

Affleck-Dine Leptogenesis from Higgs Inflation

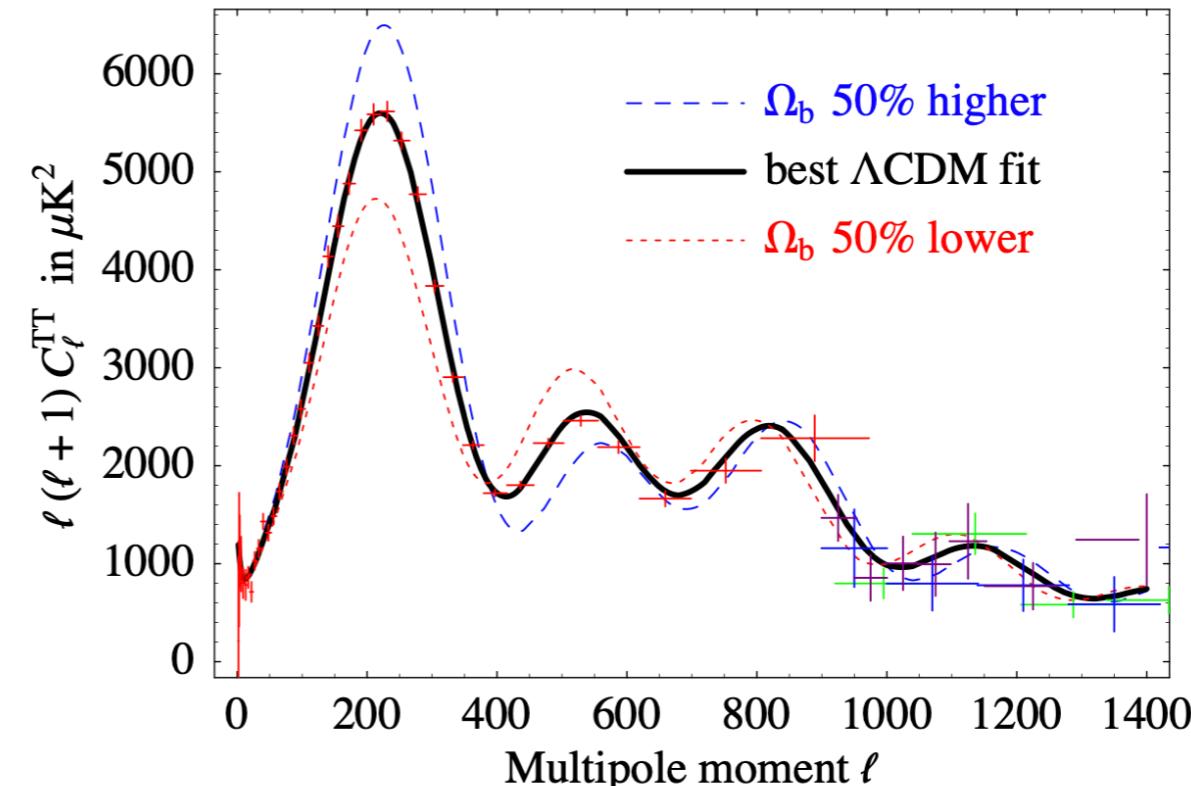
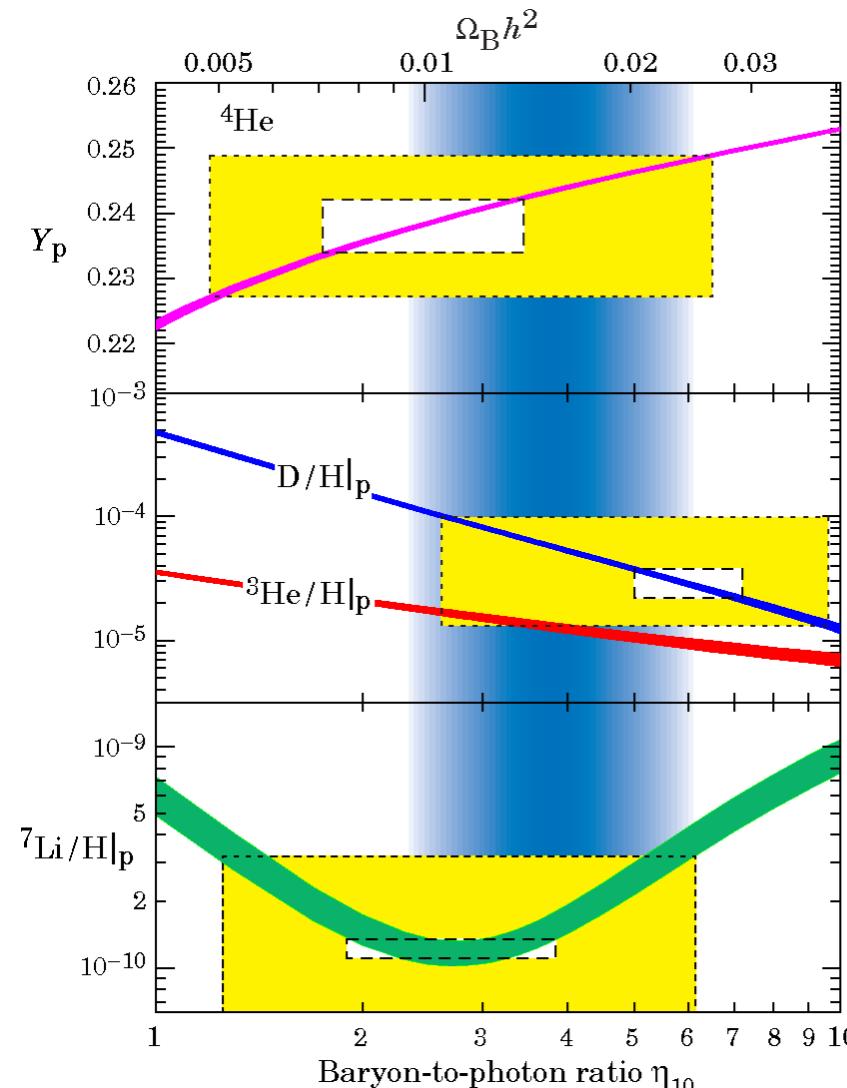
Chengcheng Han(韩成成)

Sun Yat-sen University

Based on the paper arXiv:2106.03381
with Neil D. Barrie and Hitoshi Murayama

Asia-Pacific Workshop on Particle
Physics and Cosmology 2021

Baryon asymmetry of our universe



Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2] - [1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012

BBN

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

How to generate baryon asymmetry?

Assuming no baryon asymmetry in the beginning
(if any, diluted by inflation)

Sakharov conditions

1. B number violation
2. C and CP violation
3. Out of thermal equilibrium

SM has (1) (2) but not enough CP violation, (3) does not

Three popular ways to generate baryon asymmetry

- Electroweak baryogenesis Rubakov and Shaposhnikov, 1996'
D. E. Morrissey and M. J. Ramsey-Musolf, 2012'
First order phase transition (adding scalars) + additional \cancel{CP}
- Baryogenesis via thermal leptogenesis Fukugita and Yanagida, 1986'
Connection to neutrino masses
$$n_B = \frac{28}{79} (\mathcal{B} - \mathcal{L})_i$$
- Baryogenesis from Affleck-Dine mechanism Affleck and Dine, 1985'

A well-known mechanism for high energy physics society

Baryogenesis from Affleck-Dine mechanism

Assuming a complex scalar ϕ taking U(1)B charge

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2 |\phi|^2$$

$\phi \rightarrow e^{i\alpha} \phi$ symmetry, corresponding current

$$j_B^\mu = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*)$$

ϕ is spatially constant $n_B = i(\phi^* \dot{\phi} - \phi \dot{\phi}^*)$

We can add a small U(1) breaking term

$$V = m^2 |\phi|^2 + c_n (\phi^n + \phi^{*n}) + \frac{|\phi|^{2m}}{M^{2m-4}}$$

Baryogenesis from Affleck-Dine mechanism

Equation of motion in an expansion of universe

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi^*} = 0$$

Only from U(1) breaking term

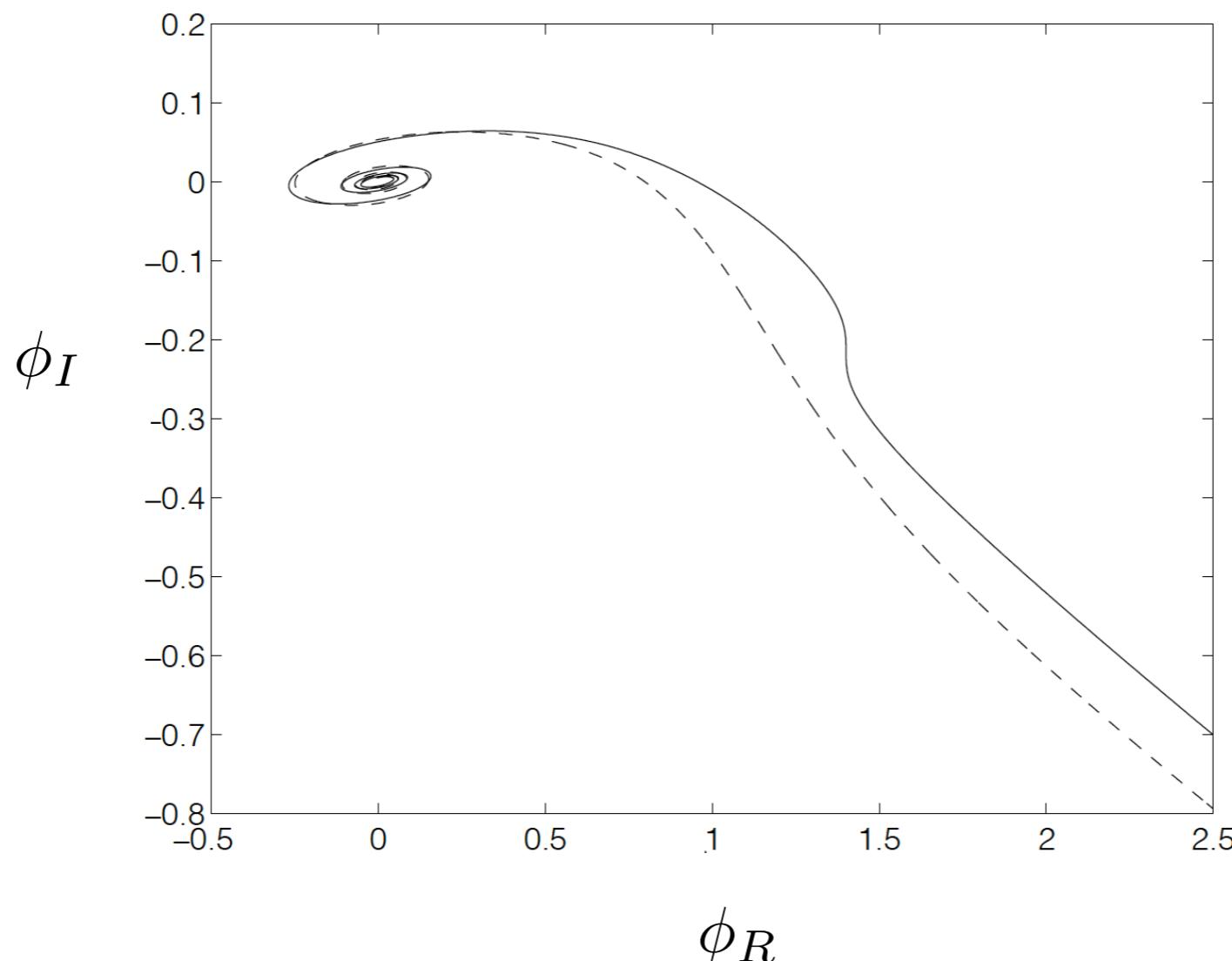
$$\dot{n}_B + 3Hn_B = \boxed{\text{Im} \left(\phi \frac{\partial V}{\partial \phi} \right)}$$

