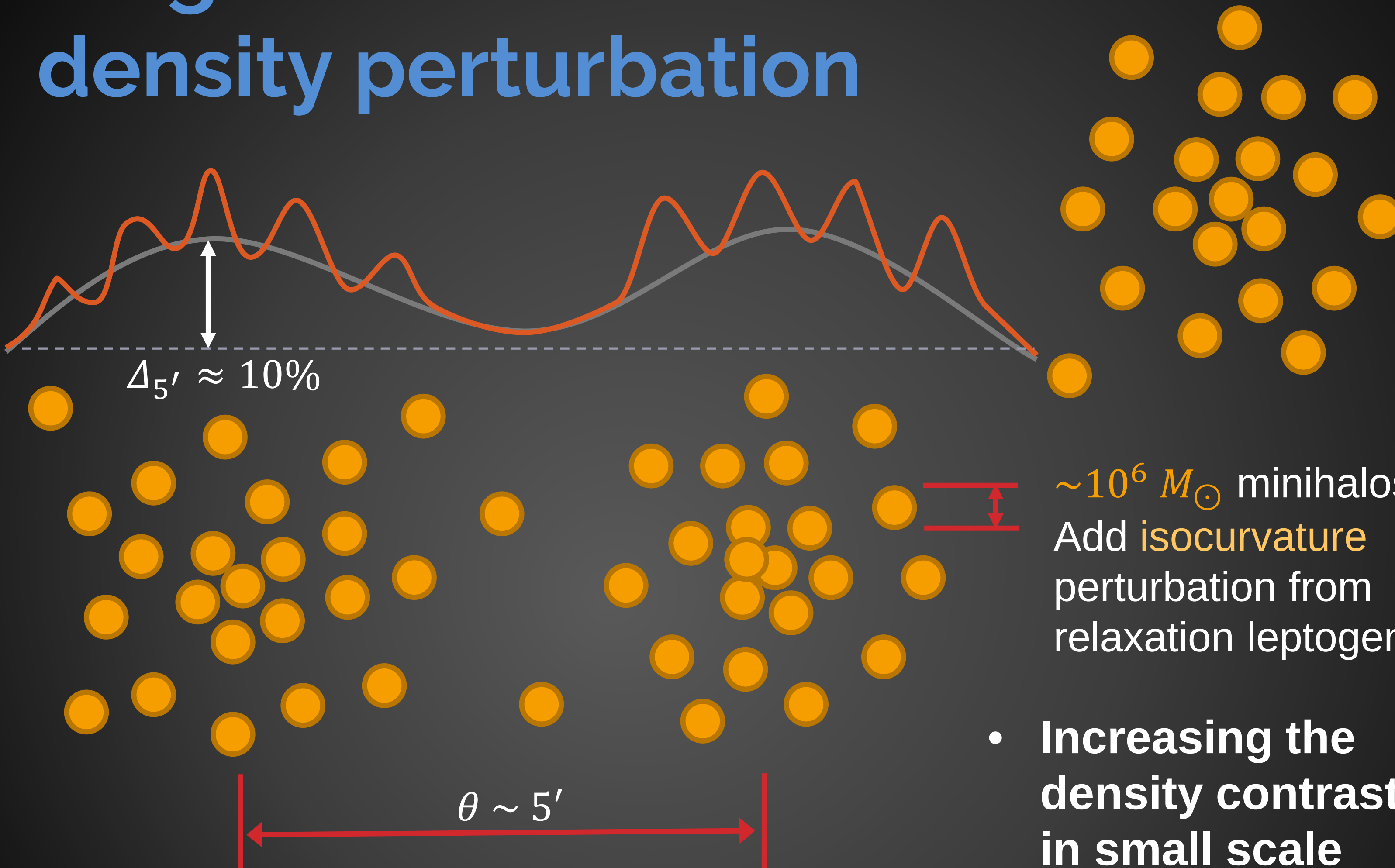
f_{halo}: mass fraction of the universe inside collapsed halos
f_* : the star formation efficiency
ϵ : radiation efficiency

- To explain the CIB fluctuation by first stars forming:

$$f_{\mathrm{halo}} \approx 0.16\left(\frac{0.007}{\epsilon}\right)\left(\frac{10^{-3}}{f_*}\right)\left(\frac{F_{FS}}{F_{CIB}}\right)$$

