Affleck-Dine Leptogenesis from Higgs Inflation

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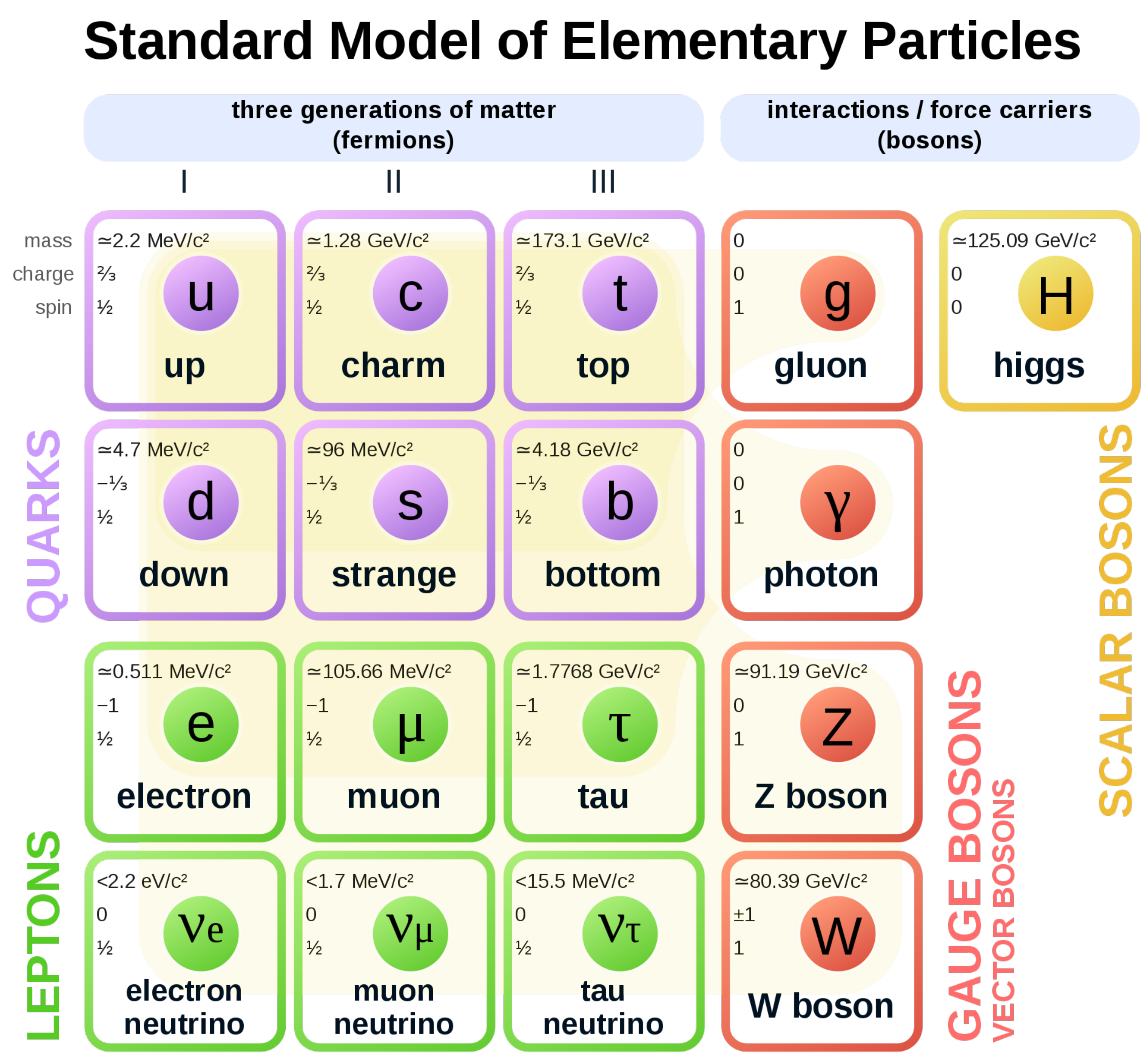
Based on the paper arXiv:2106.03381
with Neil D. Barrie and Hitoshi Murayama

TDLI
2021.6.15

Standard model



Very successful describing low energy scale physics

Observation requiring new physics

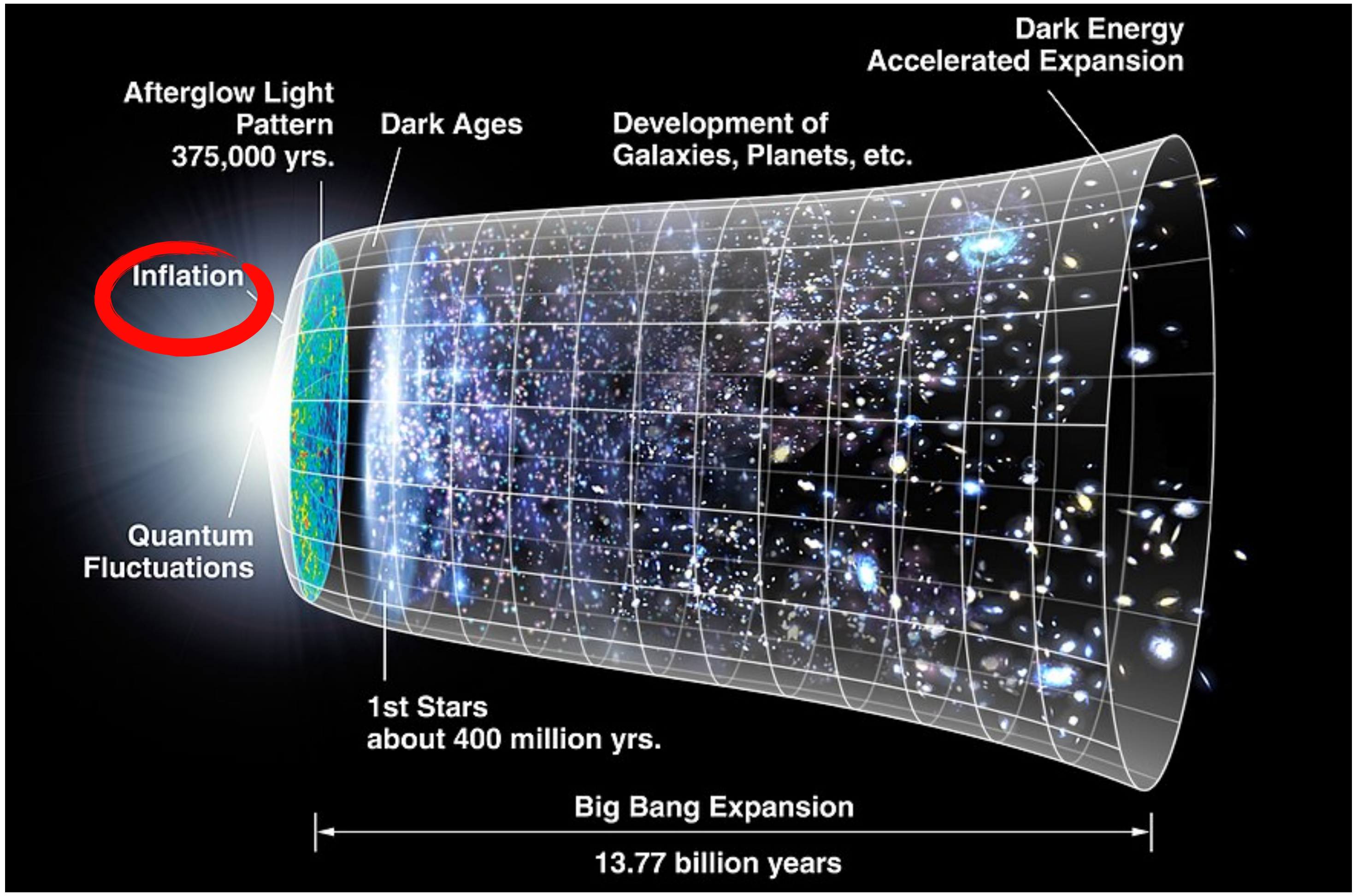
- Inflation
- Neutrino masses
- Baryon asymmetry of our universe

today's talk

- Dark matter
- Others(muon g-2?)

Inflation

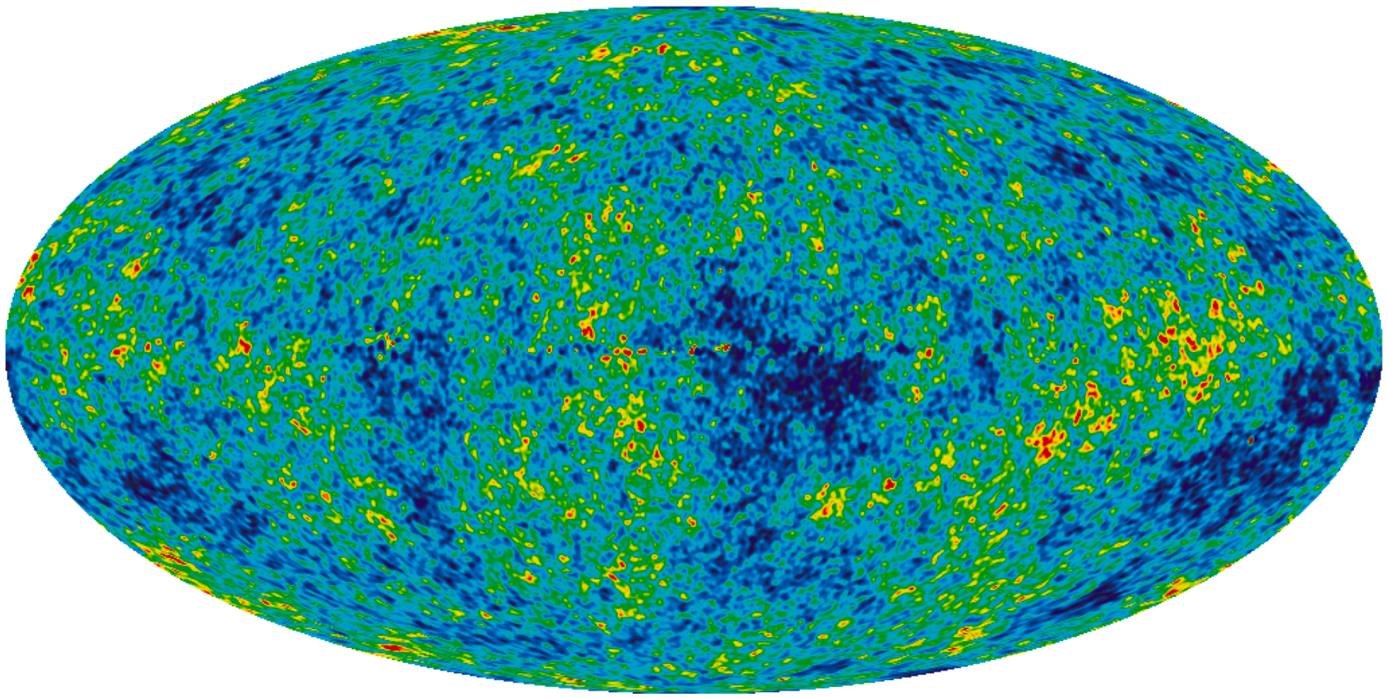
Expansion of the universe in the early time



- Flatness problem
- Horizon problem
- Monopole problem?

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

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

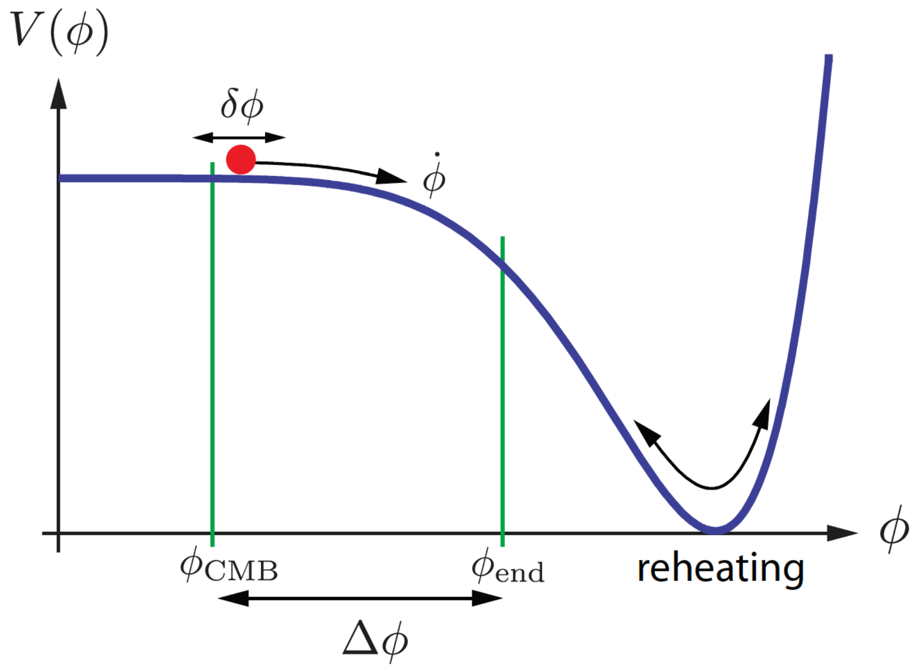
$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

Slow roll condition

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

$$\epsilon_{\rm v}(\phi) \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \eta_{\rm v}(\phi) \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V}$$

$$\epsilon_{\rm v}, |\eta_{\rm v}| \ll 1$$



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

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

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

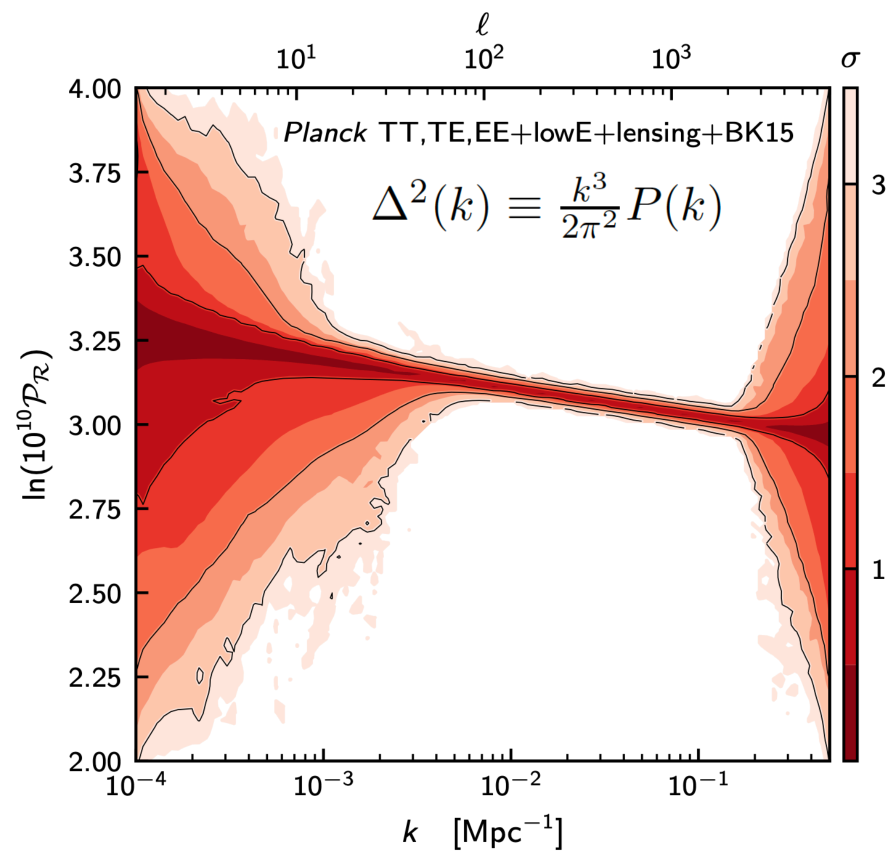
Daniel Baumann, TASI Lectures on Inflation