At $t_0 = 1/H \sim 1/m$ $n_B(t_0) \sim \frac{nc_n \phi_0^n}{m}$

$$n_B(t) = n_B(t_0)(a_0/a(t))^3$$

$$\eta = \frac{n_B}{s} \Big|_{t_{rh}} \quad t_{rh} = \frac{1}{H_{rh}} \sim \frac{M_{pl}}{T_{rh}^2} \quad s \sim T_{rh}^3$$

Baryogenesis from Affleck-Dine mechanism



CP violation appears when $\langle \phi_I \rangle \neq 0$

Affleck-Dine mechanism for SUSY

Scalar potential in SUSY

$$V = \sum_i |F_i|^2 + \frac{1}{2} \sum_a g_a^2 D^a D^a$$

$$F_i \equiv \frac{\partial W_{MSSM}}{\partial \phi_i}, \quad D^a = \phi^\dagger T^a \phi.$$

There exist particular vacuum alignment that the potential vanish(flat direction)

For example,

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}, \quad L = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix} \quad V(\phi) = 0$$

$$H_u = \phi \sin \alpha \quad L = \phi \cos \alpha \quad \alpha = \frac{\pi}{4}$$

Affleck-Dine mechanism for SUSY

The Flat directions can be lifted by adding high dimension operator
(as required by neutrino mass)

mixing with L and Hu are important

$$W = \frac{1}{M} (LH_u)^2 = \frac{1}{2M} \phi^4 \quad M \sim 10^{15} \text{ GeV}$$

Including the SUSY breaking (supergravity mediation)

$$V(\phi) = m^2 |\phi|^2 + \left(\frac{2A}{M} \phi^4 + h.c \right) + \frac{4}{M^2} |\phi|^6$$

U(1)L breaking term

m, A are SUSY breaking parameters $m, A \sim m_{3/2}$

Coupling with inflaton providing an initial condition

Many problems to answer

- How to generate the “flat directions” without SUSY?
- What is the origin of the U(1) breaking term?
- Why initial (large) value for the scalar field?

Borrowed the idea of Higgs inflation

Higgs is the only scalar field in SM

Bezrukov and Shaposhnikov, Phys.Lett.B 659 (2008) 703-706

$$S_J = \int d^4x \sqrt{-g_J} \left[\frac{M_P^2}{2} \left(1 + \boxed{\frac{\xi\phi^2}{M_P^2}} R_J \right) - \frac{1}{2} |\partial_\mu \phi|^2 - V_J(\phi) \right]$$

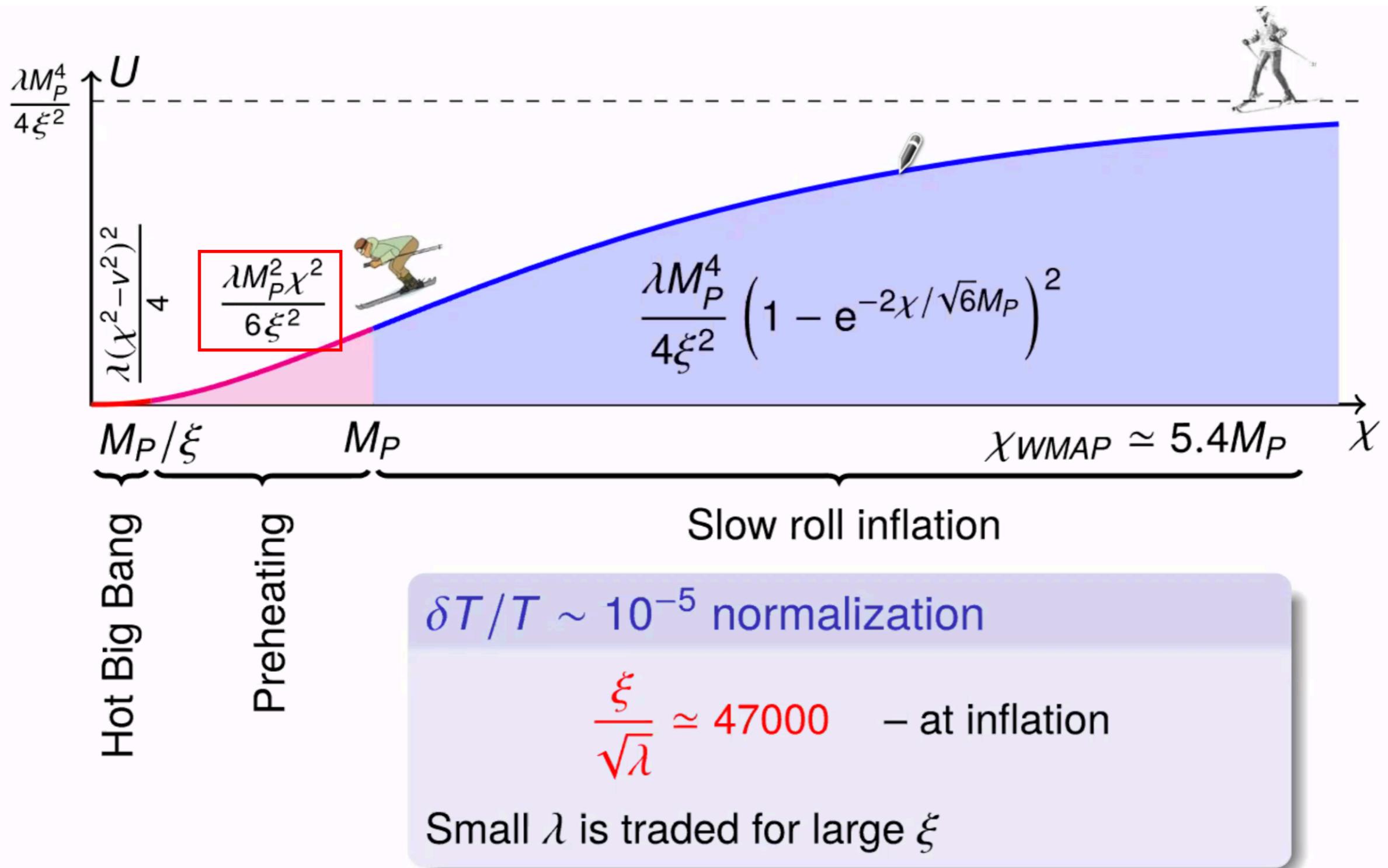
$$g_{\mu\nu} = \Omega(\phi)^2 g_{J\mu\nu} \quad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$\frac{d\chi}{d\phi} = \left(\frac{1 + \xi(1 + 6\xi)\phi^2/M_P^2}{(1 + \xi\phi^2/M_P^2)^2} \right)^{1/2}$$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V(\chi) \right] \quad V(\chi) \equiv V_J(\phi(\chi))/\Omega^4(\phi(\chi))$$

Higgs inflation

Plot borrowed from Bezrukov



SM + a triplet Higgs

Adding non-minimal couplings for inflation

$$\begin{aligned}\frac{\mathcal{L}}{\sqrt{-g}} = & -\frac{1}{2}M_P^2 R - \boxed{f(H, \Delta)R} - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) \\ & - g^{\mu\nu}(D_\mu \Delta)^\dagger(D_\nu \Delta) - V(H, \Delta) + \mathcal{L}_{\text{Yukawa}}\end{aligned}$$

$$f(H, \Delta) = \xi_H H^\dagger H + \xi_\Delta \Delta^\dagger \Delta + \dots,$$

SM + a triplet Higgs

During inflation(Oleg Lebedev and Hyun Min Lee, arXiv:1105.2284)

$$\frac{|H|}{|\Delta|} = \tan \alpha \simeq \sqrt{\frac{2\lambda_\Delta \xi_H - \lambda_H \Delta \xi_\Delta}{2\lambda_H \xi_\Delta - \lambda_H \Delta \xi_H}}$$

$$H = \phi \sin \alpha, \quad \Delta = \phi \cos \alpha$$

$$f(H, \Delta) = \frac{\xi_H}{2}|H|^2 + \frac{\xi_\Delta}{2}|\Delta|^2 = \frac{\xi}{2}|\phi|^2$$

$$\xi = \xi_H \sin^2 \alpha + \xi_\Delta \cos^2 \alpha$$

Similar to SUSY case, mixing with an angle alpha

SM + a triplet Higgs

$H(2, 1/2)$, $\Delta(3, 1)$, $L(2, -1/2)$

$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_{Yukawa} = \mathcal{L}_{Yukawa}^{\text{SM}} - \boxed{\frac{1}{2} y_{ij} \bar{L}_i^c \Delta L_j} + h.c.$$

Giving neutrino mass matrix
Delta get a lepton number -2

SM + a triplet Higgs

$$H(2, 1/2), \Delta(3, 1), L(2, -1/2)$$

$$\begin{aligned} V(H, \Delta) = & -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) \\ & + \lambda_3 \text{Tr}(\Delta^\dagger \Delta)^2 + \lambda_1 (H^\dagger H) \text{Tr}(\Delta^\dagger \Delta) \\ & + \lambda_2 (\text{Tr}(\Delta^\dagger \Delta))^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \end{aligned}$$

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\text{EW}}^2}{2m_\Delta^2}$$

$$\begin{aligned} & + \left[\mu (H^T i\sigma^2 \Delta^\dagger H) + \frac{\lambda_5}{M_P} (H^T i\sigma^2 \Delta^\dagger H)(H^\dagger H) \right. \\ & \left. + \frac{\lambda'_5}{M_P} (H^T i\sigma^2 \Delta^\dagger H)(\Delta^\dagger \Delta) + h.c. \right] + \dots \end{aligned}$$