- Difficult to reach with only adiabatic density perturbation from usual inflation.
- Solution: isocurvature perturbation in the small spatial scale

Large vs Small scale density perturbation



$\sim 10^6\, M_\odot$ minihalos
Add isocurvature perturbation from relaxation leptogenesis

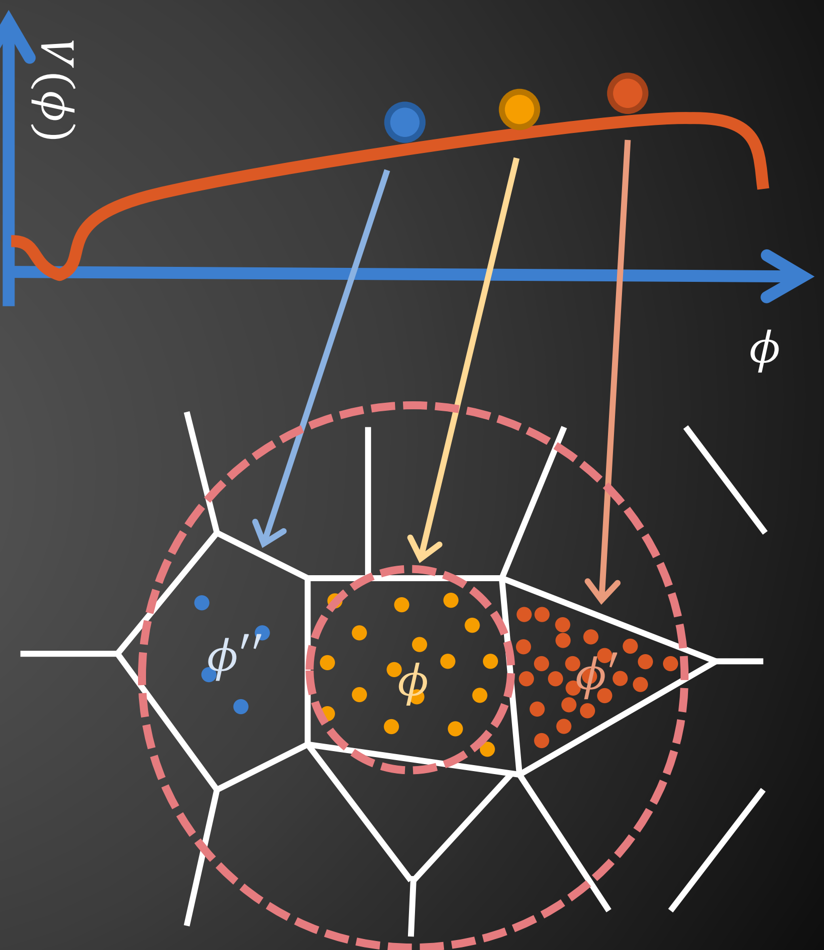
Large scale fluctuation in CIB due to the adiabatic perturbation from inflaton

- **Increasing the density contrast δ_B in small scale increase the number of collapse halos f_{halo}**