Slow roll inflation

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

$$\Delta_{\rm s}^2(k) \approx \frac{1}{24\pi^2}\frac{V}{M_{\rm pl}^4}\frac{1}{\epsilon_{\rm V}}\bigg|_{k=aH}$$

$$\Delta_{\rm t}^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}$$



$$n_{\rm s} - 1 \equiv \frac{d\ln\Delta_{\rm s}^2}{d\ln k} = 2\eta_{\rm V} - 6\epsilon_{\rm V}$$

$$r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\epsilon_{\rm V}$$

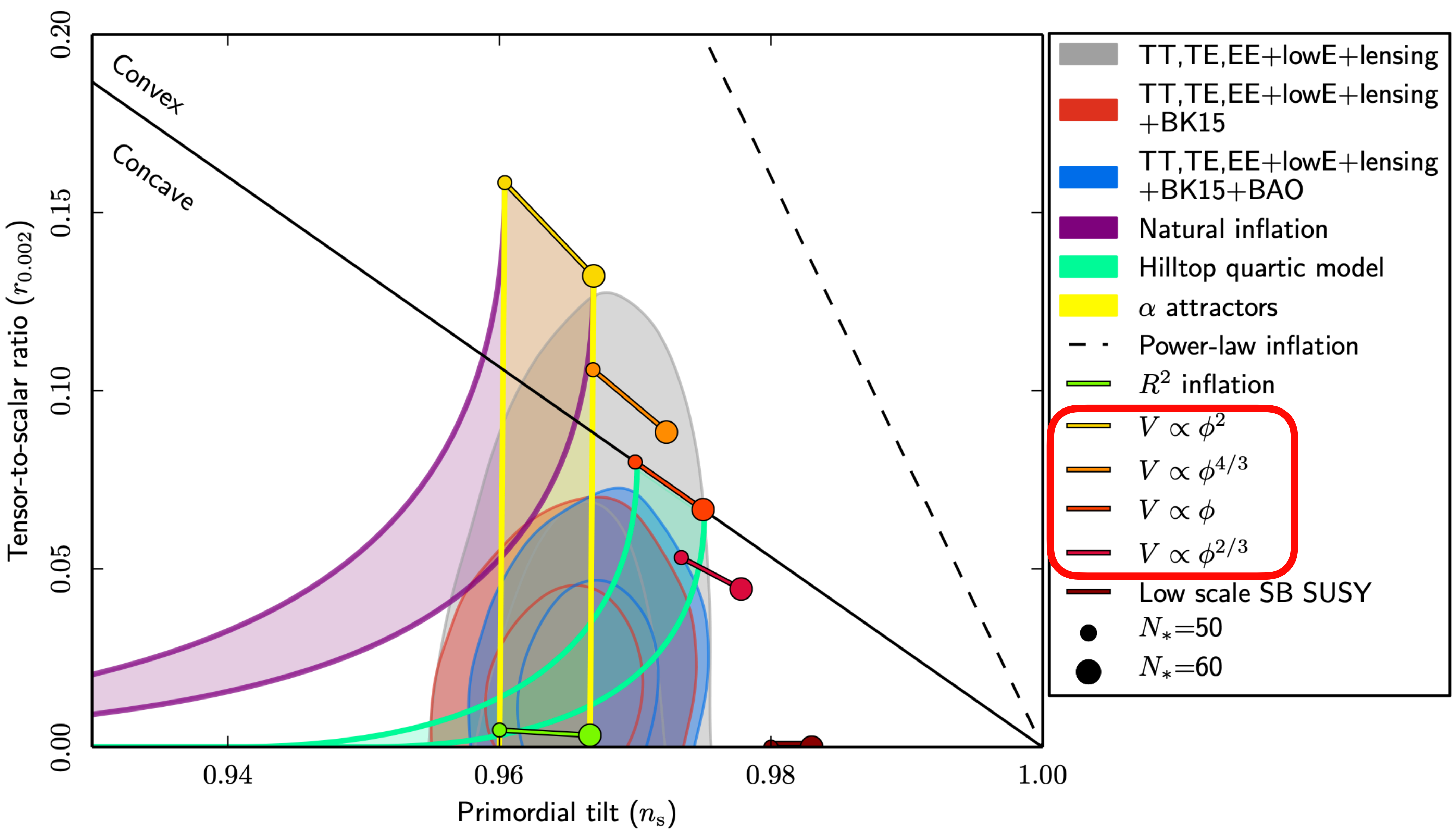
$n_s \simeq 0.965$

$r \lesssim 0.056$

n=1 to be scale invariant

tensor-scalar ratio

Current status



Concave potential is preferred by the data

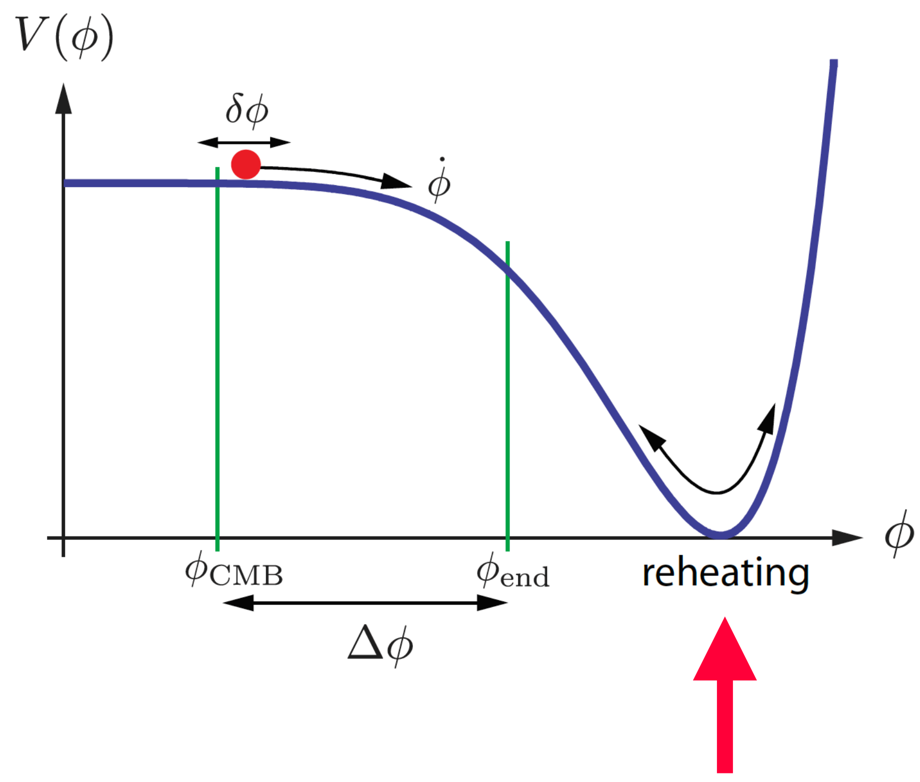
One word after inflation

When phi becomes small

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

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

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



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

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

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

More complicated case: parametric resonance or tachyonic reheating

Higgs inflation

Higgs is the only scalar field in SM

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

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

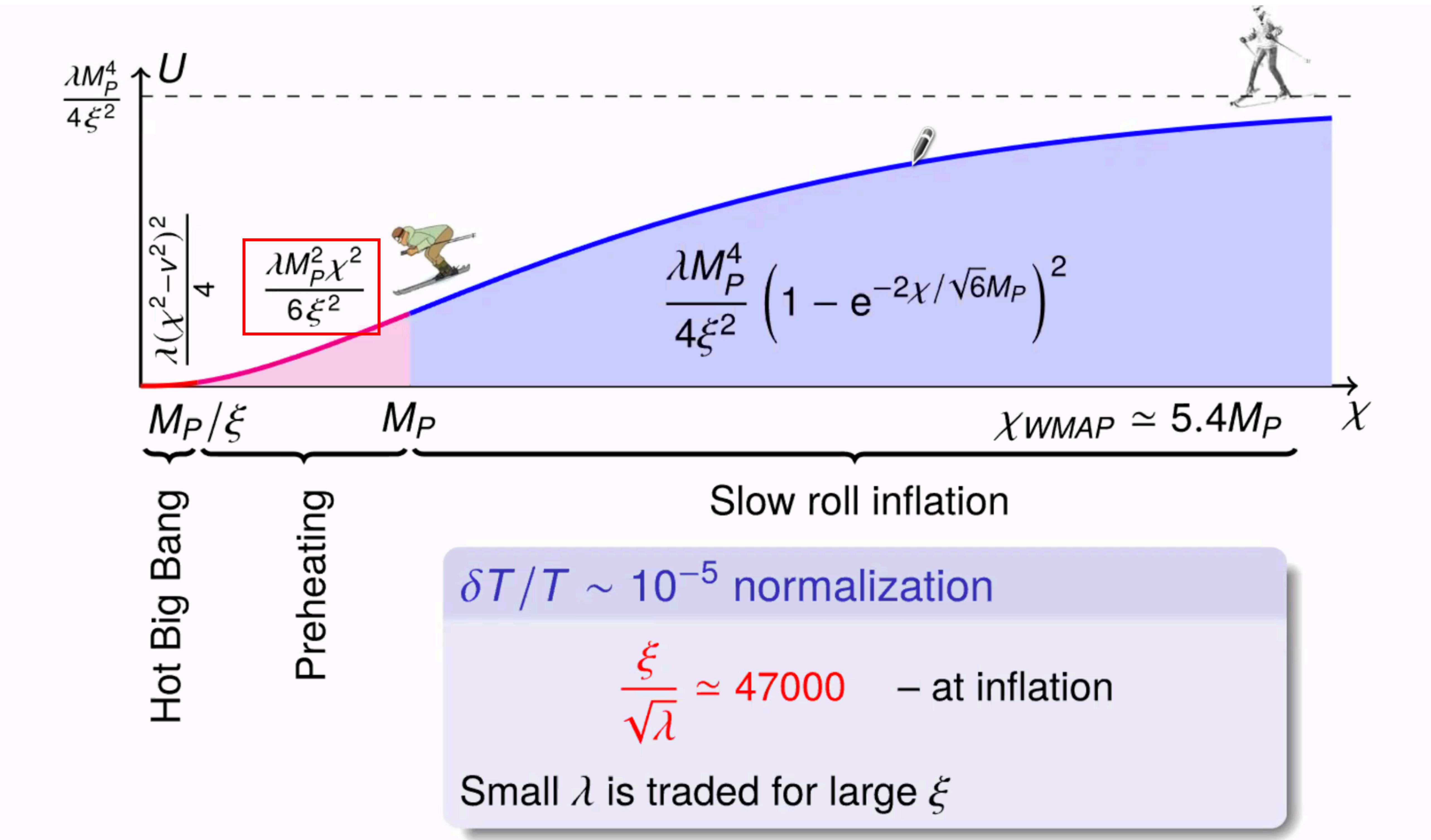
$$g_{\mu\nu} = \Omega(\phi)^2 g_{J\mu\nu} \qquad \Omega^2 = 1+\frac{\xi\phi^2}{M_P^2}$$

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

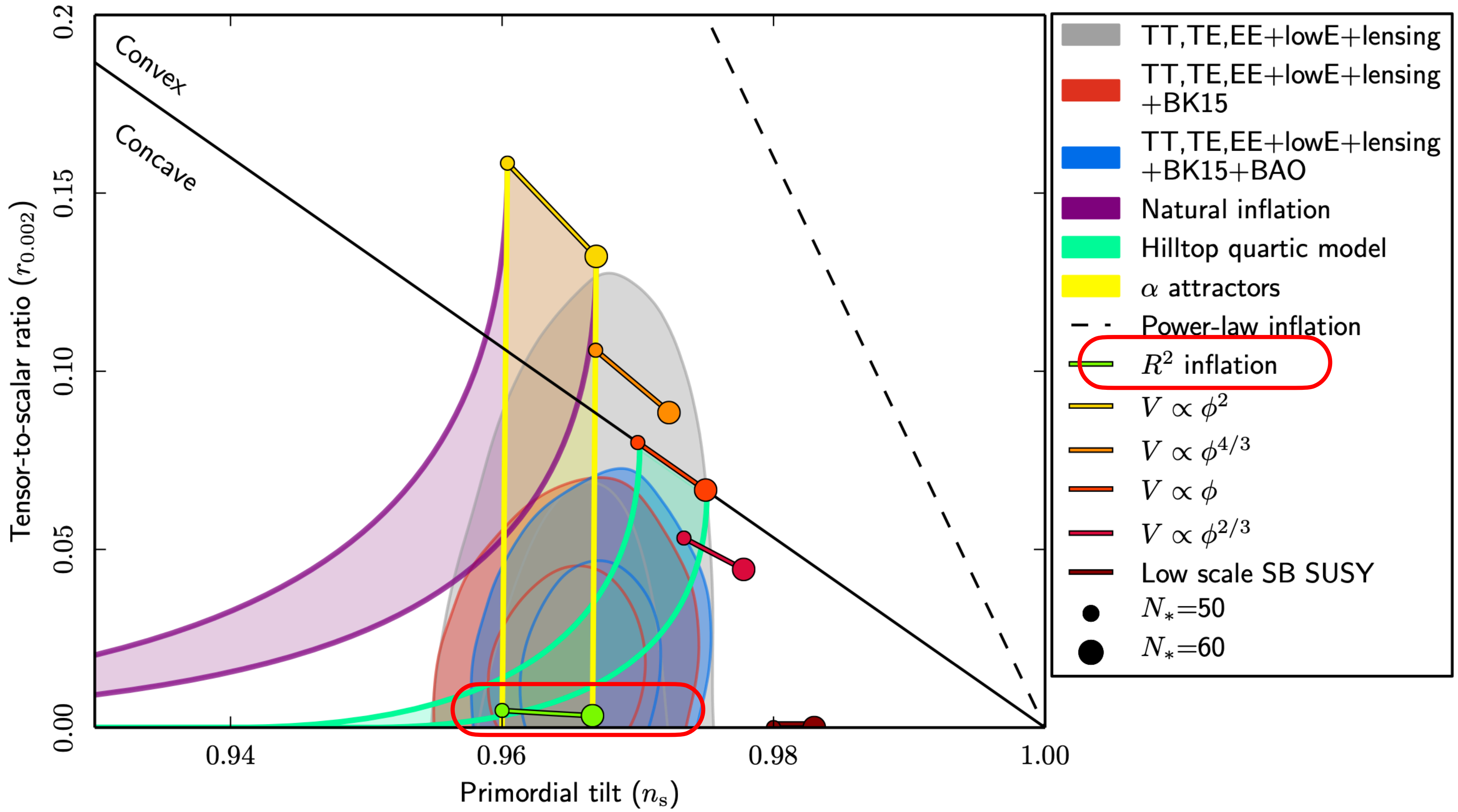
$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right] \qquad V(\chi) \equiv V_J(\phi(\chi))/\Omega^4(\phi(\chi))$$