U(1)L breaking term



$$V(\phi) = m^2 |\phi|^2 + \lambda |\phi|^4 + (\tilde{\mu} |\phi|^2 \phi + \frac{\tilde{\lambda}_5}{M_P} |\phi|^4 \phi + h.c.)$$

SM + a triplet Higgs

In practice

$$\phi = \frac{1}{\sqrt{2}} \varphi \exp(i\theta)$$

$$\begin{aligned} \frac{\mathcal{L}}{\sqrt{-g}} = & -\frac{1}{2} M_P^2 R - \frac{1}{2} \xi \varphi^2 R - \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \\ & - \frac{1}{2} \varphi^2 g^{\mu\nu} \partial_\mu \theta \partial_\nu \theta - V(\varphi, \theta) , \end{aligned}$$

$$V(\varphi, \theta) = \frac{1}{2} m^2 \varphi^2 + \frac{\lambda}{4} \varphi^4 + 2\varphi^3 \left(\tilde{\mu} + \frac{\tilde{\lambda}_5}{M_P} \varphi^2 \right) \cos \theta$$

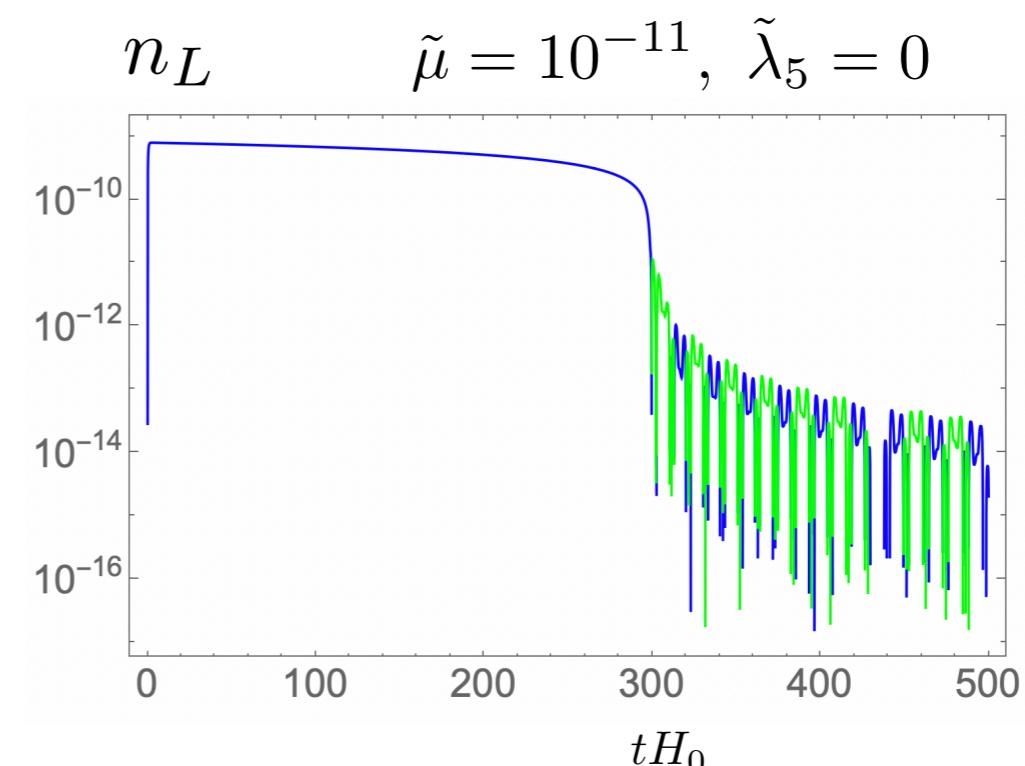
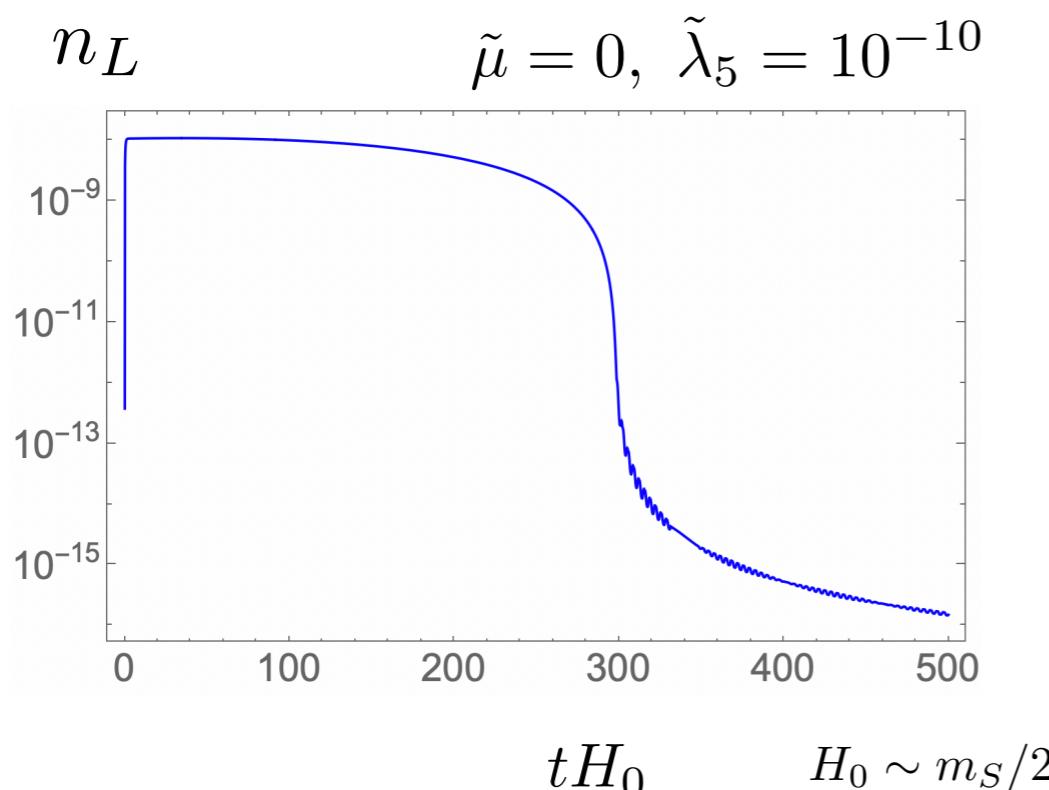
SM + a triplet Higgs

$$\frac{\chi}{M_p} \approx \begin{cases} \frac{\varphi}{M_p} & \text{for } \frac{\varphi}{M_p} \ll \frac{1}{\xi} \quad (\text{after reheating}) \\ \sqrt{\frac{3}{2}} \xi \left(\frac{\varphi}{M_p} \right)^2 & \text{for } \frac{1}{\xi} \ll \frac{\varphi}{M_p} \ll \frac{1}{\sqrt{\xi}} \quad (\text{reheating}) \\ \sqrt{\frac{3}{2}} \ln \Omega^2 = \sqrt{\frac{3}{2}} \ln \left[1 + \xi \left(\frac{\varphi}{M_p} \right)^2 \right] & \text{for } \frac{1}{\sqrt{\xi}} \ll \frac{\varphi}{M_p} \quad (\text{inflation}) \end{cases}$$

$$U(\chi) \approx \begin{cases} \frac{1}{4} \lambda \chi^4 & \text{for } \frac{\chi}{M_p} \ll \frac{1}{\xi} \quad (\text{after reheating}) \\ \frac{1}{2} m_S^2 \chi^2 & \text{for } \frac{1}{\xi} \ll \frac{\chi}{M_p} \ll 1 \quad (\text{reheating}) \\ \frac{3}{4} m_S^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_p)} \right)^2 & \text{for } 1 \ll \frac{\chi}{M_p} \quad (\text{inflation}) \end{cases}$$

SM + a triplet Higgs: baryon number

$$n_L = Q_L \phi^2(\chi) \dot{\theta} \cos^2 \alpha$$



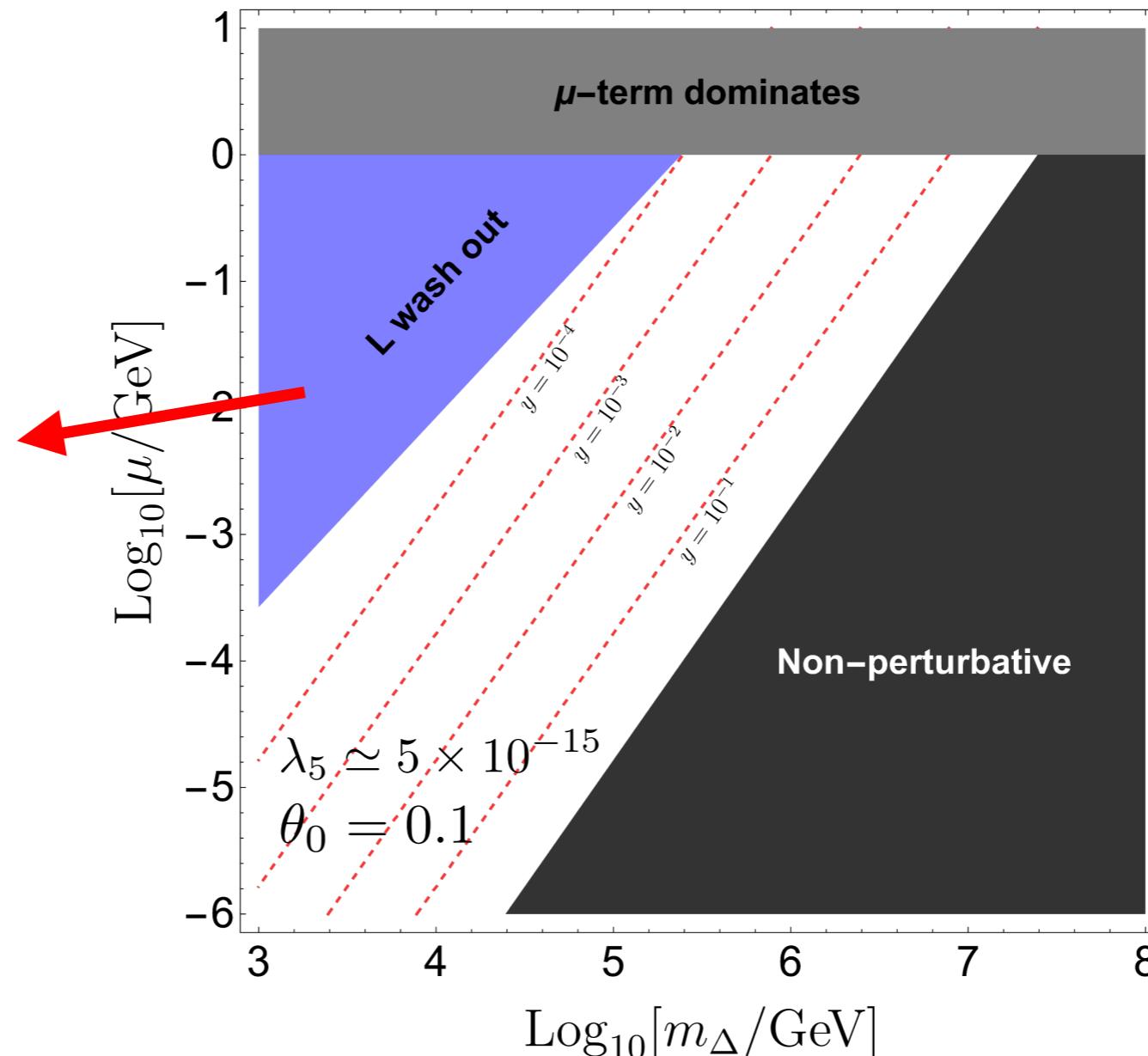
Cubic term should not be too large, otherwise baryon number oscillates
A small cubic term also benefit to avoid washing out