Isocurvature Perturbation from Relaxation Leptogenesis

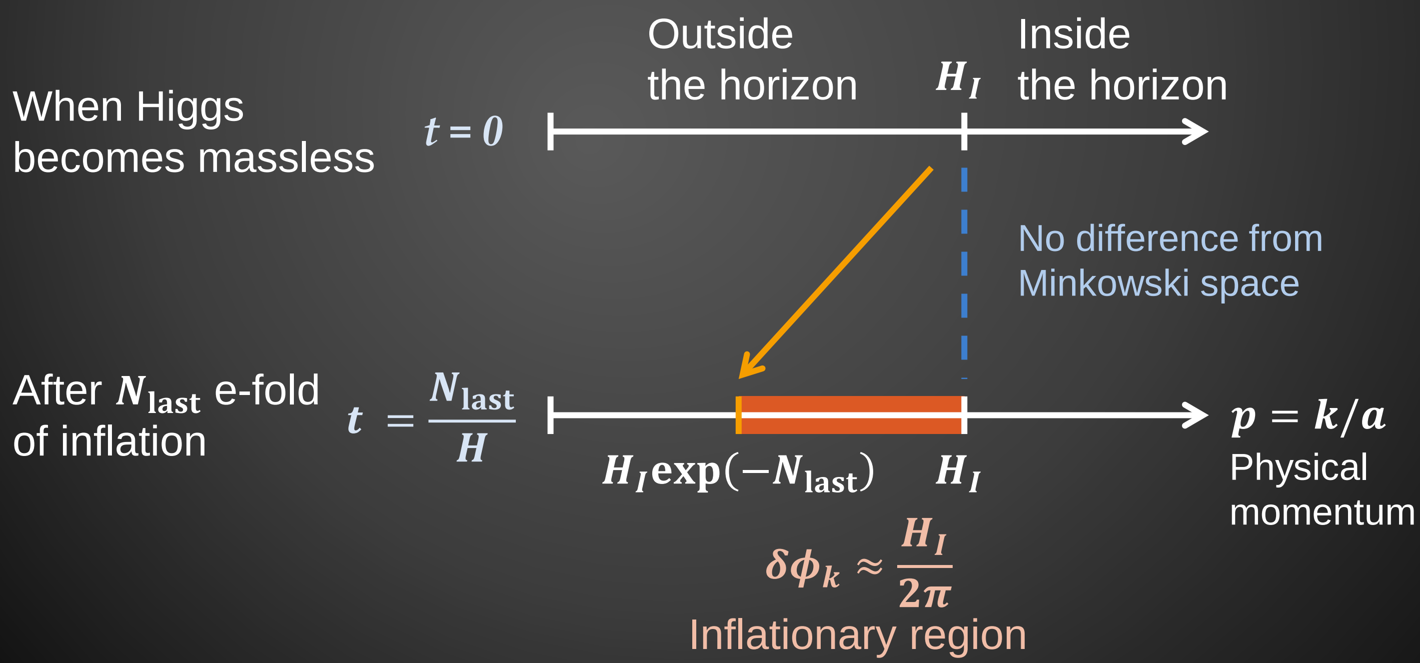
Isocurvature Perturbation

- Fluctuation of ϕ in each patch of the universe during inflation
- Variation in baryon asymmetry $\delta(B-\bar{B})$ through leptogenesis ($Y_B \propto \phi_0^2$)
- Spatial fluctuation of baryon asymmetry after patches reenter
- Baryon asymmetry δY_B $\rightarrow$ Baryon density $\delta\rho_B$
- Produce isocurvature perturbation of baryon
- No contribution to the initial curvature perturbation.



Higgs Fluctuation during Inflation

- **In IC-2, the Higgs ϕ becomes massless in the last N_{last} e-fold of inflation due to the inflaton couplings.**
- **Quantum fluctuation $\delta\phi_k \approx \frac{H_I}{2\pi}$ is produced at the scale smaller than the horizon scale $l \sim H^{-1}$ at that time**



Higgs Fluctuation during Inflation

- The horizon at N_{last} before the end of inflation has a scale k_S at present

$$k_S \simeq 2\pi e^{-N_{\text{last}}} H_I \left(\frac{T_{RH}}{\Lambda_I}\right)^{4/3} \frac{g_{*S}^{1/3}(T_{\text{now}})}{g_{*S}^{1/3}(T_{RH})} \frac{T_{\text{now}}}{T_{RH}}$$