Higgs inflation

Plot borrowed from Bezrukov



Higgs inflation

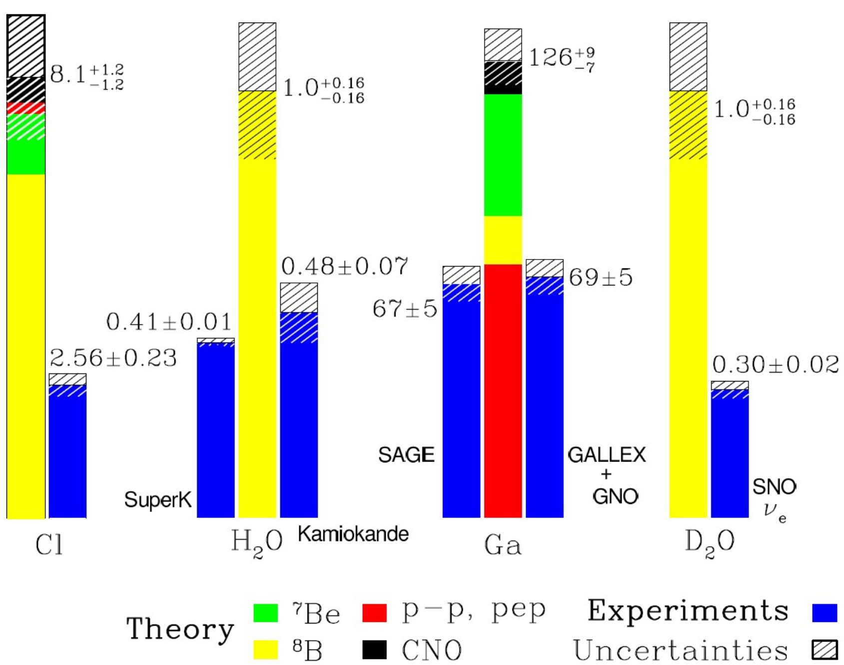


Problems to understand for this scenario

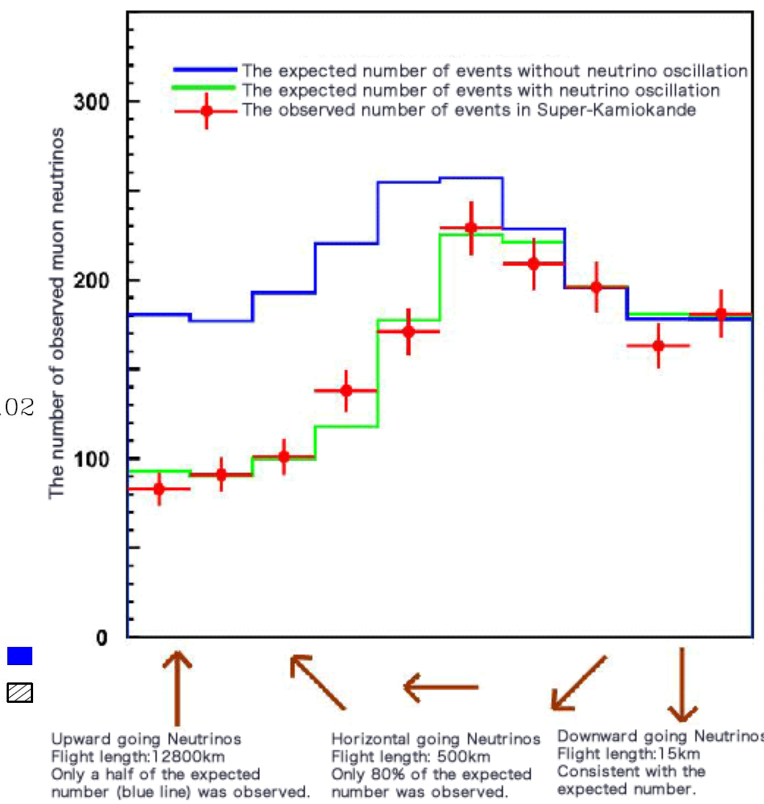
- Higgs instability problem
- Unitarity problem(during reheating)
- Reheating in Higgs inflation

Neutrino masses

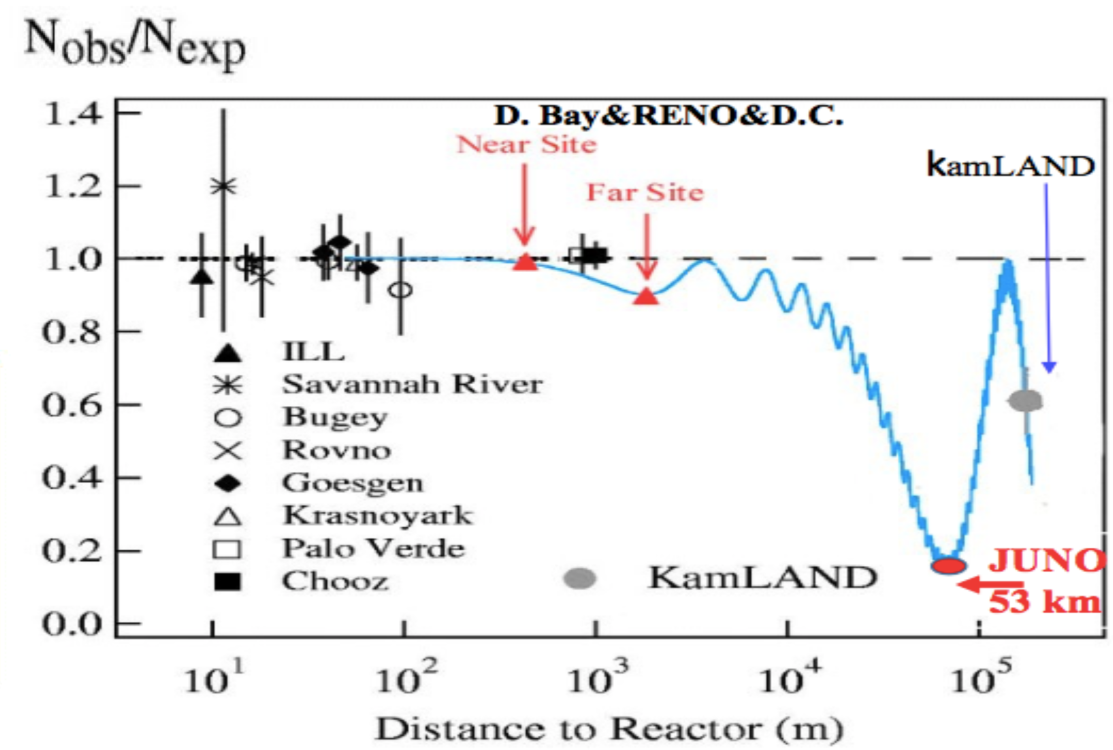
Neutrino oscillation requiring massive neutrinos



Solar Neutrino oscillations



Atmospheric Neutrino Oscillations



Reactor Neutrino Oscillations

$$\Delta m_{21}^2 \simeq 7.42 \times 10^{-5}\ \mathrm{eV}^2$$

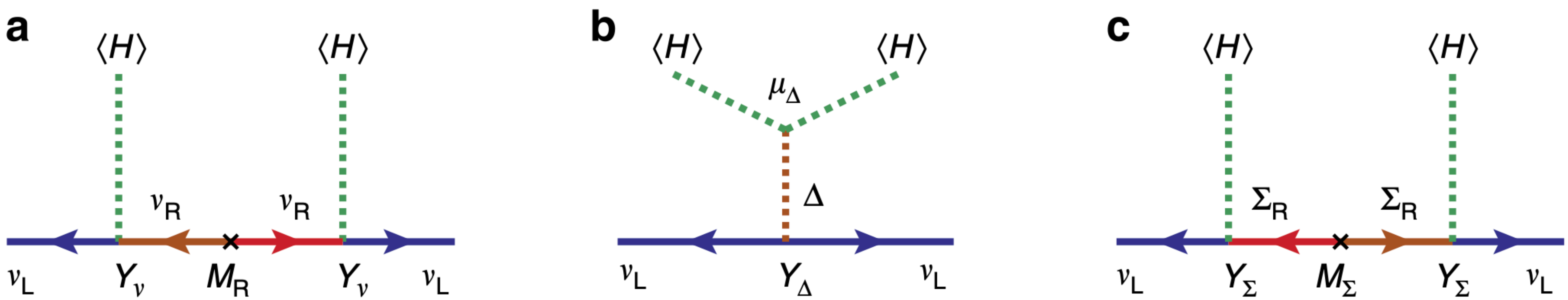
$$\Delta m_{13}^2 \approx \Delta m_{23}^2 \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

At least a neutrino mass larger or similar to 0.05 eV

Origin of neutrino masses

Three types of seesaw model(tree level)

Tommy Ohlsson, Shun Zhou, Nature Commun. 5 (2014) 5153



$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$

$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$

$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$

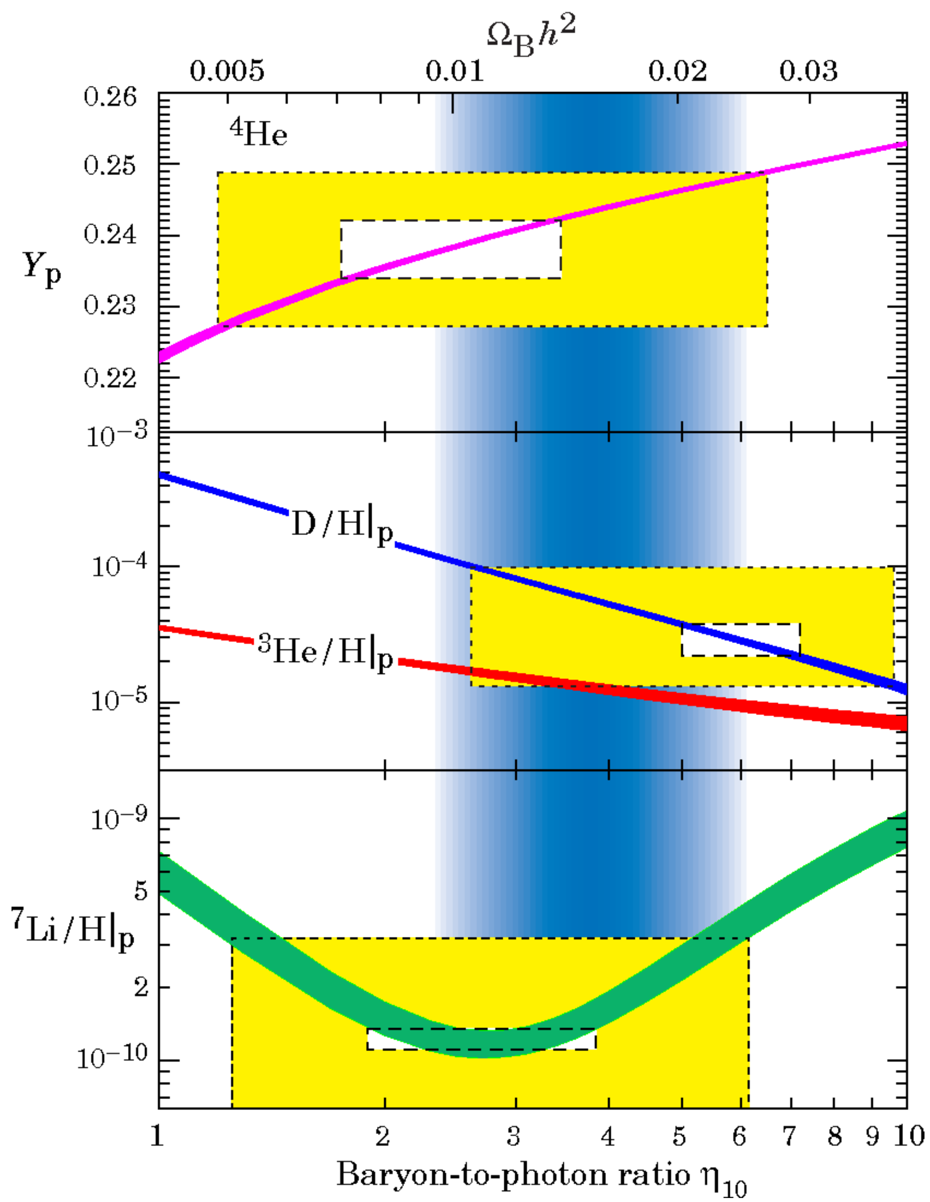
SM + 3 singlets

SM + 1 triplet Higgs

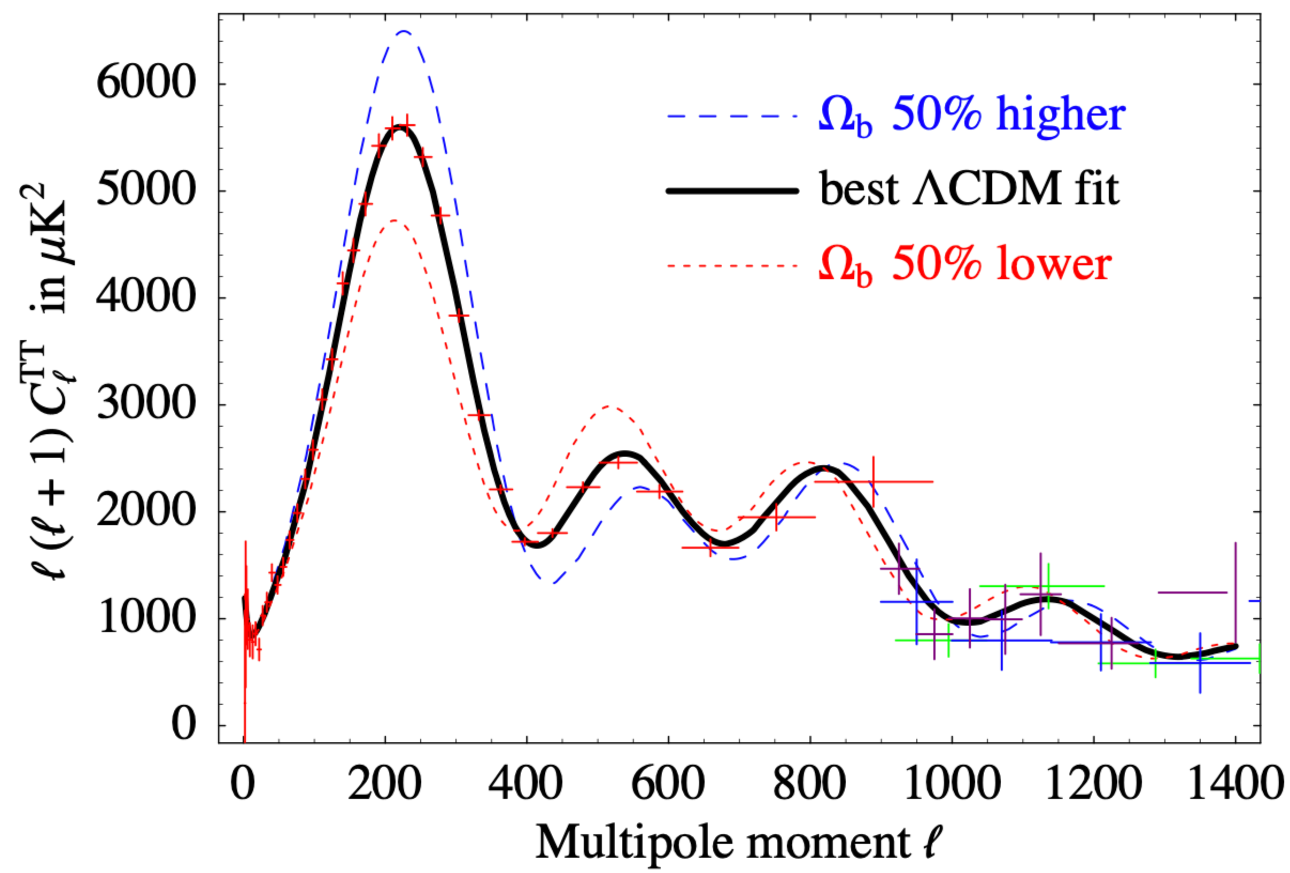
SM + 3 triplet fermions

Many people contribute, including people here

Baryon asymmetry of our universe



BBN



Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_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

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

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 $\not{C}P$

- 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'