Model with triplet Higgs

$$\lambda_H \simeq 0.1, \lambda_\Delta \simeq 4.5 \times 10^{-5}, \xi_H \sim \xi_\Delta = 300, \alpha \simeq 0.022$$

Avoid washing out
the lepton asymmetry

$$\Gamma_{ID}(HH \leftrightarrow \Delta)|_{T=m_\Delta} < H|_{T=m_\Delta}$$



$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\text{EW}}^2}{2m_\Delta^2}$$

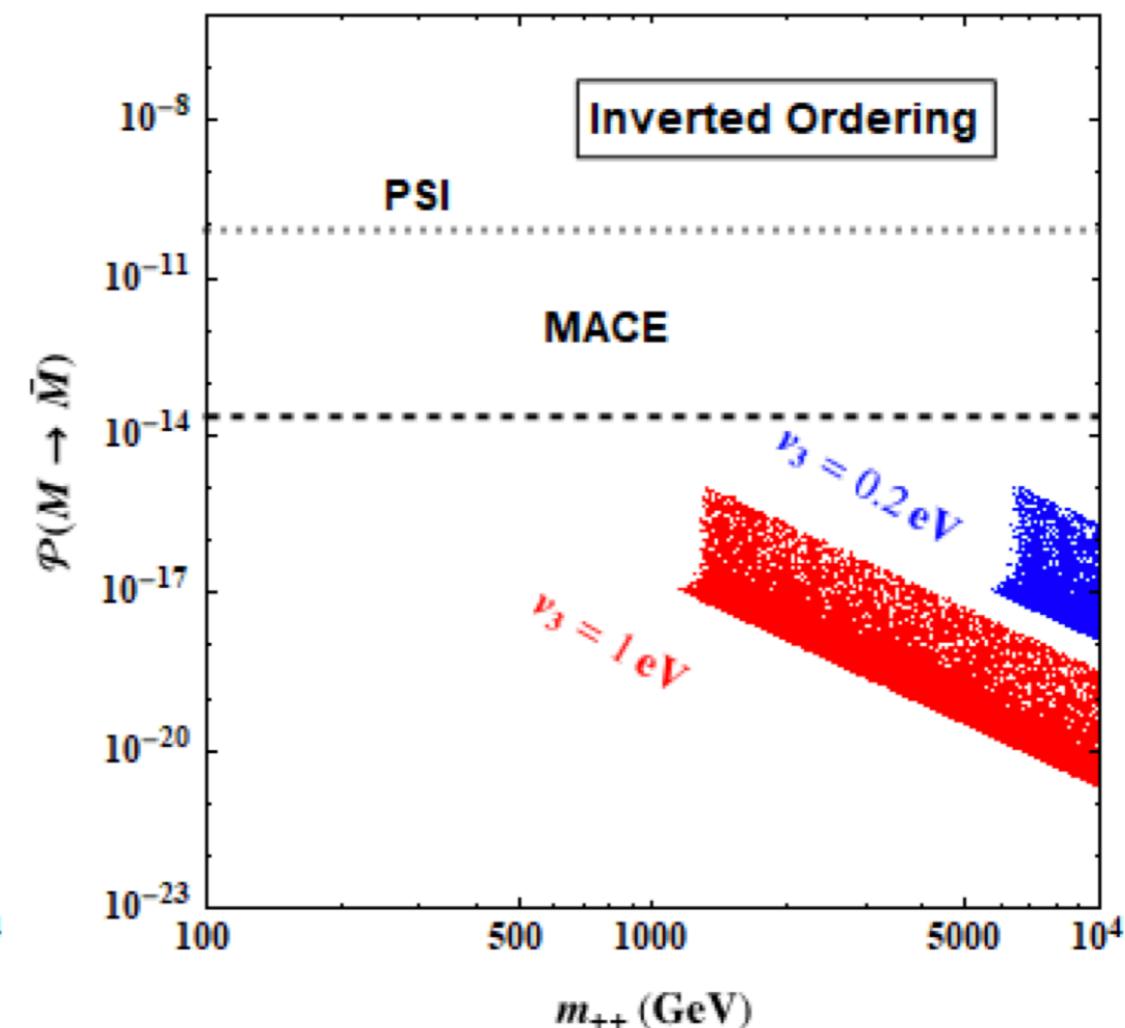
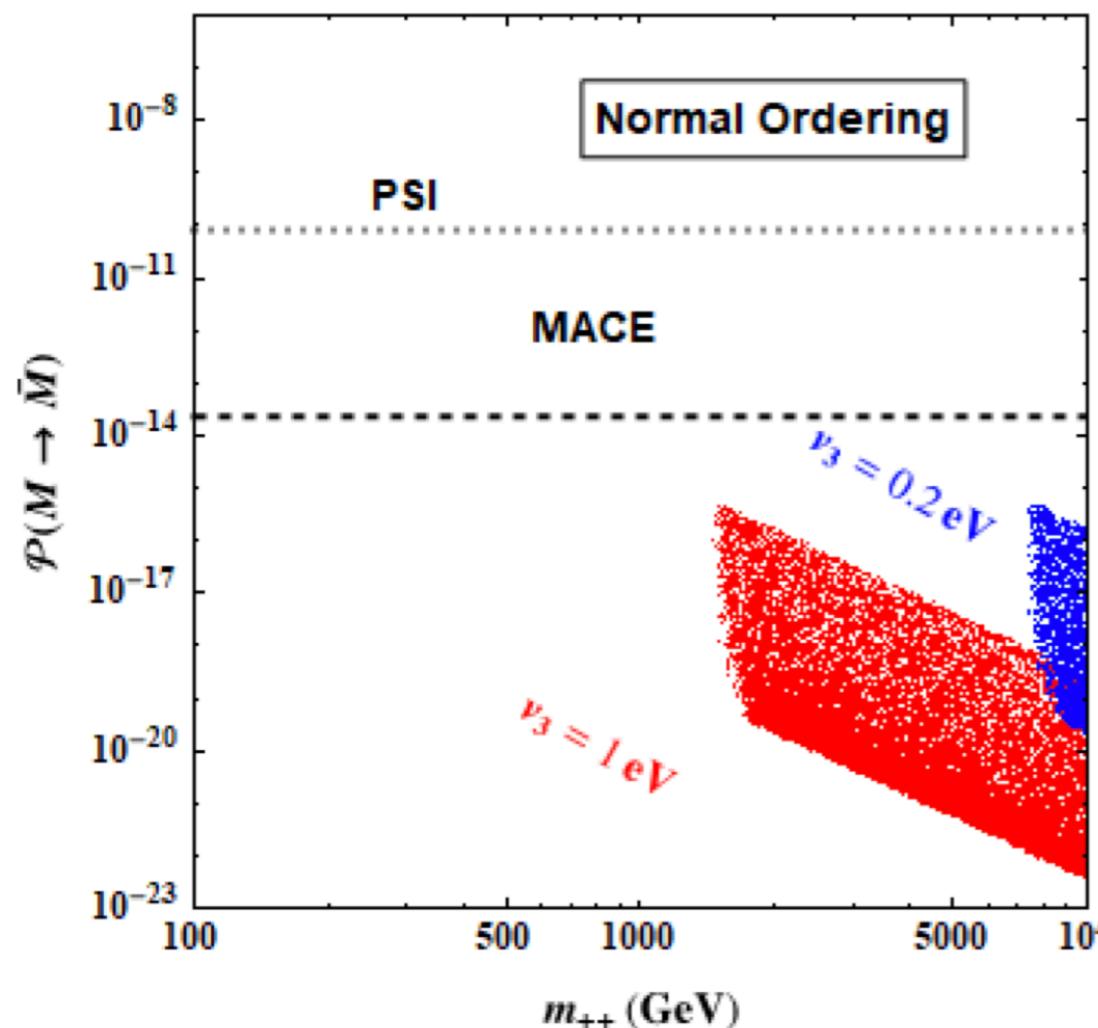
(at least one neutrino mass 0.05 eV)

Indication for low energy physics

$$\mathcal{B}(\mu^+ \rightarrow e^+ e^- e^+) = \frac{|(y_N)_{\mu e}(y_N^\dagger)_{ee}|^2}{16G_F^2 m_{++}^4} \quad \mathcal{B}(\mu^+ \rightarrow e^+ e^- e^+) \leq 1.0 \times 10^{-12}$$