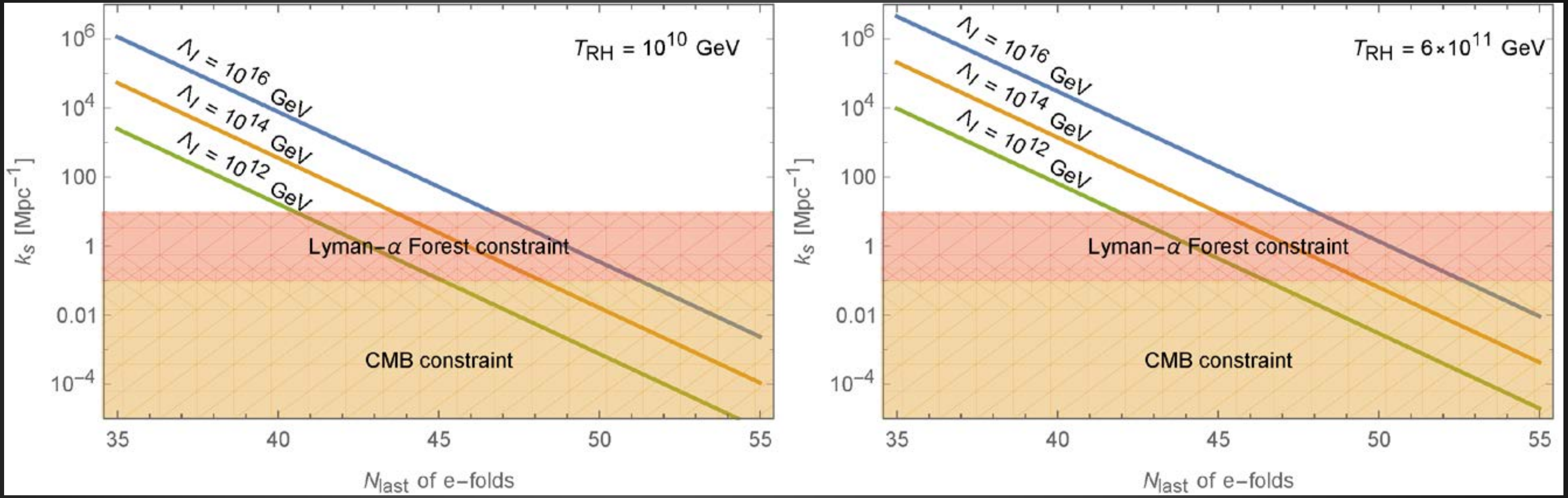
- Power spectrum of ϕ

$$\mathcal{P}_\phi(k) \approx \begin{cases} \left(\frac{H_I}{2\pi}\right)^2 & \text{for } k \geq k_S \\ 0 & \text{otherwise} \end{cases}$$

- Baryonic isocurvature perturbation for $k > k_S$

$$\delta_B(k) \equiv \left.\frac{\delta\rho_B}{\rho_B}\right|_k = \left.\frac{\delta Y_B}{Y_B}\right|_k = \frac{\delta(\phi^2)_k}{\langle\phi^2\rangle} \approx 2\frac{\ln^{1/2}(k/k_S)}{N_{\text{last}}}\theta(k-k_S)$$

Constraints on Isocurvature Perturbation

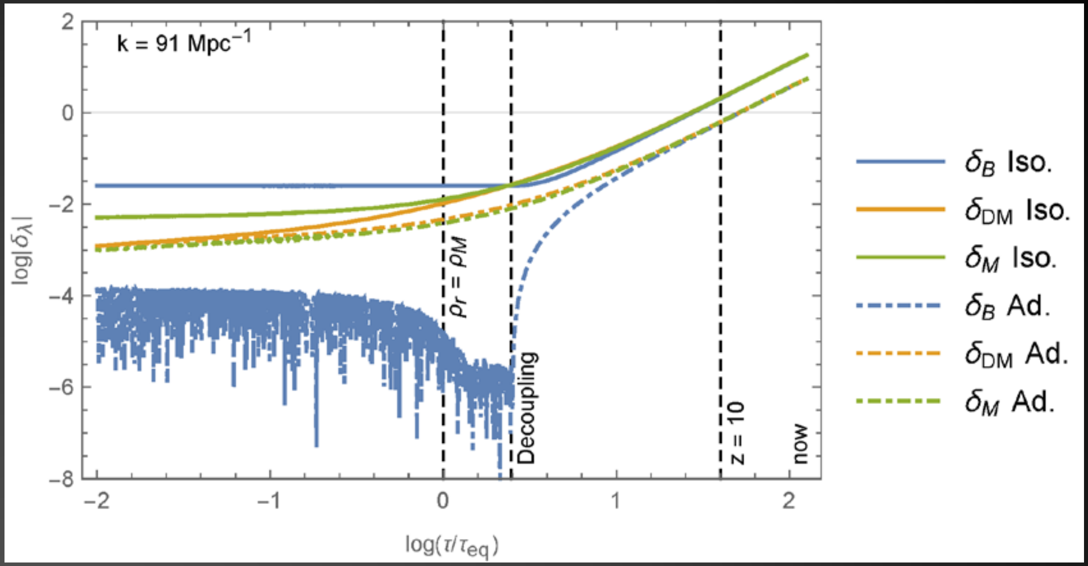


- **CMB:** $0.002\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 0.1\ \mathrm{Mpc}^{-1}$ **(Limited by Silk damping)**
- **Lyman-α:** $0.1\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 10\ \mathrm{Mpc}^{-1}$
- **Allowed N of e-folds of inflation for the Higgs field:**