Baryogenesis from Affleck-Dine mechanism

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

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

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

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

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

We can add a small U(1) breaking term

$$V = m^2 |\phi|^2 + \lambda(\phi^4 + \phi^{*4}) + \frac{|\phi|^6}{M^2}$$

Baryogenesis from Affleck-Dine mechanism

Equation of motion in an expansion of universe

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

Assuming a matter dominated universe(after inflation) $a(t) = t^{2/3}$

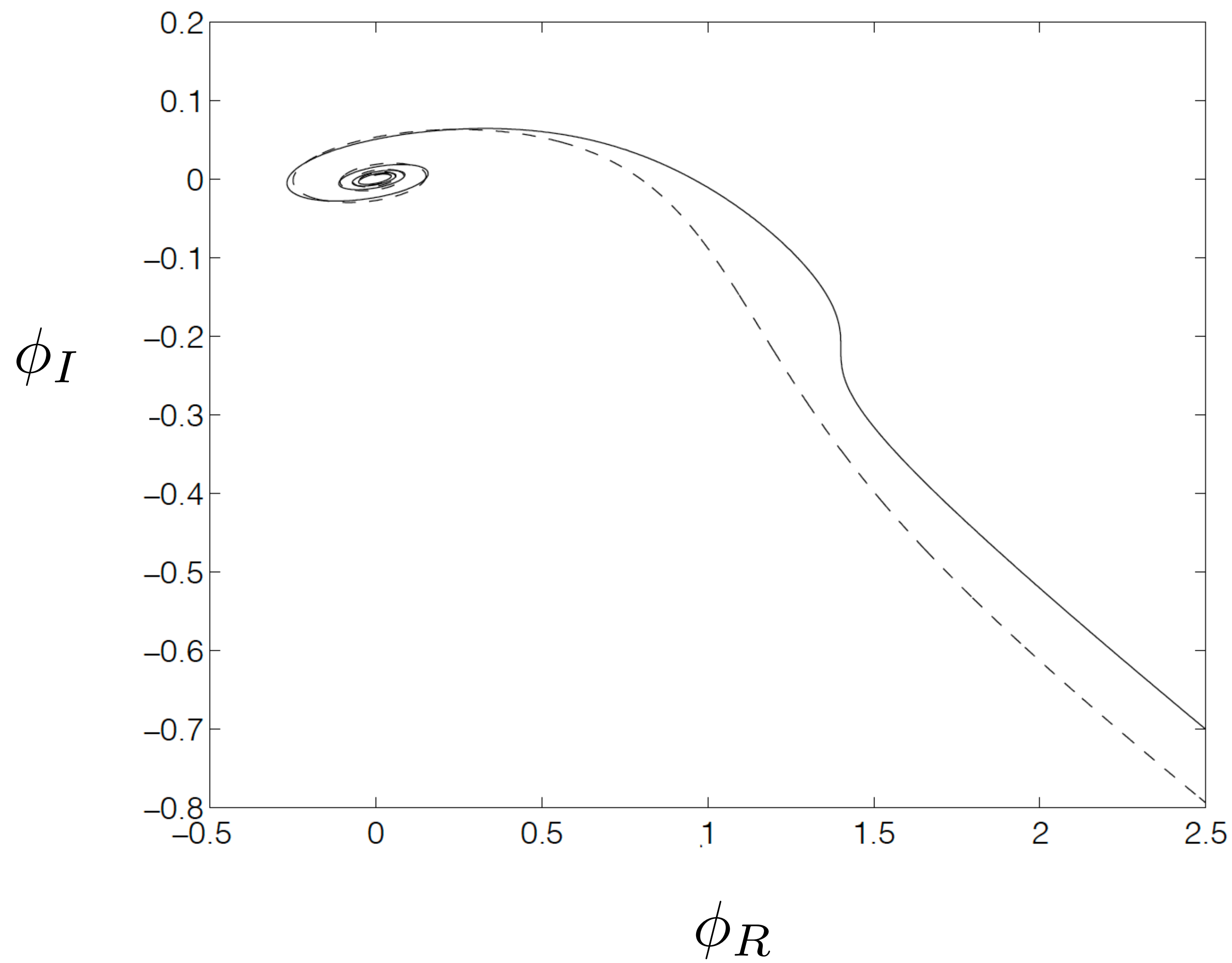
$$\phi_k = \frac{A_k}{mt}\sin(mt + \delta_k)\ , \quad k = I, R$$

$$n_B = 2(\phi_I \dot{\phi}_R - \phi_R \dot{\phi}_I) = \frac{2A_I A_R}{mt^2}\sin(\delta_i - \delta_R)$$

$$\phi = i\phi_0,\ \dot{\phi} = 0 \qquad A_I = \phi_0 \quad A_R = a_R \lambda \phi_0^3/m^2 \qquad \delta_I - \delta_R = 1.54$$

$$n_B = \frac{1.7\lambda\phi_0^4}{m^3 t^2}$$

Baryogenesis from Affleck-Dine mechanism



CP violation appears when $\langle \phi_2 \rangle \neq 0$

Baryogenesis from Affleck-Dine mechanism

An approximation

Only from U(1) breaking term

$$\dot{n}_B + 3Hn_B = \boxed{\mathrm{Im}\left(\phi\frac{\partial V}{\partial \phi}\right)} \qquad n_B \sim \frac{nc_n\phi_0^n}{m^3t^2}$$

At $\quad t_0 = 1/H \sim 1/m \qquad n_B(t_0) \sim 4\lambda\phi_0^4/m \qquad a(t) = t^{2/3}$

$$n_B(t) \sim n_B(t_0)(t_0/t)^2 = \frac{4\lambda\phi_0^4}{m^3t^2}$$

Baryogenesis from Affleck-Dine mechanism

Important questions to answer

- What are the scalar field carrying baryon number?
- Why the quartic-term and breaking term so small(flat)?
- How are the scalars converted to SM particles?

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,

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

Phi is the mixing state of H and L with mixing angle pi/4

Affleck-Dine mechanism for SUSY

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

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

Including the SUSY breaking (supergravity mediation)

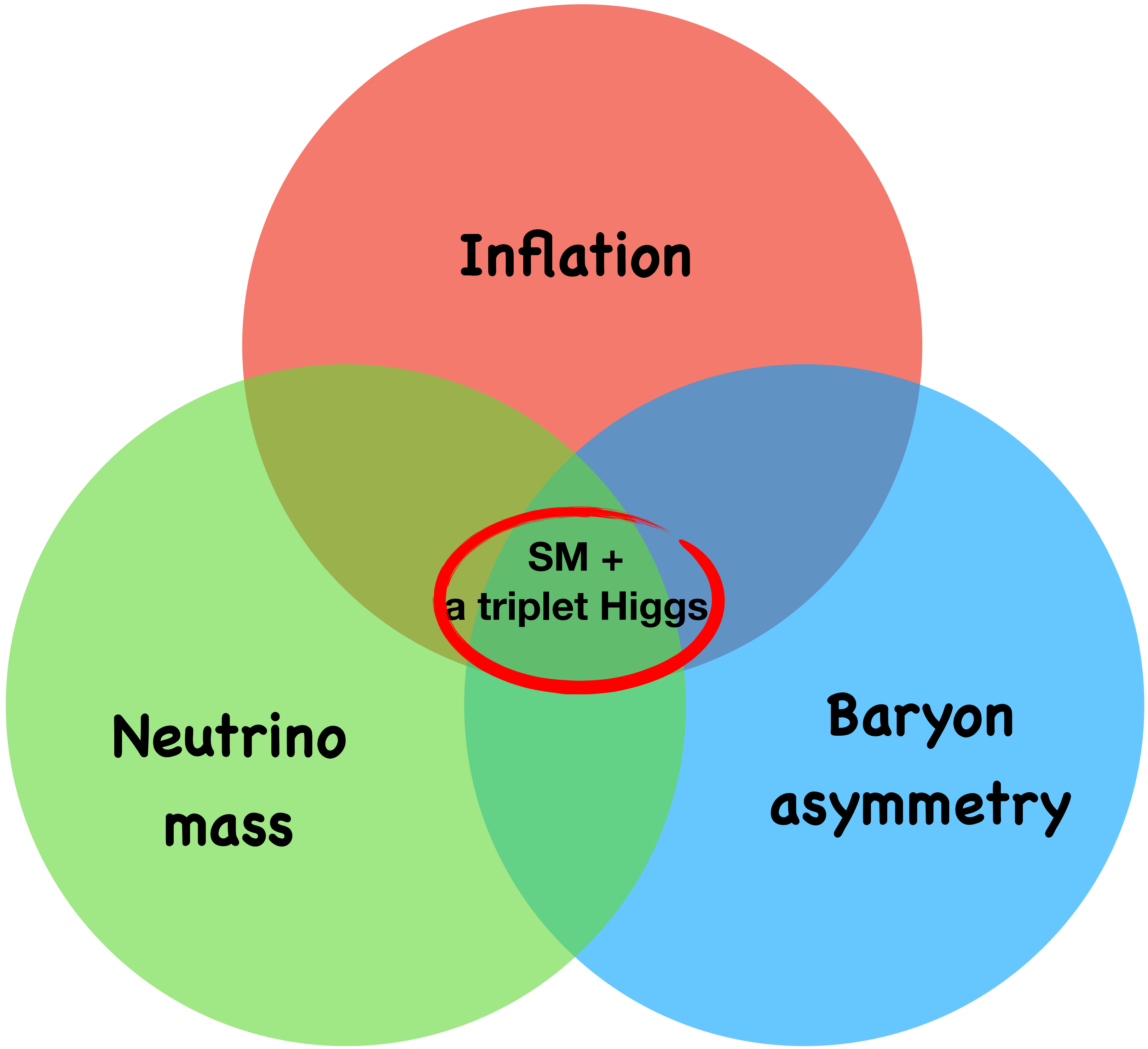
$$V(\phi) = m^2|\phi|^2 + \boxed{(\frac{2A}{M}\phi^4 + h.c)} + \frac{4}{M^2}|\phi|^6$$

U(1)L breaking term

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

Coupling with inflaton providing an initial condition

Do we have a simple extension of SM combining all above ideas and addressing three problems? Yes!



SM + a triplet Higgs

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

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

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

Giving neutrino mass matrix
Delta get a lepton number -2

SM + a triplet Higgs

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

$$\begin{aligned}
V(H,\Delta) = & -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) \\
& + \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) \\
& + \lambda_2 (\mathrm{Tr}(\Delta^\dagger \Delta))^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \\
& + \left[\mu (H^T i\sigma^2 \Delta^\dagger H) + \frac{\lambda_5}{M_P} (H^T i\sigma^2 \Delta^\dagger H)(H^\dagger H) \right. \\
& \left. + \frac{\lambda_5'}{M_P} (H^T i\sigma^2 \Delta^\dagger H)(\Delta^\dagger \Delta) + h.c. \right] + \ldots
\end{aligned}$$

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

U(1)L breaking term

Similar to the case of SUSY, we need mixing H and Delta

SM + a triplet Higgs

Adding non-minimal couplings for inflation

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

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

SM + a triplet Higgs

$$h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta}, \quad \Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$$

$$f(H,\Delta) = \xi_H|h|^2 + \xi_\Delta|\Delta^0|^2 = \frac{1}{2}\xi_H\rho_H^2 + \frac{1}{2}\xi_\Delta\rho_\Delta^2$$

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

$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha \simeq \sqrt{\frac{2\lambda_\Delta\xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H\xi_\Delta - \lambda_{H\Delta}\xi_H}}$$

$$\rho_H = \varphi\sin\alpha, \; \rho_\Delta = \varphi\cos\alpha,$$
$$\xi \equiv \xi_H\sin^2\alpha + \xi_\Delta\cos^2\alpha \; .$$

Similar to SUSY case, mixing with an angle alpha

SM + a triplet Higgs

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_P^2 R - \frac{1}{2}\xi\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi$$

$$-\boxed{\frac{1}{2}\varphi^2\cos^2\alpha}\, g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi,\theta)\ ,$$

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

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

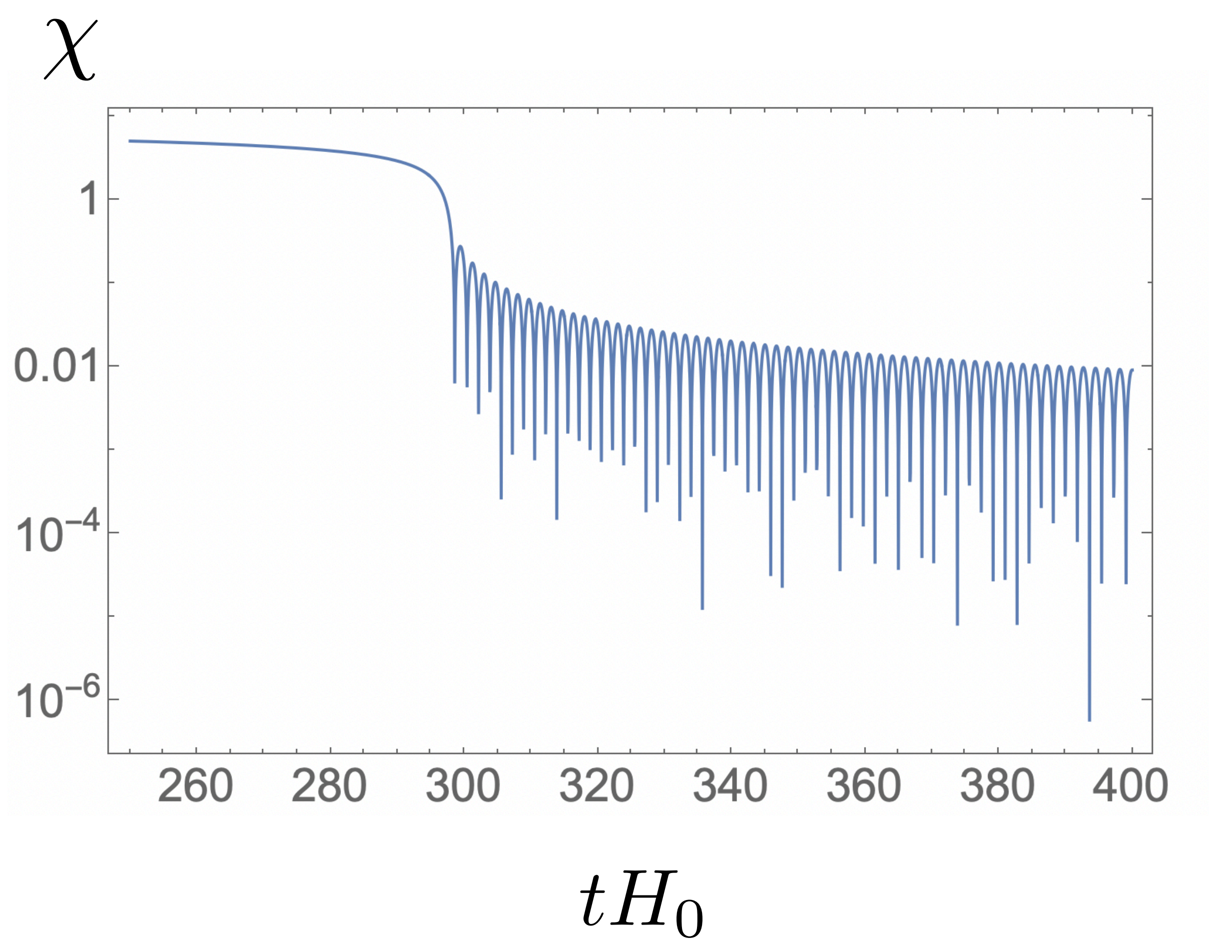
SM + a triplet Higgs: inflation + reheating