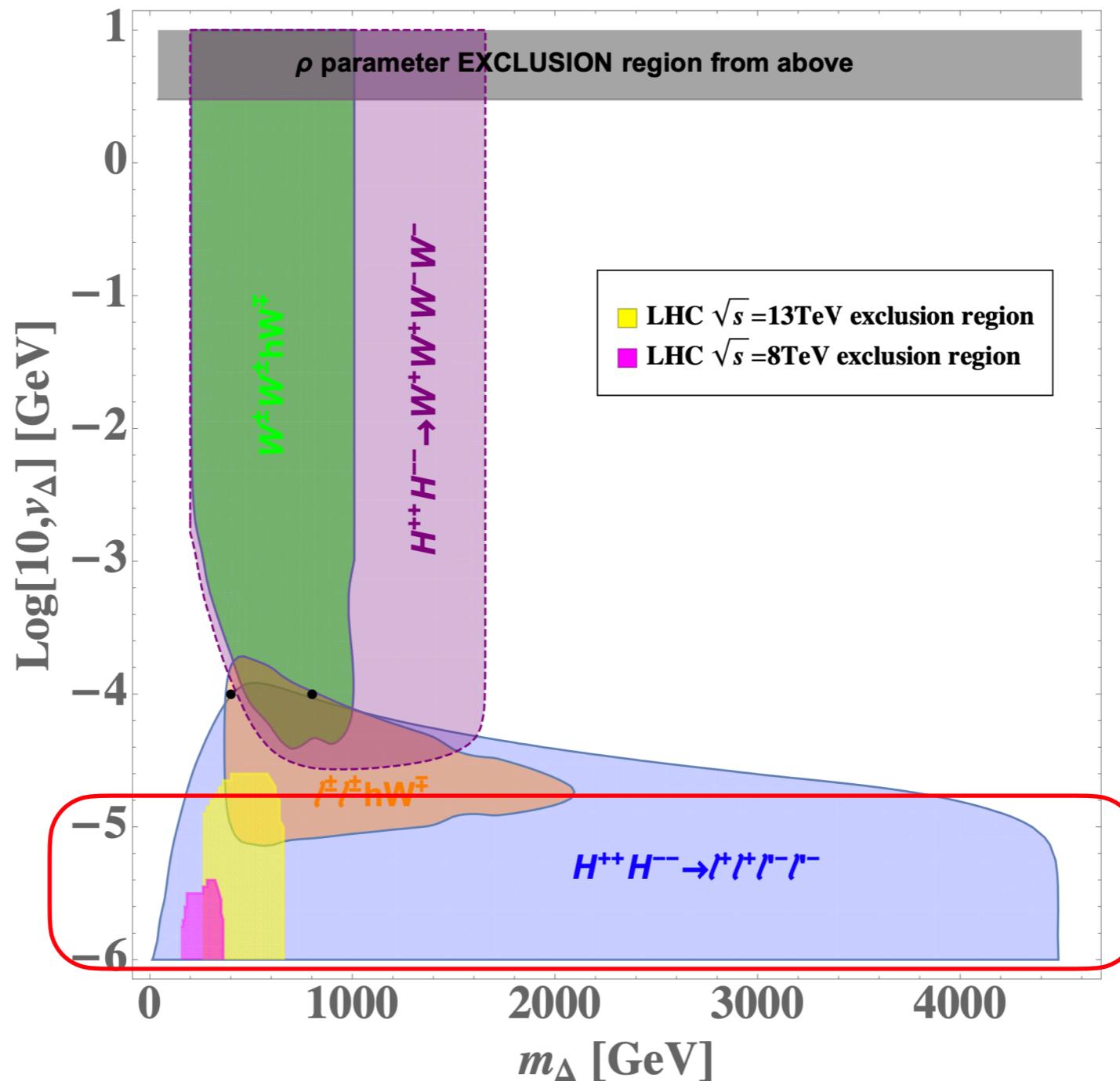
$$\mathcal{B}(\mu \rightarrow e\gamma) \simeq \frac{\alpha}{768\pi} \frac{\left|(y_N^\dagger y_N)_{e\mu}\right|^2}{G_F^2} \left(\frac{1}{m_+^2} + \frac{8}{m_{++}^2}\right)^2 \quad \mathcal{B}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$$

CH, D. Huang, J. Tang, Y. Zhang, Phys. Rev. D 103, 055023 (2021)



Indication for low energy physics

Y. Du, A. Dunbrack, M. J. Ramsey-Musolf, J. Yu, JHEP01(2019)101



5 sigma discover region @100 TeV collider

Summary

- We present a simple extension of SM to resolve three important problems: inflation, baryon asymmetry and neutrino masses
- Neutrino masses are majorana-type: $0\nu\beta\beta$
- A sizable tensor to scalar ratio: $r \sim 0.005$, which can be reached by next generation CMB measurement
- Leaving a light triplet Higgs at low energy scale: which might be probed by collider physics and LFV measurement

SM + a triplet Higgs

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \xi \varphi^2 / M_P^2 .$$

$$\chi(\varphi) = 1/\sqrt{\xi}(\sqrt{1+6\xi} \sinh^{-1}(\sqrt{\xi+6\xi^2}\varphi) - \sqrt{6\xi} \sinh^{-1}(\sqrt{6\xi^2}\varphi/\sqrt{1+\xi\varphi^2})$$

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}f(\chi)g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - U(\chi, \theta)$$

$$f(\chi) \equiv \frac{\varphi(\chi)^2}{\Omega^2(\chi)} \qquad U(\chi, \theta) \equiv \frac{V(\varphi(\chi), \theta)}{\Omega^4(\chi)}$$

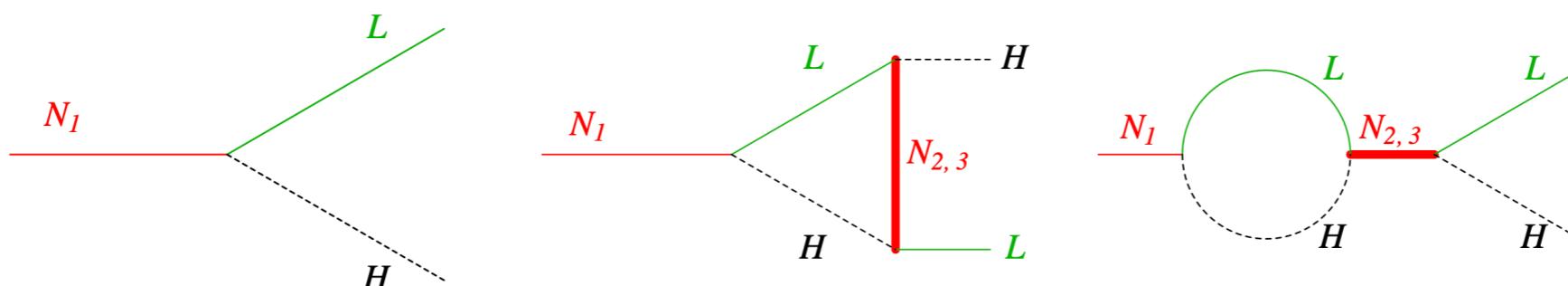
Baryogenesis via thermal leptogenesis

SM + 3 right-handed neutrinos

Fukugita and Yanagida, 1986'

$$\begin{aligned}\mathcal{L} = & \mathcal{L}_{\text{SM}} + \bar{N}_1 i\partial N_1 + \lambda_1 N_1 H L + \frac{M_1}{2} N_1^2 + \\ & + \bar{N}_{2,3} i\partial N_{2,3} + \lambda_{2,3} N_{2,3} H L + \frac{M_{2,3}}{2} N_{2,3}^2 + \text{h.c.}\end{aligned}$$

$$Y_{\Delta B} \simeq \frac{135\zeta(3)}{4\pi^4 g_*} \epsilon \times \eta \times C$$



$$\Gamma(N_1 \rightarrow LH) \propto |\lambda_1 + A\lambda_1^* \lambda_{2,3}^2|^2, \quad \Gamma(N_1 \rightarrow \bar{L}\bar{H}) \propto |\lambda_1^* + A\lambda_1 \lambda_{2,3}^{2*}|^2$$

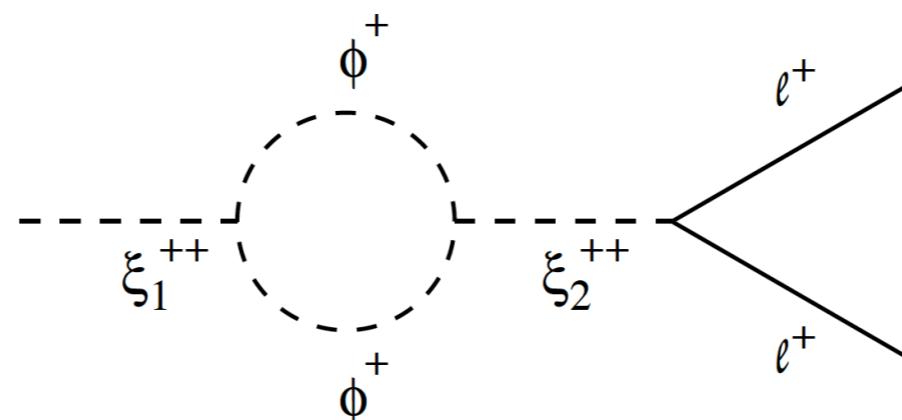
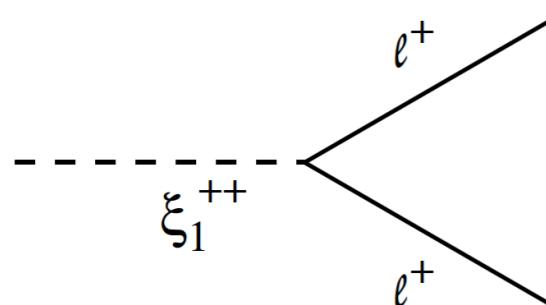
$$\epsilon \equiv \frac{\Gamma(N_1 \rightarrow LH) - \Gamma(N_1 \rightarrow \bar{L}\bar{H})}{\Gamma(N_1 \rightarrow LH) + \Gamma(N_1 \rightarrow \bar{L}\bar{H})} \sim \frac{1}{4\pi} \frac{M_1}{M_{2,3}} \text{Im} \lambda_{2,3}^2$$

Thermal leptogenesis from triplet Higgs

Type II seesaw

$M \sim 10^{13}$ GeV

Neutrino Masses and Leptogenesis with Heavy Higgs Triplets,
E. Ma, U. Sarkar, Phys.Rev.Lett. 80 (1998) 5716-5719