$$N_{\rm last} < 48.2 - \ln\left(\frac{k_*}{10\ \mathrm{Mpc}^{-1}}\right) + \frac{2}{3}\ln\left(\frac{\Lambda_{\rm I}}{10^{16}\ \mathrm{GeV}}\right) + \frac{1}{3}\ln\left(\frac{T_{RH}}{10^{12}\ \mathrm{GeV}}\right)$$

Growth of density perturbation

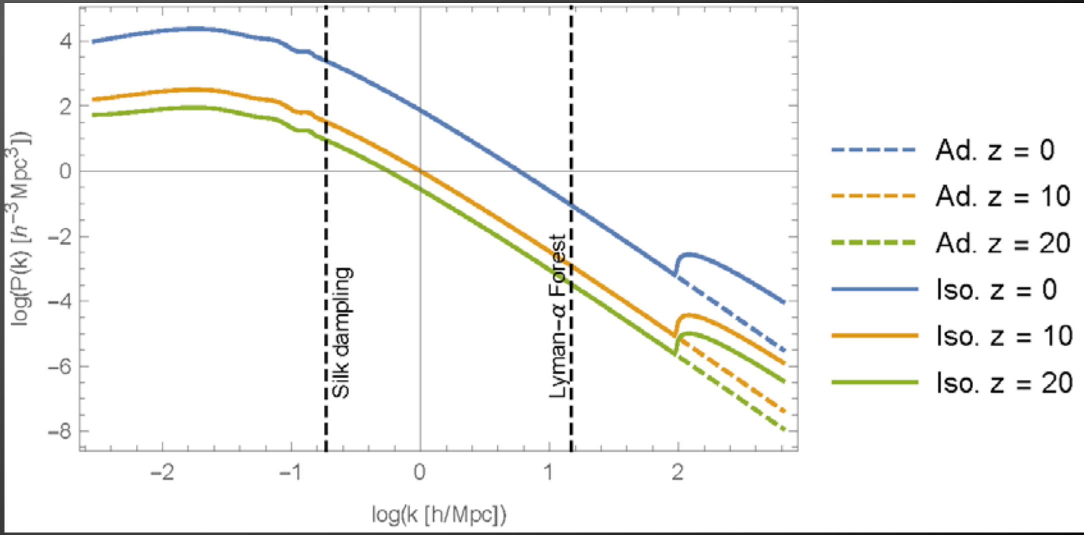
- Baryon isocurvature perturbation only growth after decoupling
- But the induced potential allows dark matter to grows faster.
- δ_M becomes nonlinear earlier



- $\delta_{B,0} = 0.025$, $k_S = 65\ \mathrm{Mpc}^{-1}$, $N_{\mathrm{last}} = 46.5$