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

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

SM + a triplet Higgs: inflation + reheating

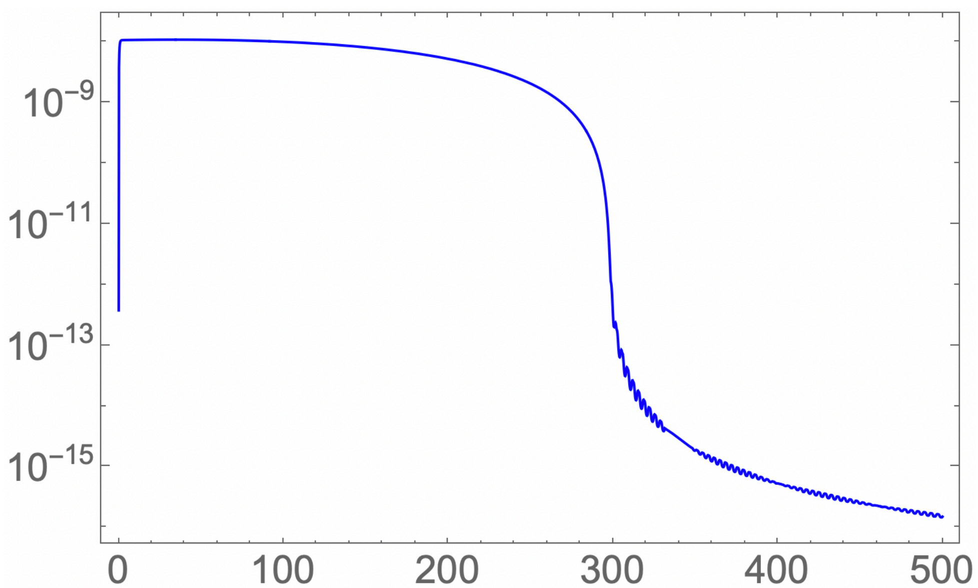
$$\ddot{\chi} - \frac{1}{2} f'(\chi)\dot{\theta}^2 + 3H\dot{\chi} + U_{,\chi} = 0$$



SM + a triplet Higgs: baryon number

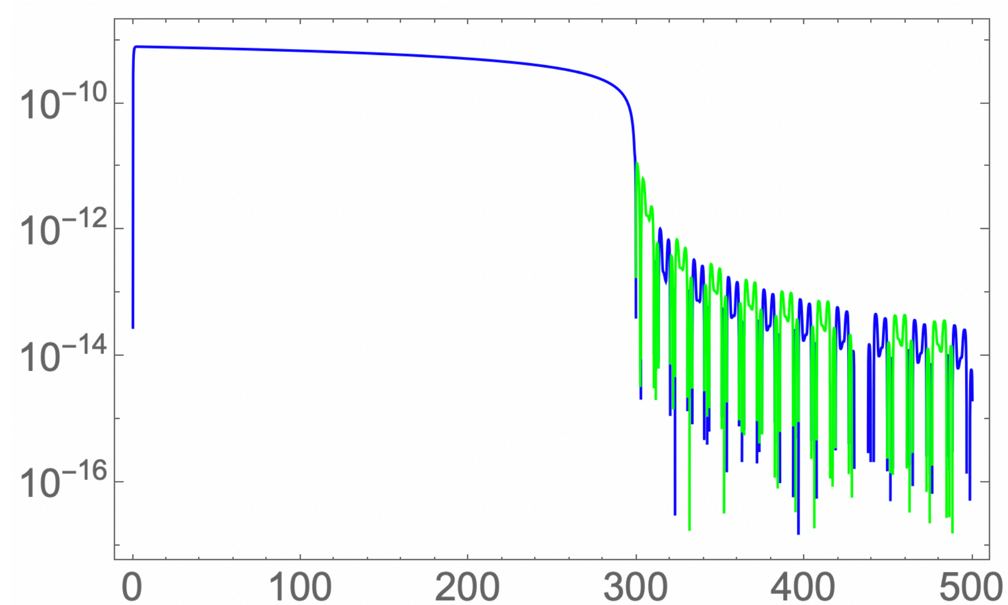
$$\ddot{\theta} + \frac{f'(\chi)}{f(\chi)}\dot{\theta}\dot{\chi} + 3H\dot{\theta} + \frac{1}{f(\chi)}U_{,\theta} = 0 \qquad n_L = Q_L \phi^2(\chi)\dot{\theta}\cos^2\alpha$$

n_L $\quad c_3 = 0, \; c_5 = 10^{-10}$



$tH_0 \qquad H_0 \sim m_S/2$

n_L $\quad c_3 = 10^{-11}, \; c_5 = 0$

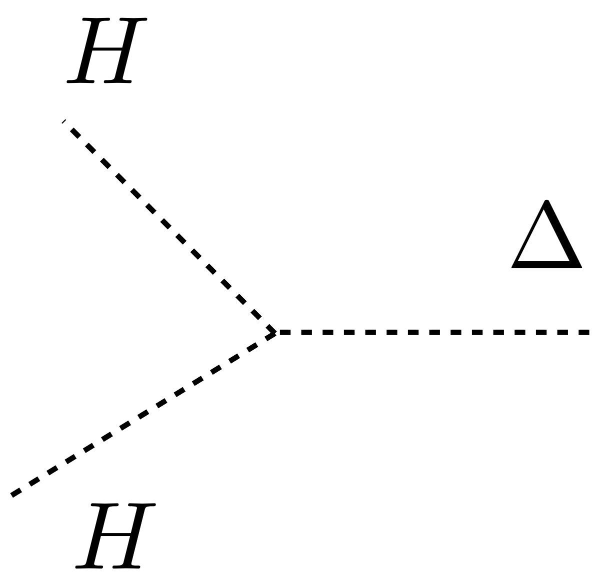


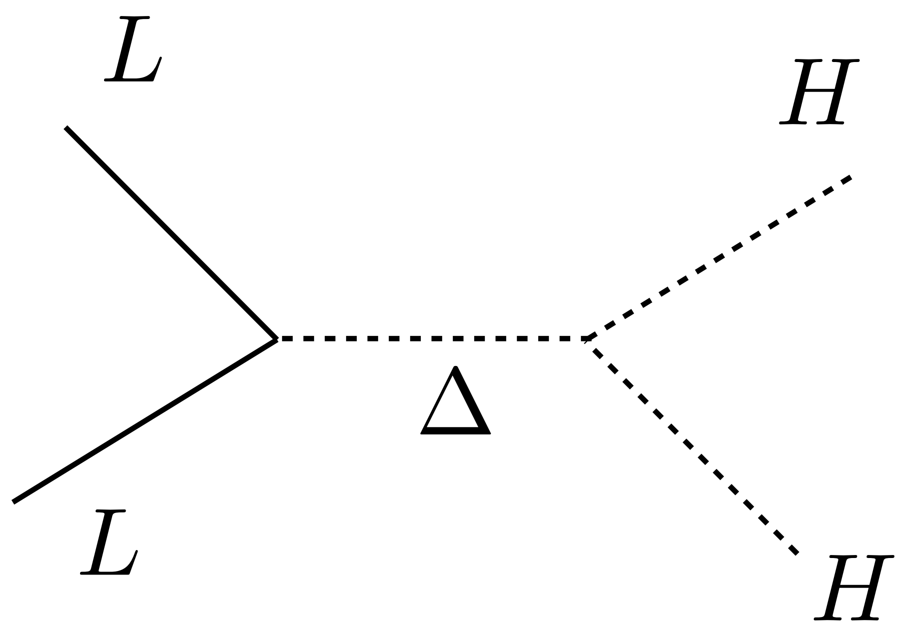
tH_0

C3 term should not be too large, otherwise baryon number oscillates

A small C3 term also benefit from washout process, see next

Wash out process





$$\frac{\mu^2}{8\pi m_\Delta} < H(m) = \frac{m_\Delta^2}{M_P}$$

$$m_\Delta < 10^{12}\ \mathrm{GeV}$$

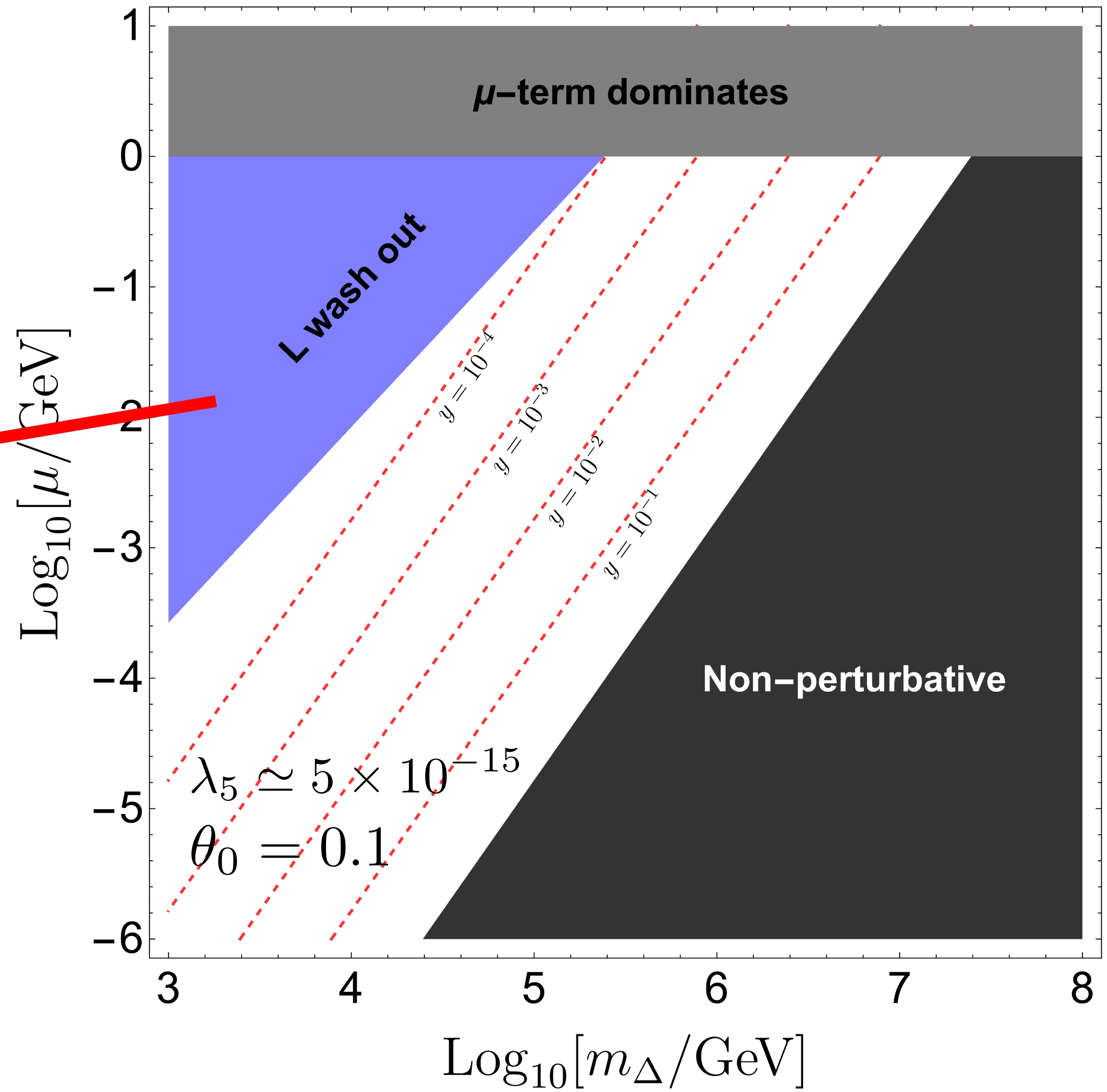
A small mu term is preferred

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

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



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

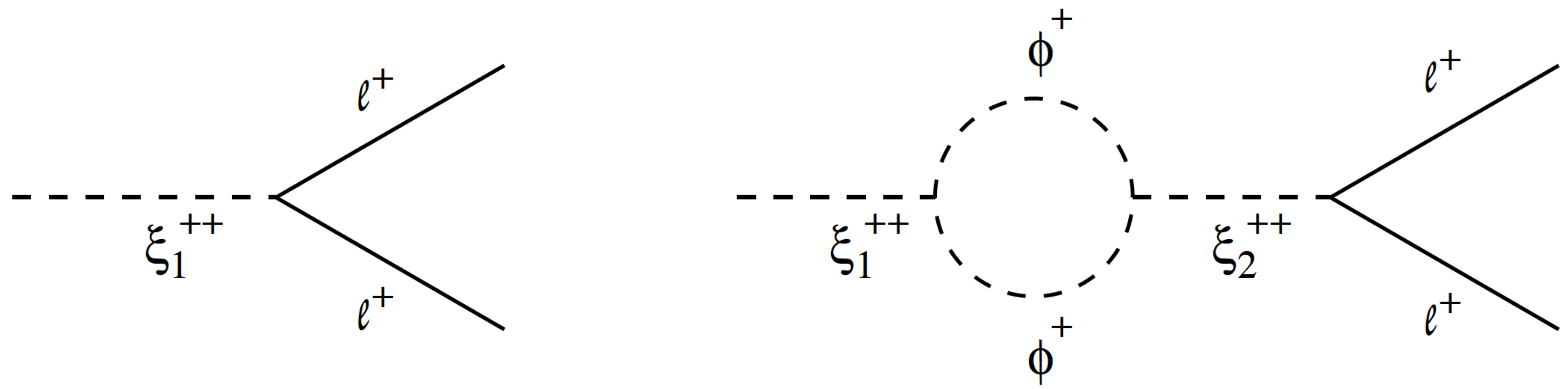
(at least one neutrino mass 0.05 eV)

One word on 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



At least two triplet Higgs are needed to generate the baryon asymmetry

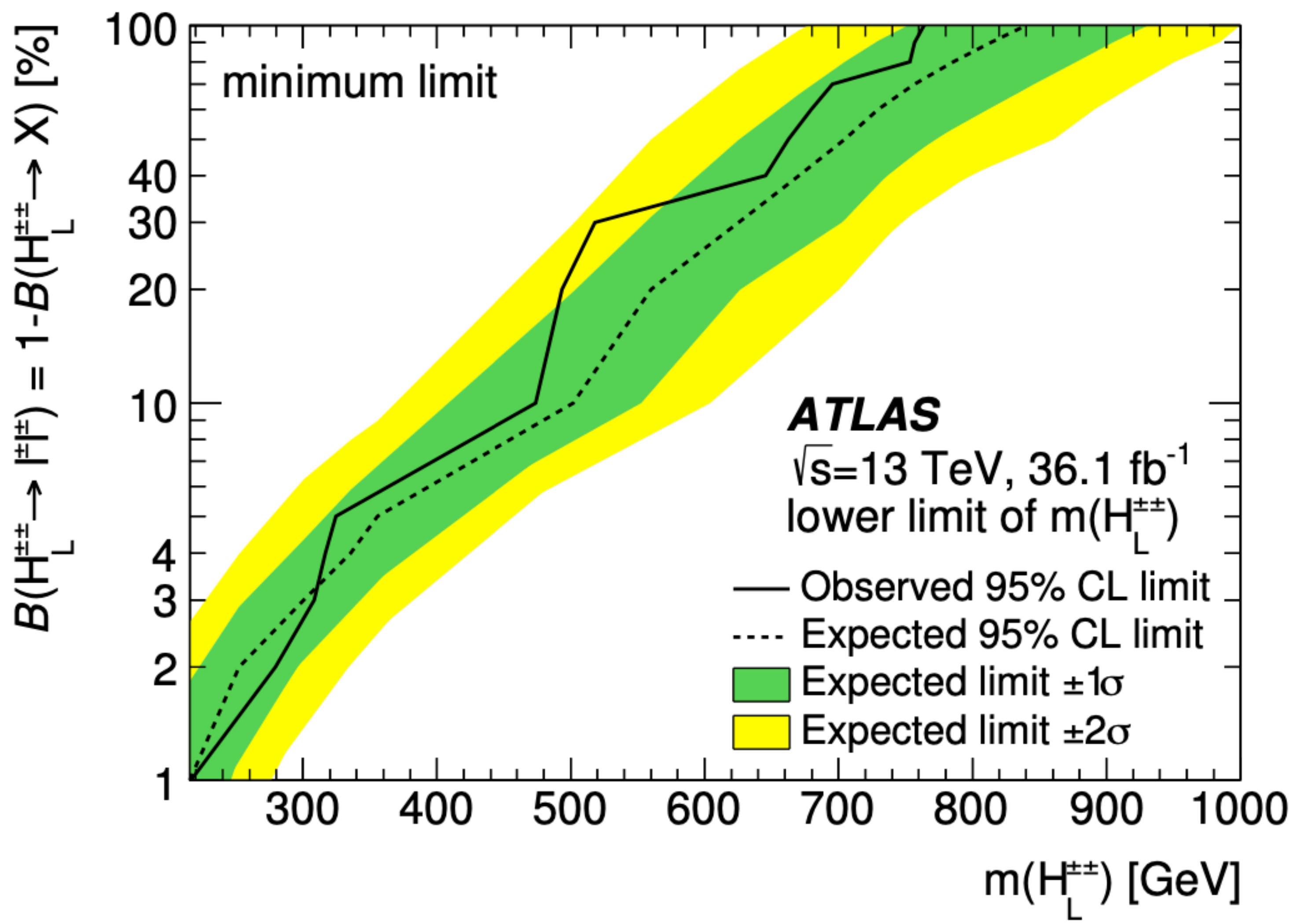
Or one triplet Higgs + right-handed neutrino