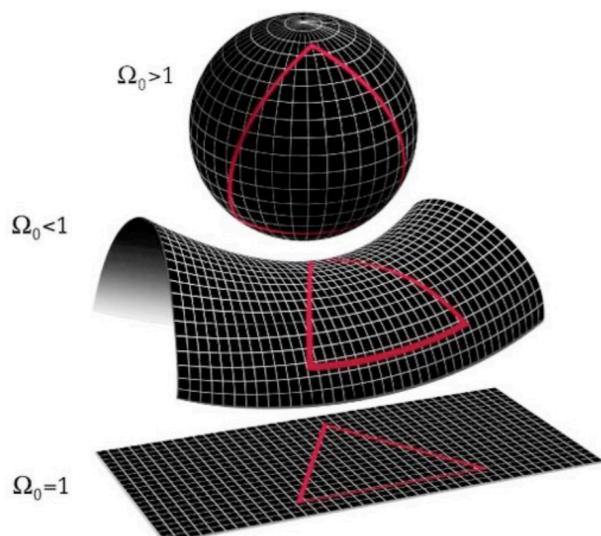
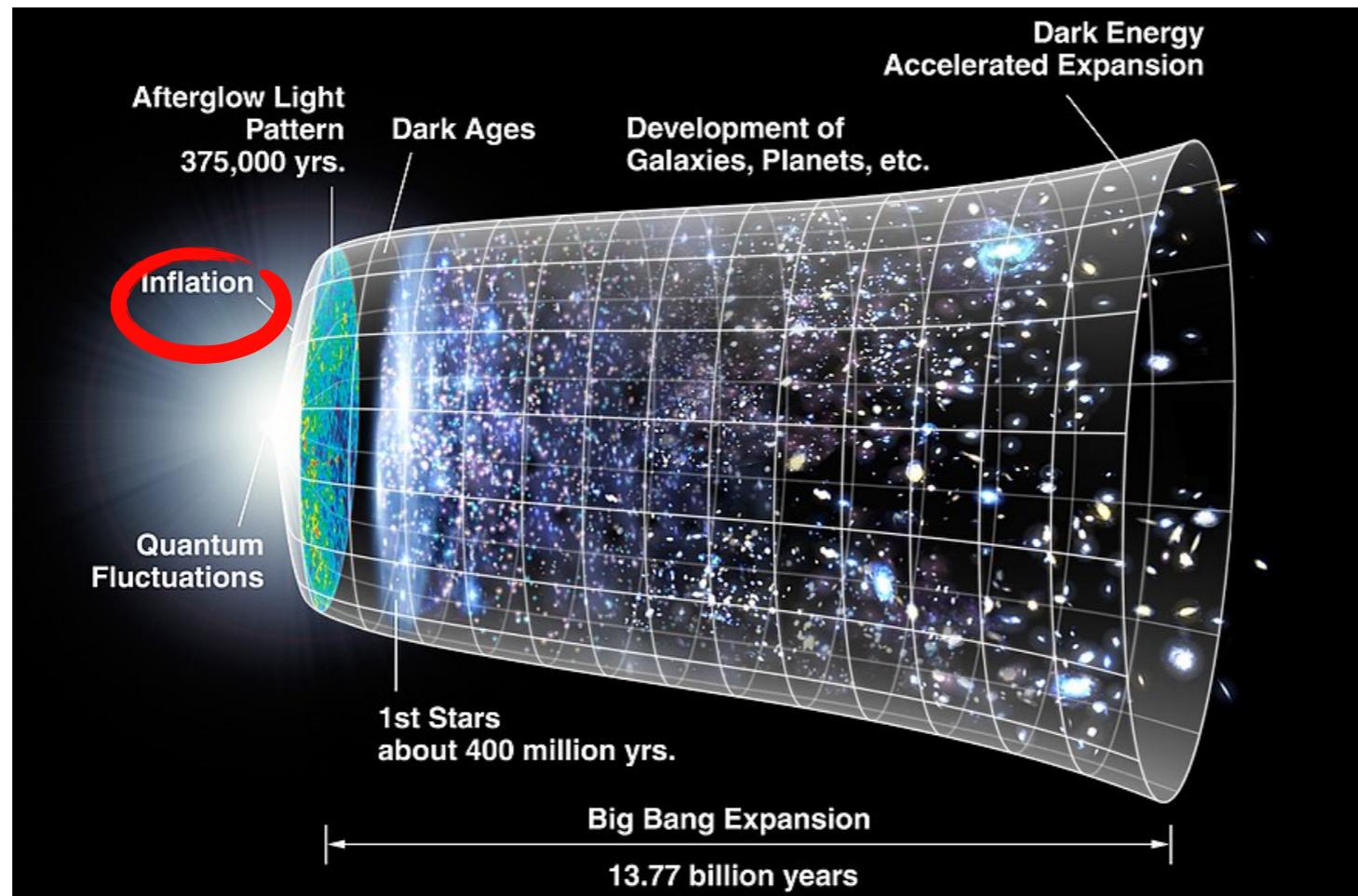


- Unfortunately, one triplet Higgs can not generate the lepton asymmetry
- Two triplet Higgs are needed to generate the baryon asymmetry
- Or one triplet Higgs + right-handed neutrino or ...

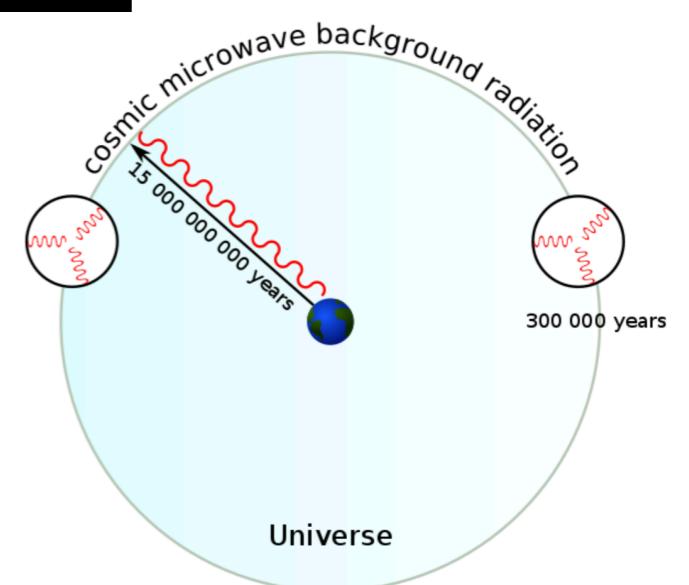
Pei-Hong Gu, He Zhang, Shun Zhou, PhysRevD.74.076002(2006)

Inflation

Expansion of the universe in the early time



- Flatness problem
- Horizon problem
- Monopole problem?

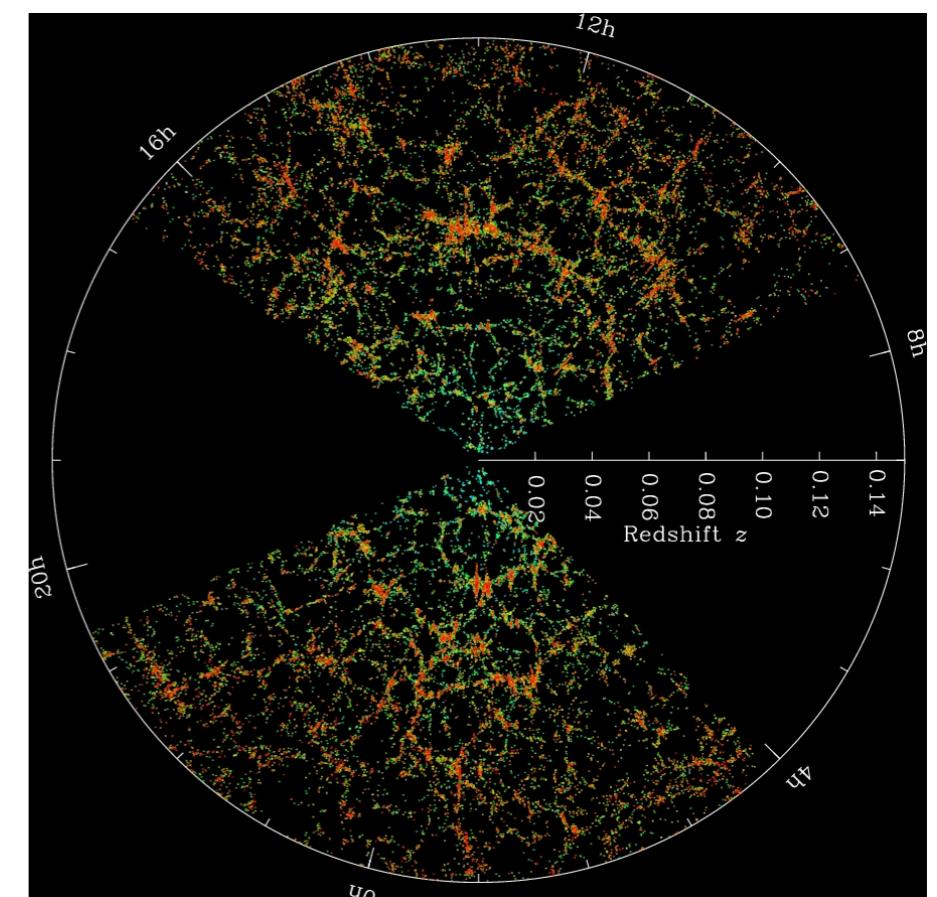
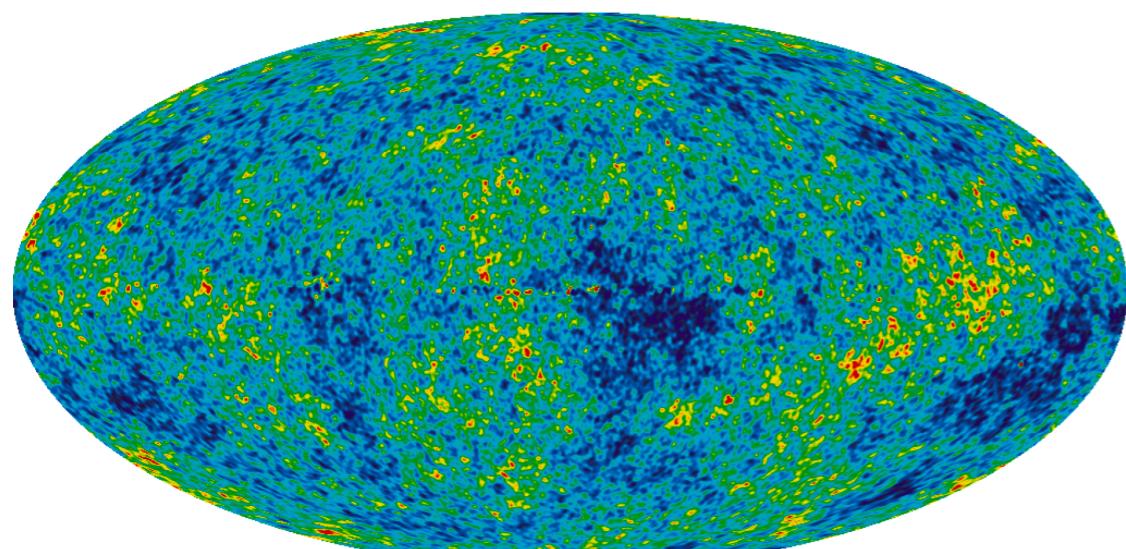


Expansion of the universe in the early time

- Flatness problem
- Horizon problem
- Monopole problem?
- Seeding the primordial anisotropies in CMB

Inflation

Generating quantum fluctuations(anisotropies in CMB)