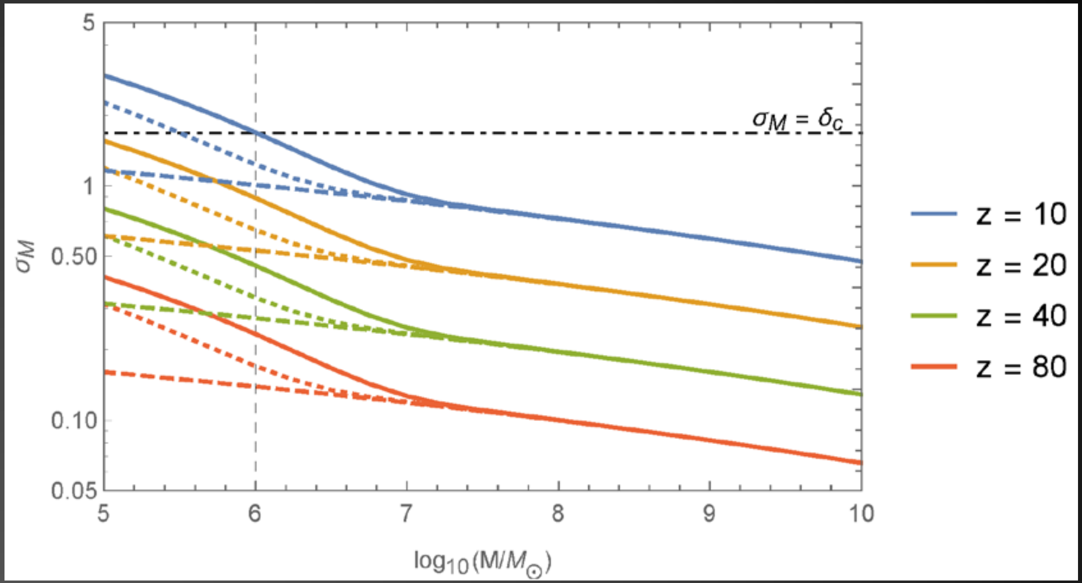
Matter power Spectrum

- Contribution from relaxation leptogenesis model only appear in the small scale
- Silk damping does not affect baryonic isocurvature perturbation.



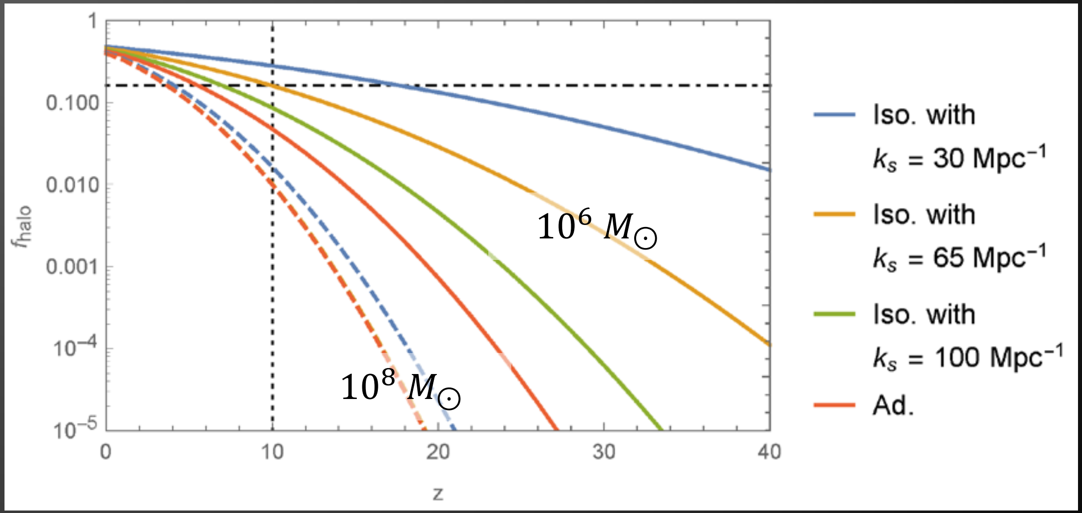
Variance of the density contrast

- Solid lines: Isocurvature perturbations from $k_s = 65\ \mathrm{Mpc}^{-1}$
- Dashed lines: with only adiabatic perturbation
- Dash-dot line: $\delta_c = 1.686$
- Halos with $10^6\ M_\odot$ collapsed by $z = 10$.



Mass fraction in collapsed halos

- Solid lines: $10^6\ M_\odot$ halos
- Reach $f_{\mathrm{halo}} = 0.16$ by $z = 10$ for $k_s = 65\ \mathrm{Mpc}^{-1}$
- Dashed lines: $10^8\ M_\odot$ halos unchanged



Can explain the CIB fluctuation excess!

Summary

- Our universe seems to be right at the meta-stable vacuum.
- A small quartic coupling of the Higgs potential at high energy scale gives a shallow potential.
- Higgs can obtain a large vacuum expectation during inflation.
- The relaxation of the Higgs VEV happens during reheating.
- Higgs relaxation provides the out of thermal equilibrium condition and breaks T invariant.
- Leptogenesis via the Higgs relaxation is possible.
- Isocurvature perturbation generated by the relaxation leptogenesis might explain the CIB fluctuation excess.
- Higgs relaxation is an interesting epoch in the early universe.

Thanks for your listening!