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

Indication for low energy physics

Current limit from LHC

ATLAS, Eur. Phys. J. C 78 (2018) 199

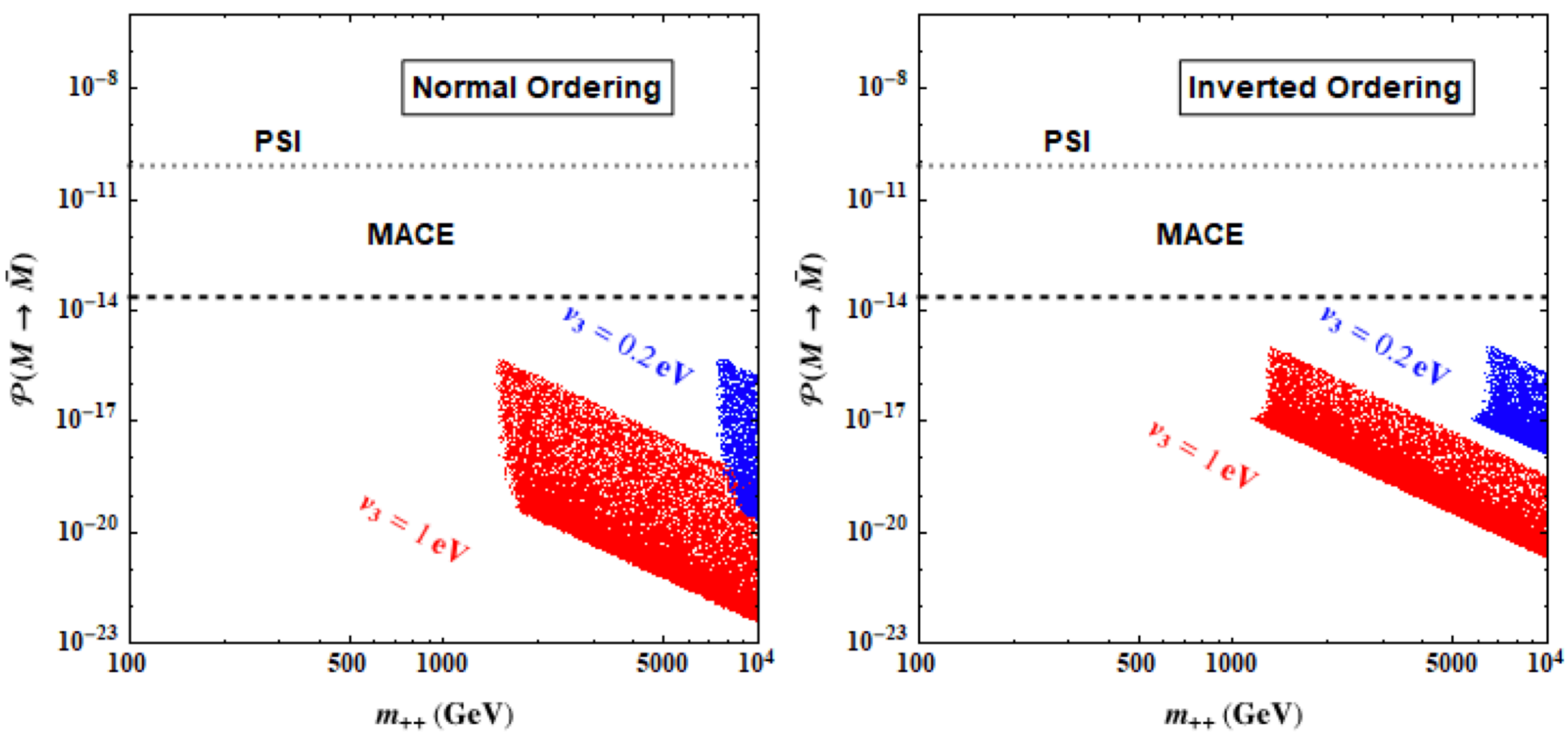


Indication for low energy physics

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

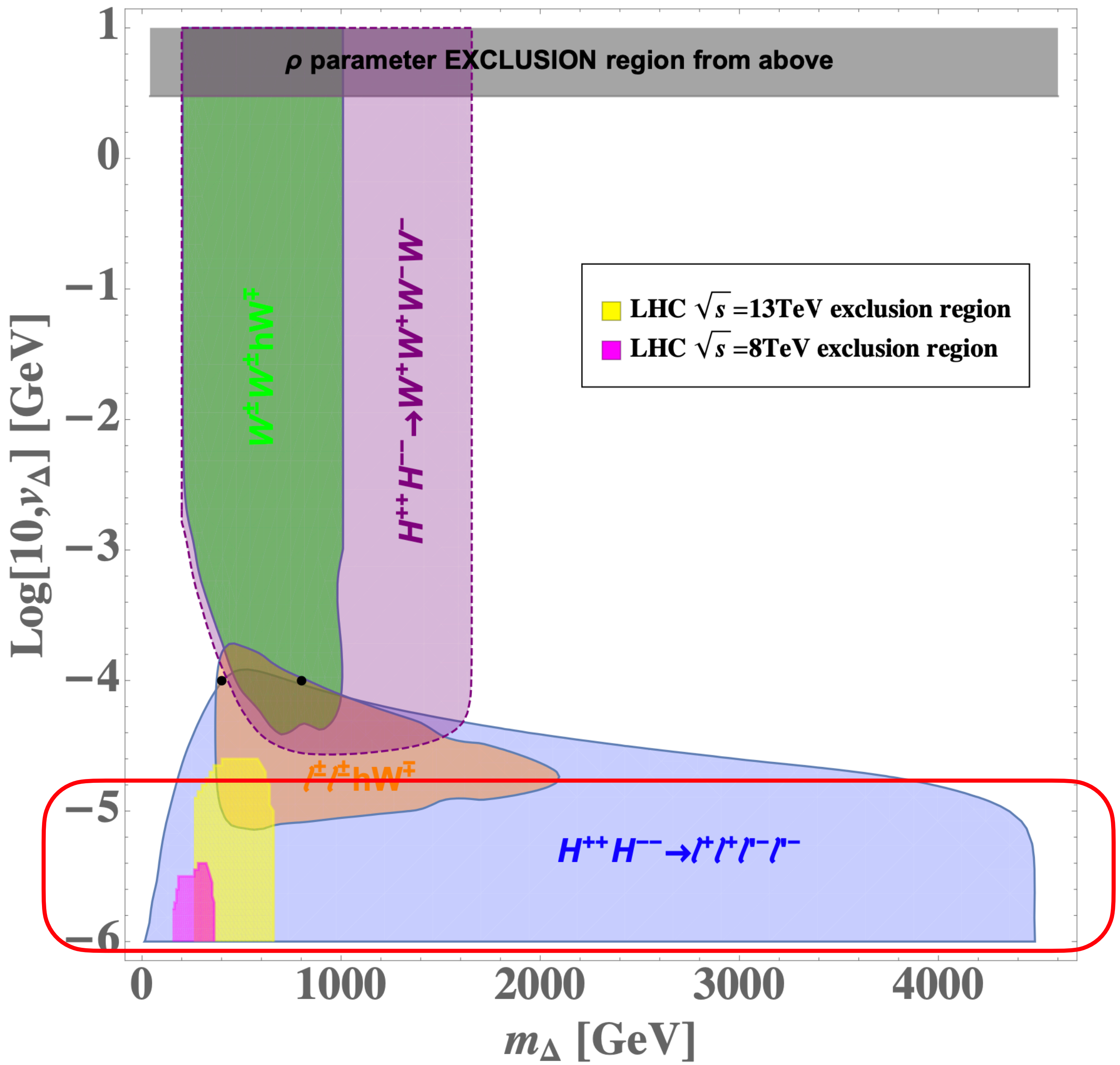
$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha}{768\pi} \frac{\left|(y_N^\dagger y_N)_{e\mu}\right|^2}{G_F^2} \left(\frac{1}{m_+^2} + \frac{8}{m_{++}^2}\right)^2 \qquad \mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

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 ~ 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

Back up

Motion of theta

During inflation

$$\ddot{\theta} + 3H\dot{\theta} + C_{\rm inf}\sin\theta \simeq 0 \qquad C_{\rm inf} \simeq \frac{2M_p^2\tilde{\lambda}_5}{\xi^{3/2}\cos^2\alpha}\sqrt{e^{\sqrt{\frac{2}{3}}\frac{\chi}{M_p}} - 1}$$

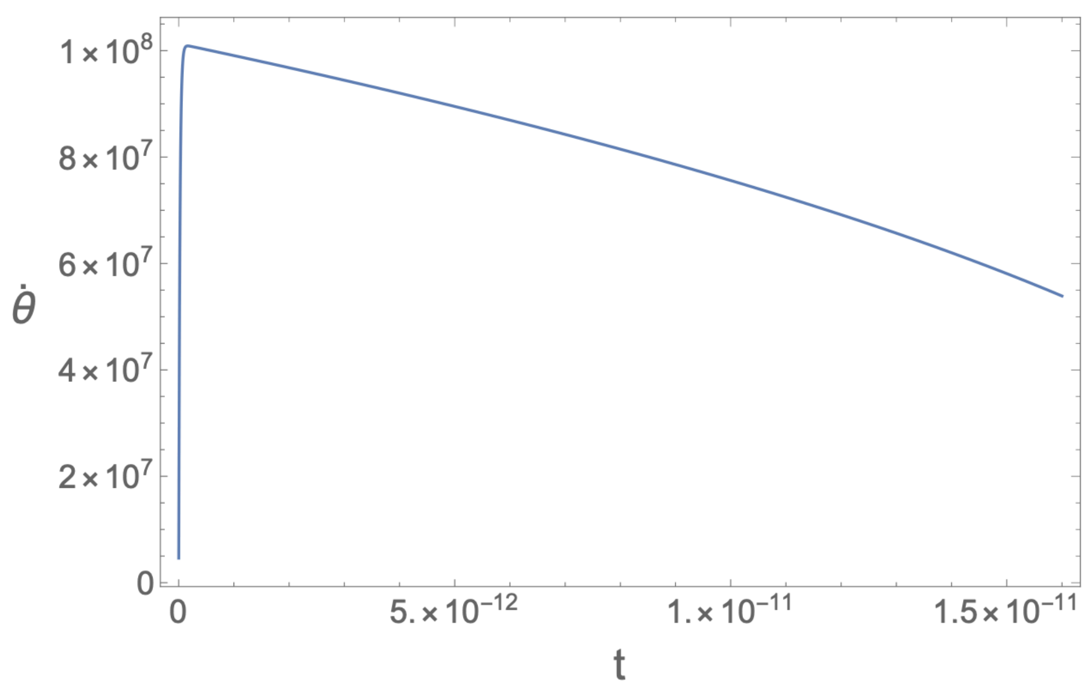
In the beginning, $\dot{\theta} = 0$

$$\ddot{\theta} \approx C_{\rm inf}\sin\theta \qquad \dot{\theta} \simeq \theta_0\sqrt{C_{\rm inf}}(e^{\sqrt{C_{\rm inf}}t} - 1)$$

After few e-folding

$$3H\dot{\theta} \approx C_{\rm inf}\sin\theta$$

$$\dot{\theta} \approx \frac{C_{\rm inf}\theta_0}{3H}$$



Limit from isocurvature perturbation

$$\langle \delta\theta^2 \rangle \approx \frac{1}{4\pi^2}\frac{H_i^2}{\chi_0^2} \qquad \frac{\delta n_b}{n_b} = \cot(\theta_0)\delta\theta$$

$$\left(\frac{\delta T}{T}\right)_{iso} = -\frac{6}{15}\frac{\Omega_b}{\Omega_m}\frac{\delta n_b}{n_b}$$

$$\left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle_{iso} \approx \frac{9}{225\pi^2}\frac{\Omega_b^2}{\Omega_m^2}\frac{H_i^2}{\chi_0^2}\cot^2(\theta_0) \qquad \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle_{adi} \approx \frac{1}{20}\frac{H_i^2}{8\pi^2 M_p^2 \epsilon}$$

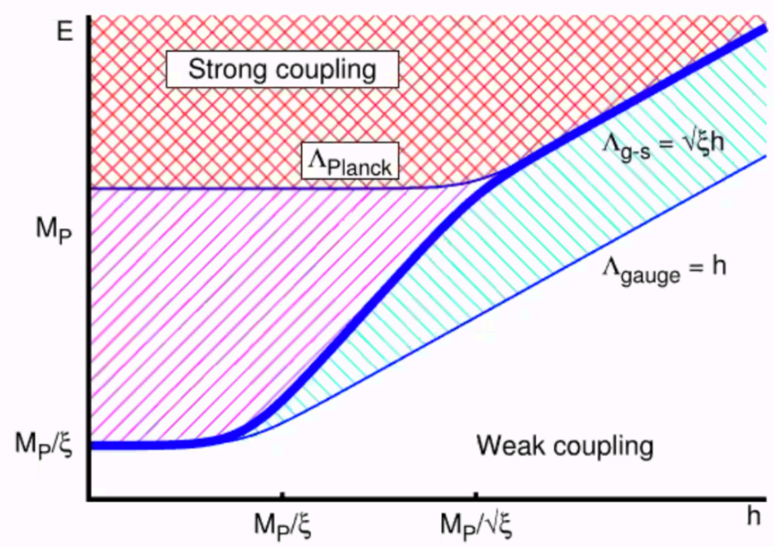
$$\alpha_{\text{non-adi}} = \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle_{iso} / \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle_{adi} = \frac{24\cot^2(\theta_0)}{5N^2}\frac{\Omega_b^2}{\Omega_m^2}\frac{M_p^2}{\chi_0^2}\,.$$

$$\alpha_{\text{non-adi}} < 1.9 \times 10^{-2} \qquad \theta_0 > \frac{2}{N\ln\left(\frac{4N}{3}\right)}$$