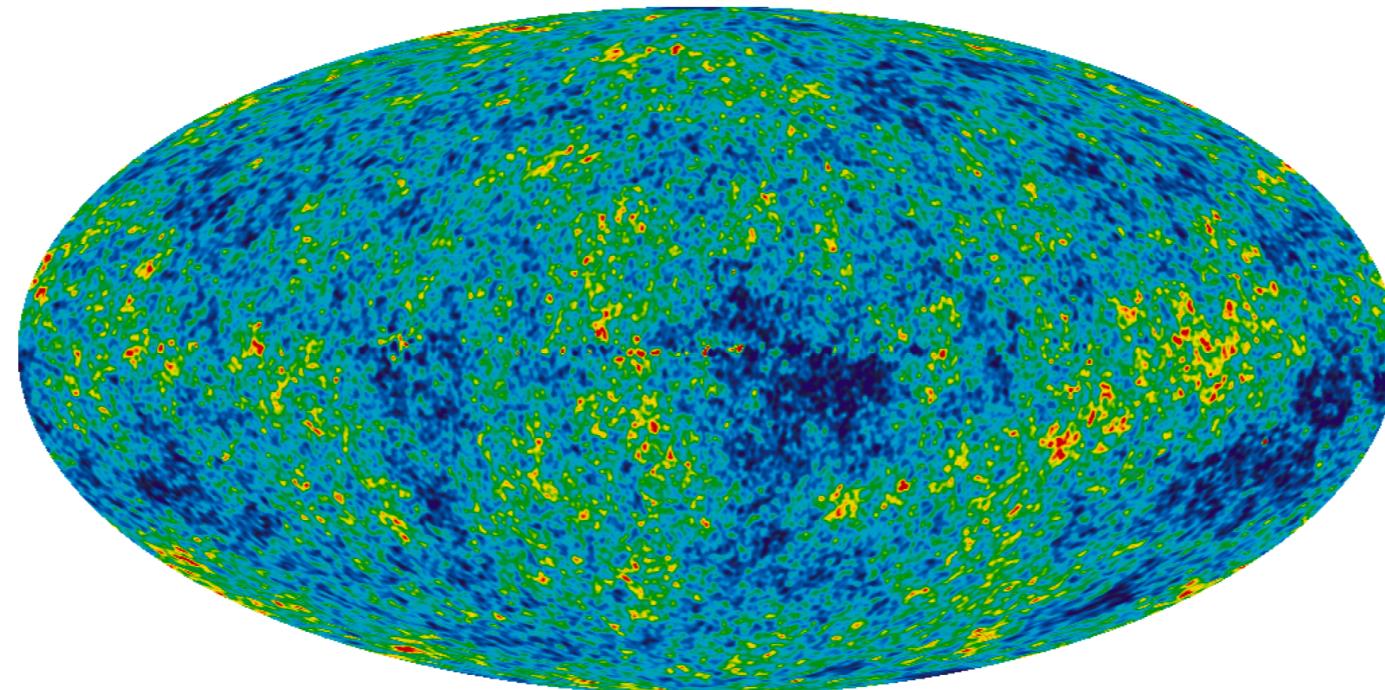


$$\frac{\delta T}{T} \sim 10^{-5}$$

Such small fluctuations finally develops the large structure of our universe

Inflation

Generating quantum fluctuations(anisotropies in CMB)



$$\frac{\delta T}{T} \sim 10^{-5}$$

Such small fluctuations finally develops the large structure of our universe

Slow roll inflation

Assume a scalar field, with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

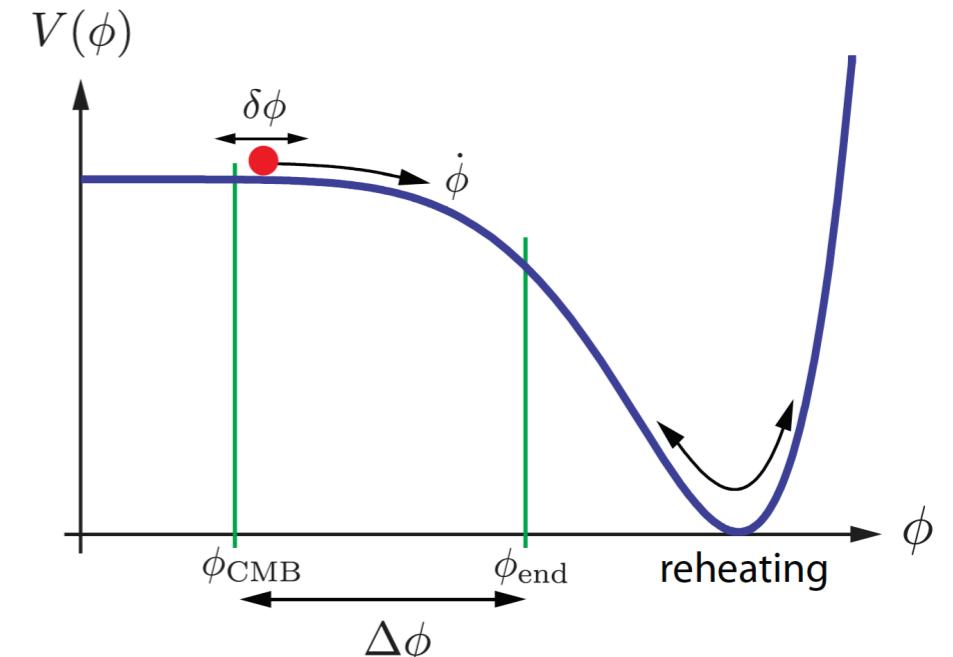
$$H^2 = \frac{1}{3} \left(\frac{1}{2}\dot{\phi}^2 + V(\phi) \right)$$

Slow roll condition

$$\dot{\phi}^2 \ll V(\phi) \quad |\ddot{\phi}| \ll |3H\dot{\phi}|, |V_{,\phi}|$$

$$\epsilon_v(\phi) \equiv \frac{M_{\text{pl}}^2}{2} \left(\frac{V_{,\phi}}{V} \right)^2 \quad \eta_v(\phi) \equiv M_{\text{pl}}^2 \frac{V_{,\phi\phi}}{V}$$

$$\epsilon_v, |\eta_v| \ll 1$$



$$H^2 \approx \frac{1}{3}V(\phi) \approx \text{const.}$$

$$\dot{\phi} \approx -\frac{V_{,\phi}}{3H},$$



$$a(t) \sim e^{Ht}$$

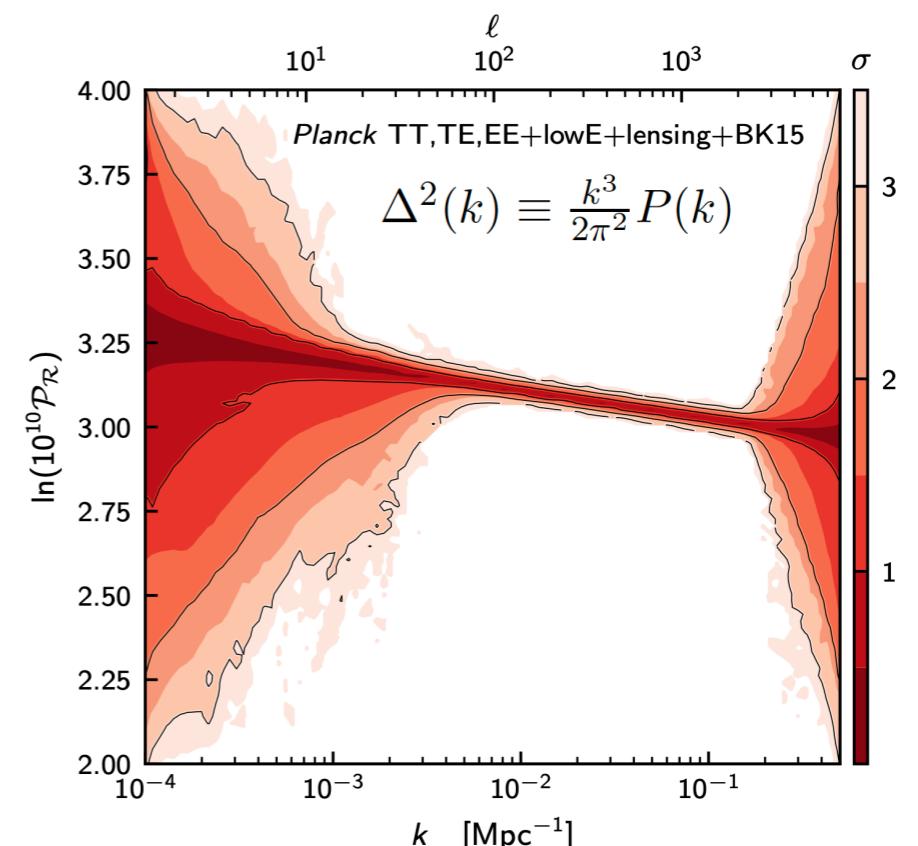
Daniel Baumann, TASI Lectures on Inflation

Slow roll inflation

Power spectrum $\Delta_s^2(k) \equiv \frac{k^3}{2\pi^2} \langle \delta\phi(k) \delta\phi(k') \rangle$

$$\Delta_s^2(k) \approx \frac{1}{24\pi^2} \frac{V}{M_{\text{pl}}^4} \frac{1}{\epsilon_V} \Big|_{k=aH}$$

$$\Delta_t^2(k) \approx \frac{2}{3\pi^2} \frac{V}{M_{\text{pl}}^4} \Big|_{k=aH}$$



$$n_s - 1 \equiv \frac{d \ln \Delta_s^2}{d \ln k} = 2\eta_V - 6\epsilon_V \quad r \equiv \frac{\Delta_t^2}{\Delta_s^2} = 16\epsilon_V$$