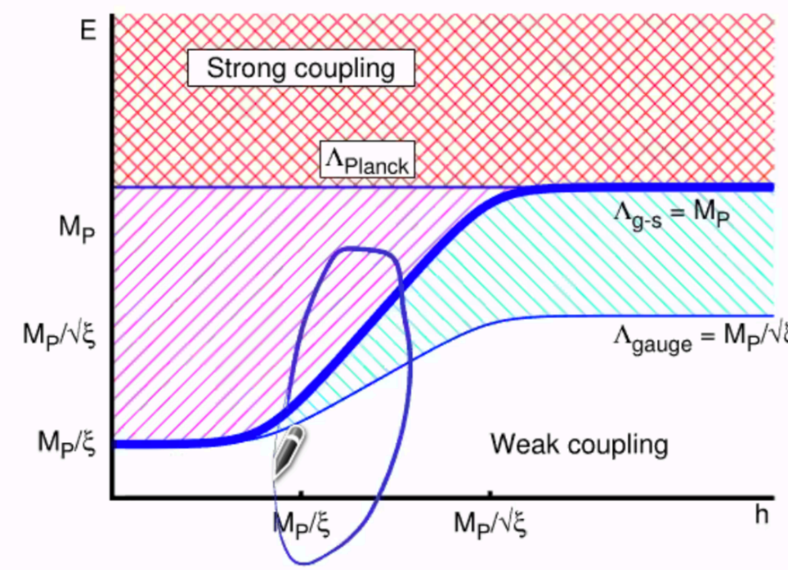
Unitary problem for Higgs inflation

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

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

Inflation

- Flatness problem

$$\Omega(a) \equiv \frac{\rho(a)}{\rho_{\rm crit}(a)}, \qquad \rho_{\rm crit}(a) \equiv 3H(a)^2$$

$$1 - \Omega(a) = \frac{-k}{(aH)^2}$$

$$\begin{aligned} |\Omega(a_{\rm BBN}) - 1| &\leq \mathcal{O}(10^{-16}) \\ |\Omega(a_{\rm GUT}) - 1| &\leq \mathcal{O}(10^{-55}) \\ |\Omega(a_{\rm pl}) - 1| &\leq \mathcal{O}(10^{-61}) \end{aligned}$$

1/aH Comoving Hubble radius

$$(aH)^{-1} = H_0^{-1} a^{\frac{1}{2}(1+3w)}$$

Inflation

- Horizon problem

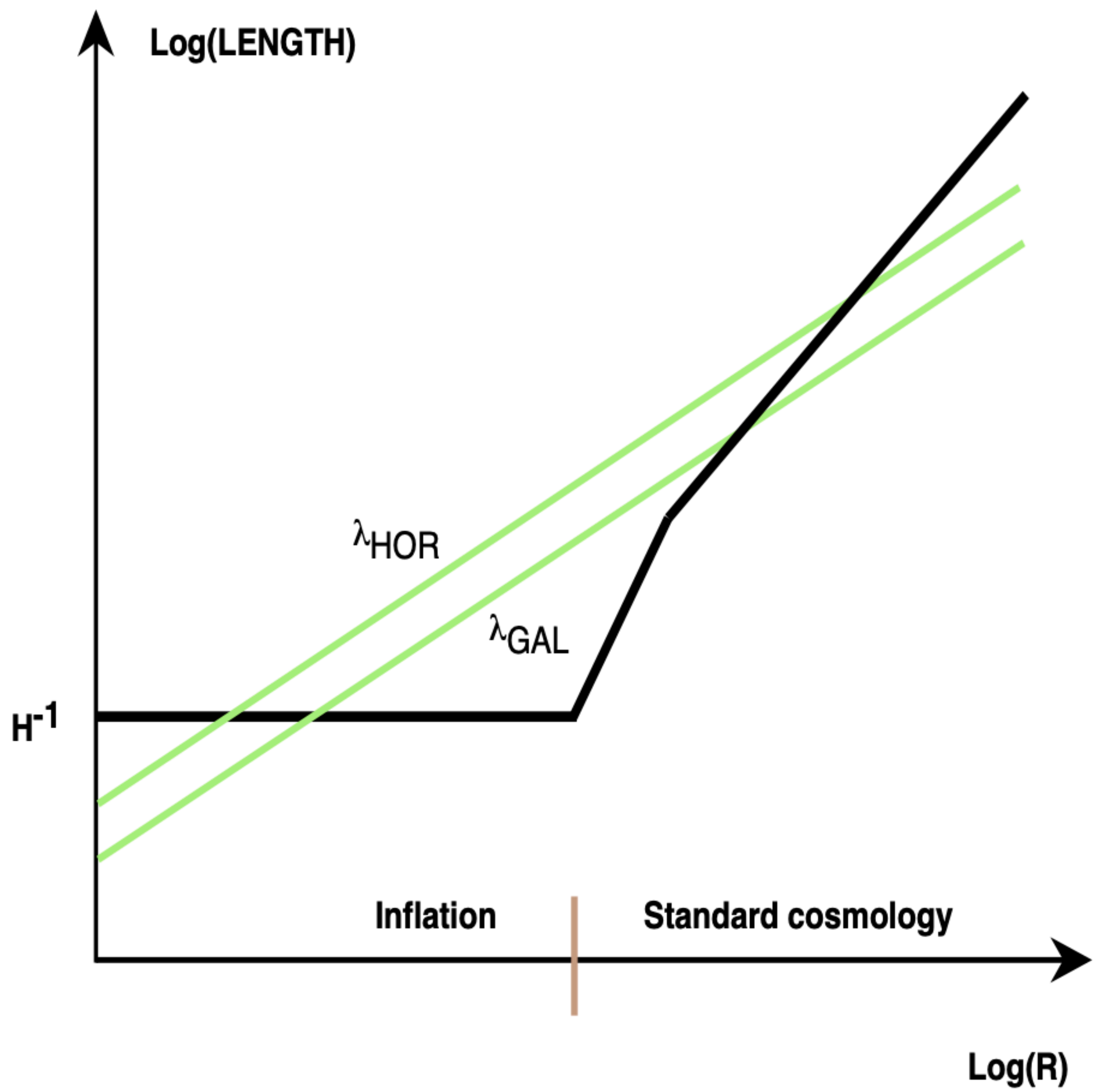
Comoving horizon

$$\tau \equiv \int_0^t \frac{\mathrm{d}t'}{a(t')} = \int_0^a \frac{\mathrm{d}a}{Ha^2}$$

$$\tau = \int_0^a \frac{\mathrm{d}a}{Ha^2} \propto \begin{cases} a & \mathrm{RD} \\ a^{1/2} & \mathrm{MD} \end{cases}$$

Comoving horizon grows monotonically with time

Horizon re-enter



Baryon asymmetry via leptogenesis

1. the sphaleron interactions themselves:

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

2. a similar relation for QCD sphalerons:

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0.$$

3. vanishing of the total hypercharge of the universe:

$$\sum_i \left(\mu_{q_i} - 2\mu_{\bar{u}_i} + \mu_{\bar{d}_i} - \mu_{\ell_i} + \mu_{\bar{e}_i}\right) + \frac{2}{N}\mu_H = 0$$

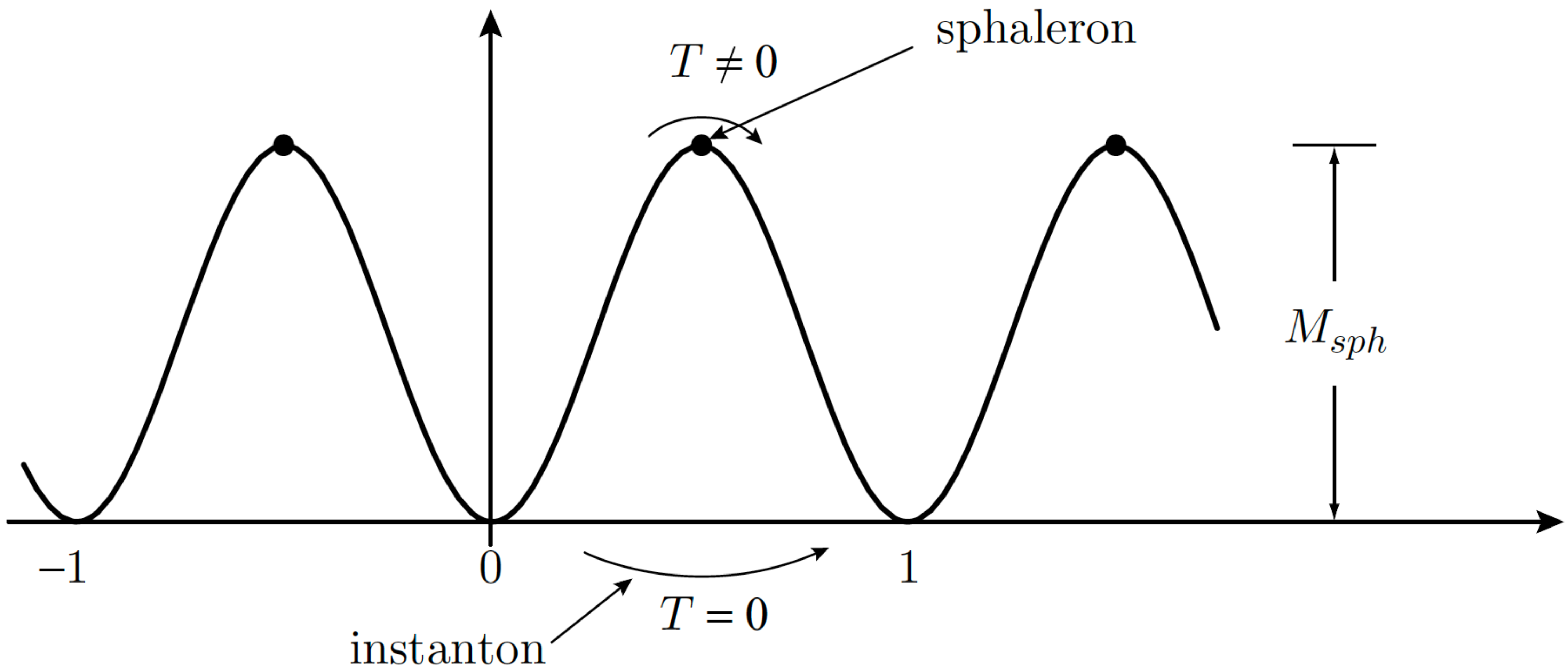
4. the quark and lepton Yukawa couplings give relations:

$$\mu_{q_i} - \mu_\phi - \mu_{d_j} = 0, \quad \mu_{q_i} - \mu_\phi - \mu_{u_j} = 0, \quad \mu_{\ell_i} - \mu_\phi - \mu_{e_j} = 0.$$

$$B = \frac{8N+4}{22N+13}(\mathcal{B} - \mathcal{L})_i$$

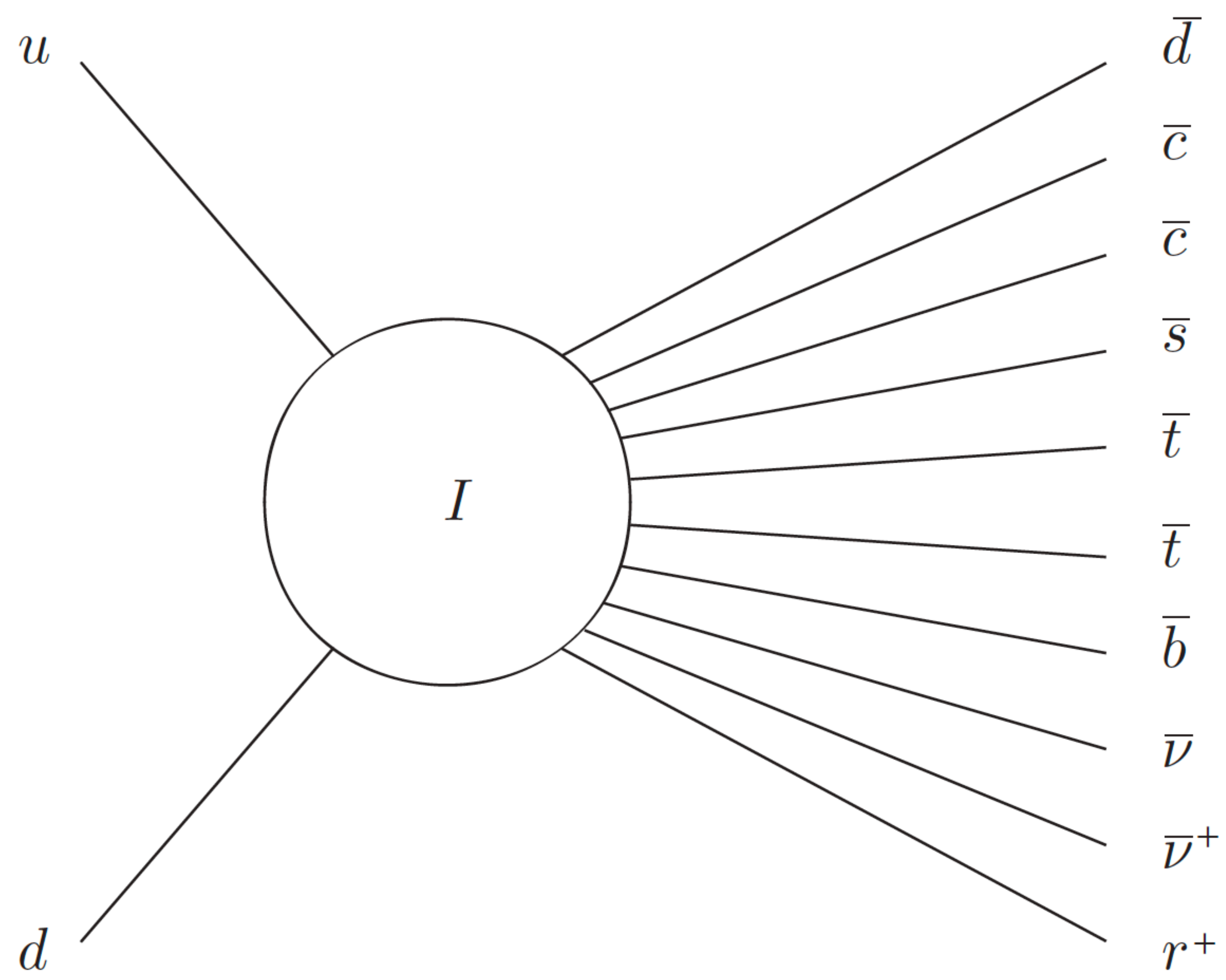
Instanton, sphaleron

$$\exp\left(-\frac{M_{sph}(T)}{T}\right) \sim \exp\left(-2\pi\frac{M_W(T)}{\alpha_w T}\right)$$