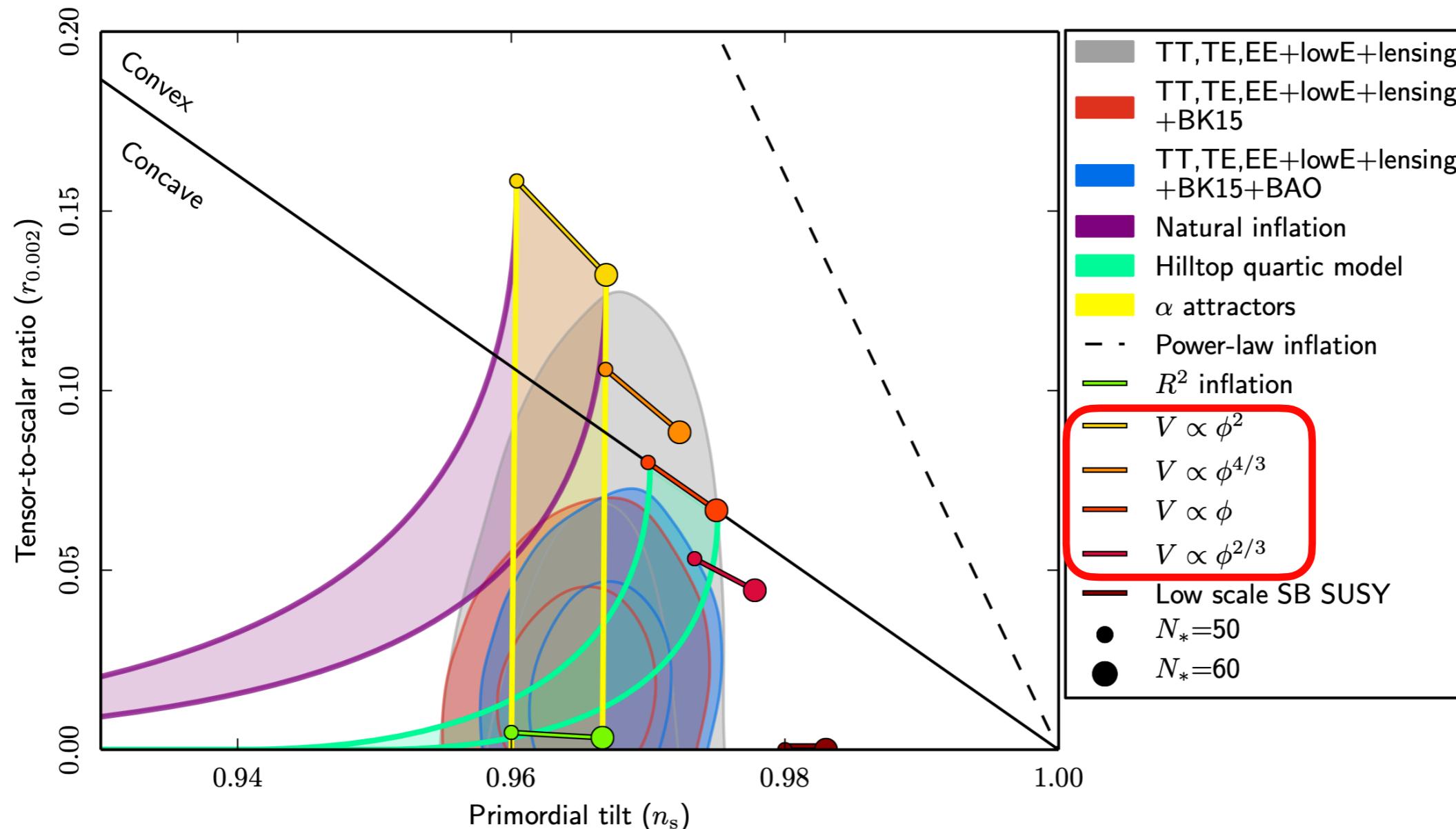
$$n_s \simeq 0.965$$

$$r \lesssim 0.056$$

$n=1$ to be scale invariant

tensor-scalar ratio

Current status



Concave potential is preferred by the data

Higgs inflation

Higgs is the only scalar field in SM

Bezrukov and Shaposhnikov, Phys.Lett.B 659 (2008) 703-706

$$S_J = \int d^4x \sqrt{-g_J} \left[\frac{M_P^2}{2} \left(1 + \boxed{\frac{\xi\phi^2}{M_P^2}} R_J \right) - \frac{1}{2} |\partial_\mu \phi|^2 - V_J(\phi) \right]$$

$$g_{\mu\nu} = \Omega(\phi)^2 g_{J\mu\nu} \quad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$\frac{d\chi}{d\phi} = \left(\frac{1 + \xi(1 + 6\xi)\phi^2/M_P^2}{(1 + \xi\phi^2/M_P^2)^2} \right)^{1/2}$$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V(\chi) \right] \quad V(\chi) \equiv V_J(\phi(\chi))/\Omega^4(\phi(\chi))$$

One word after inflation

When phi becomes small

$$V(\phi) = \frac{1}{2}m^2\phi^2$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

$$H^2 = \frac{1}{3} \left(\frac{1}{2}\dot{\phi}^2 + V(\phi) \right)$$

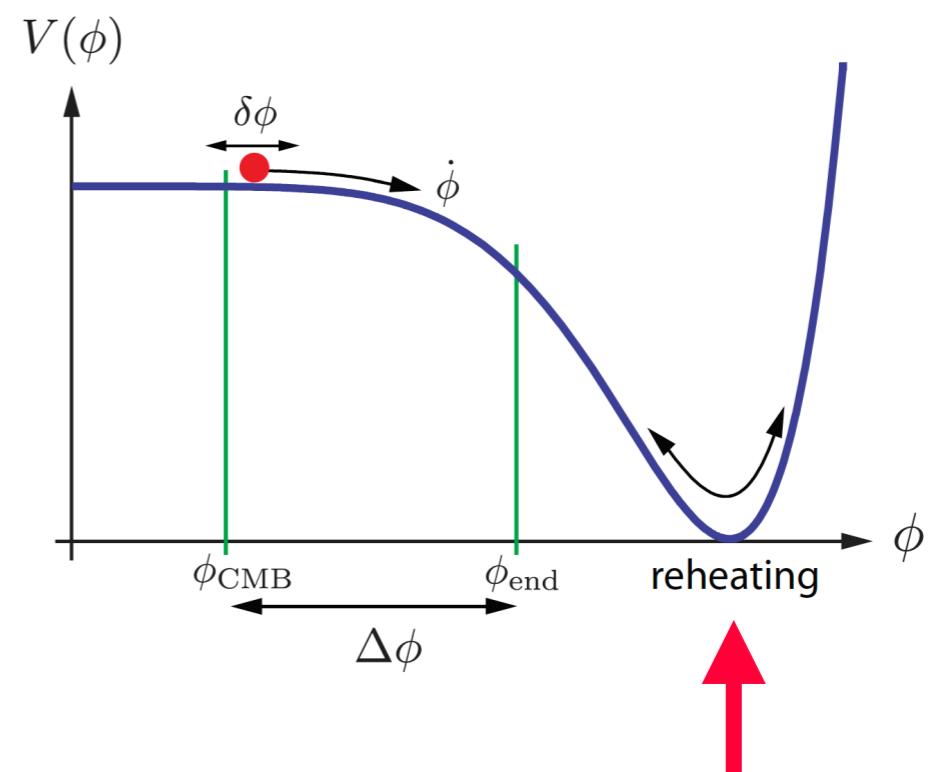
$$\phi(t) \sim \Phi(t) \cos(mt) \quad \Phi(t) = \frac{1}{mt}$$

$$H(t) \equiv \frac{\dot{a}}{a} \sim \frac{2}{3t} \quad \text{similar to matter dominate universe} \quad a(t) = t^{2/3}$$

Reheating at $\frac{1}{\Gamma_\phi} = \frac{1}{H} \sim \frac{M_P}{T_{rh}^2}$

$$T_{rh} \sim \sqrt{M_P \Gamma_\phi}$$

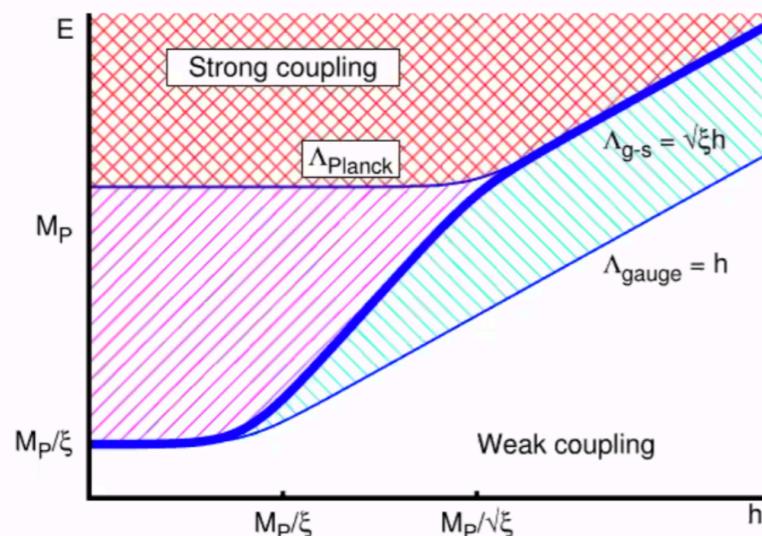
More complicated case: parametric resonance or tachyonic reheating



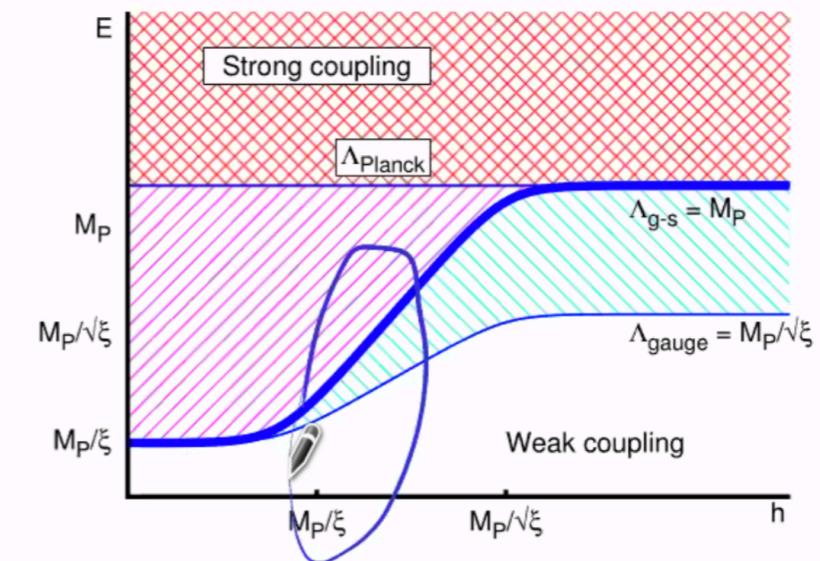
Unitary problem for Higgs inflation

Cut-off grows with the field background

Jordan frame



Einstein frame



Relation between cut-offs in different frames:

$$\Lambda_{\text{Jordan}} = \Lambda_{\text{Einstein}} \Omega$$

Relevant scales at inflation

$$\text{Hubble scale } H \sim \lambda^{1/2} \frac{M_P}{\xi}$$

Energy density at inflation

$$V^{1/4} \sim \lambda^{1/4} \frac{M_P}{\sqrt{\xi}}$$

Reheating temperature $M_P/\xi < T_{\text{reheating}} < M_P/\sqrt{\xi}$

Problems during reheating