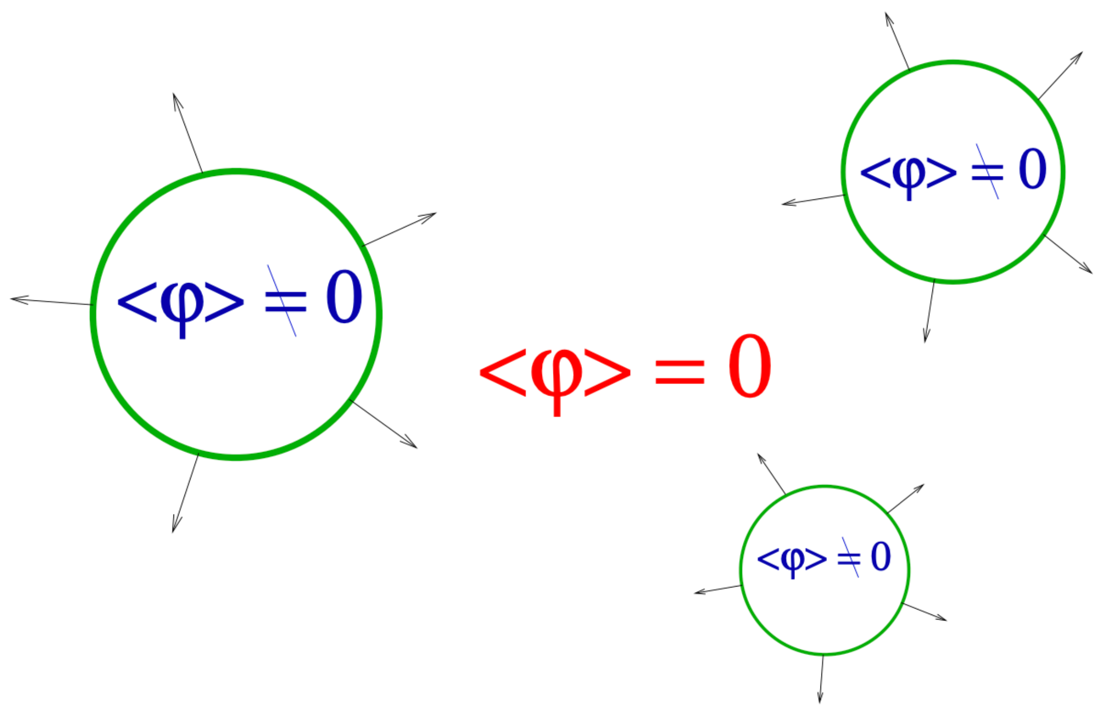


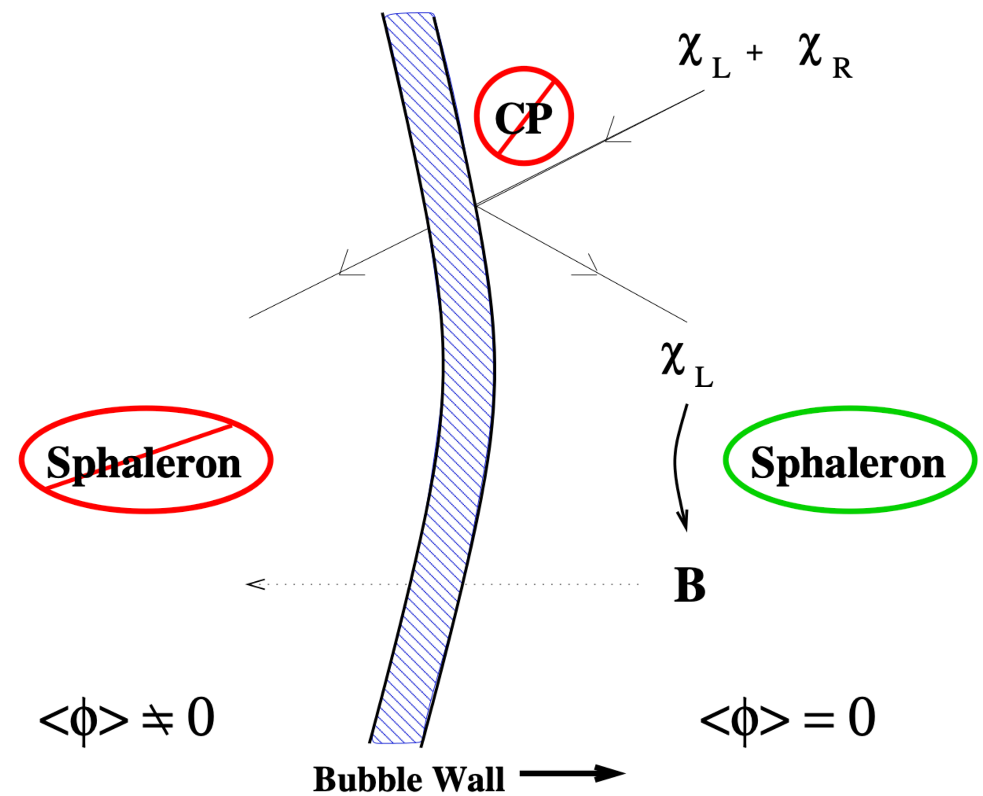
$$\Gamma \propto \exp\left(-\frac{4\pi}{\alpha}\right)$$

Instanton, sphaleron

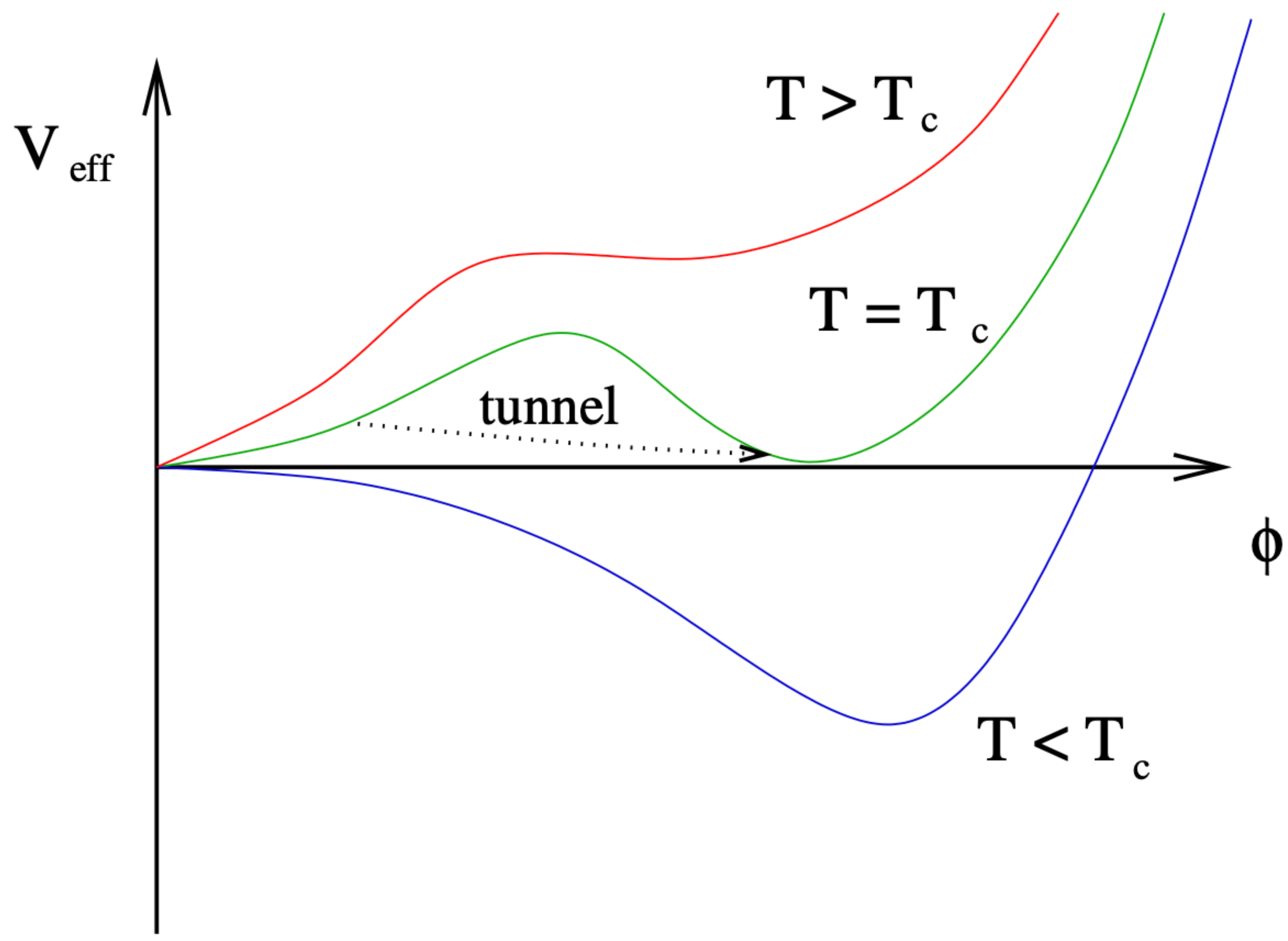


Electroweak baryogenesis





Electroweak baryogenesis



Baryogenesis via thermal leptogenesis

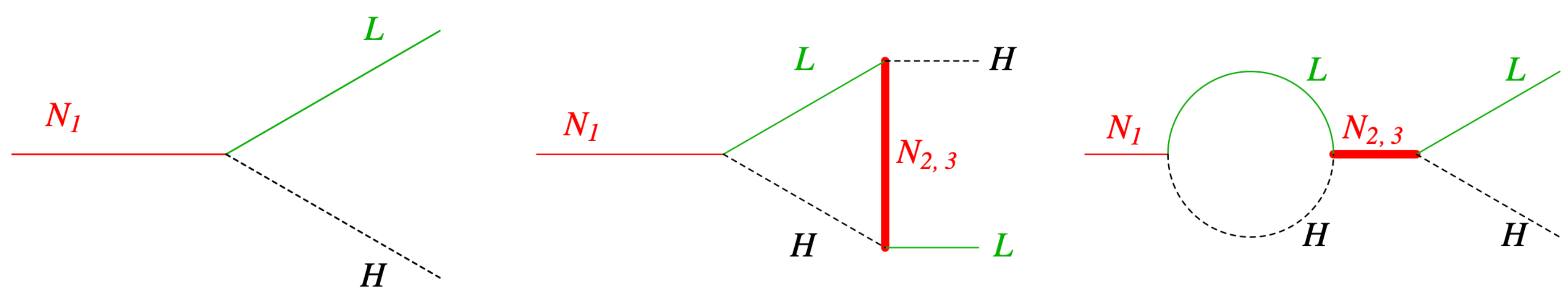
Type I seesaw: SM + 3 right-handed neutrinos $M \gtrsim 10^8$ GeV

sphaleron process

1. B number violation ⟷ L number violation

2. C and CP violation

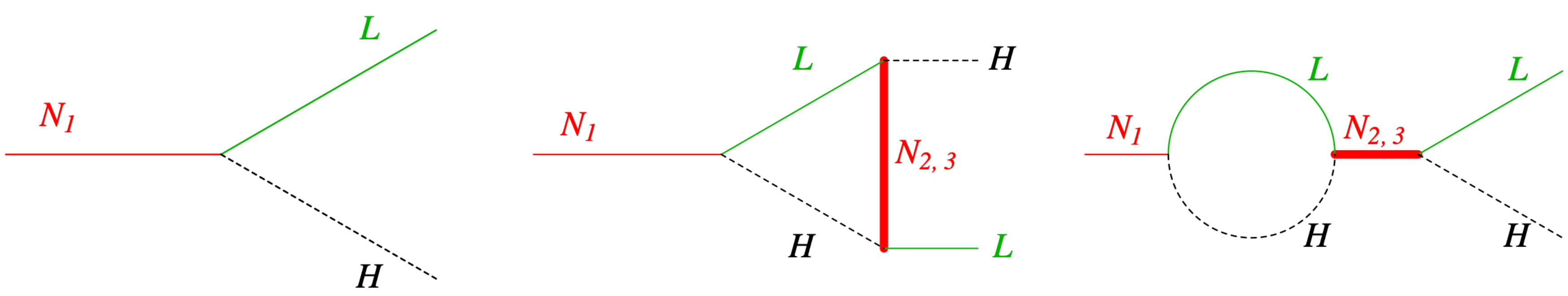
3. Out of thermal equilibrium (N decouples at the early universe and late decay)

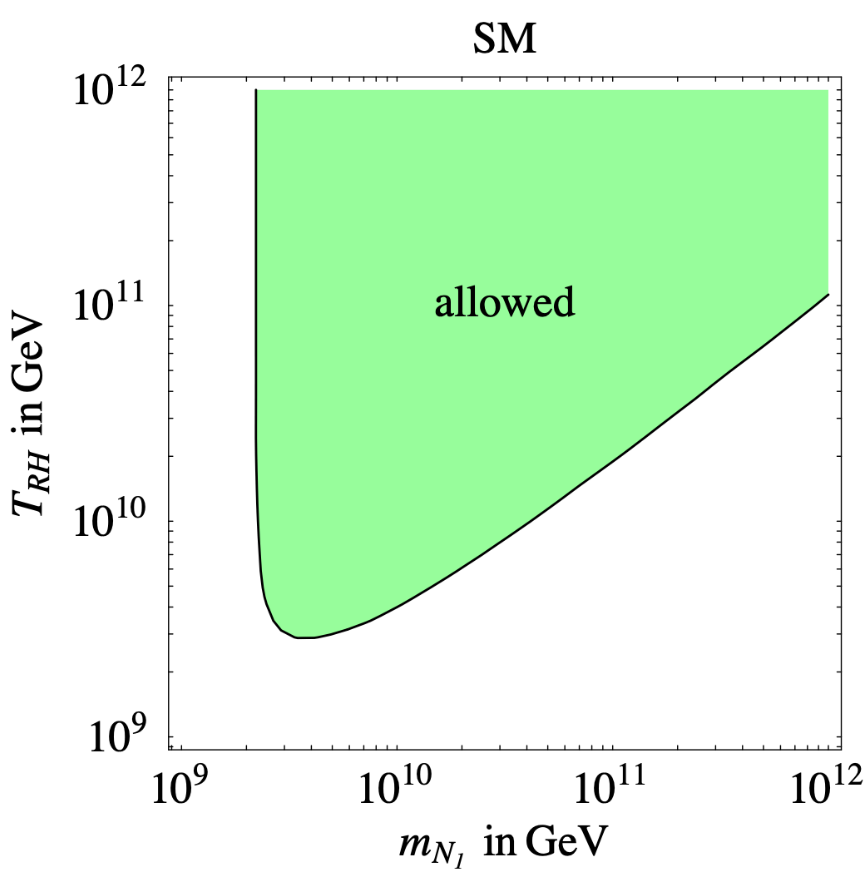


N decay is CP violated due to interference between tree level diagram and loop diagrams

Baryogenesis via thermal leptogenesis

Type I seesaw: SM + 3 right-handed neutrinos





Heavy right-handed neutrinos are generally required

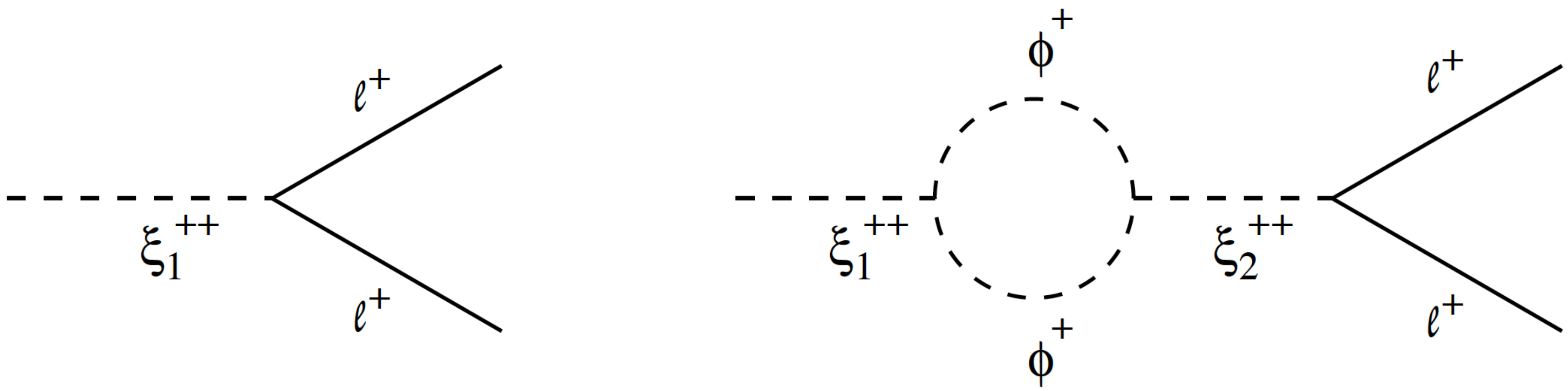
G.F. Giudice, A. Notari, M. Raidal, A. Riotto, A. Strumia, Nucl.Phys.B685:89-149,2004

Baryogenesis via thermal leptogenesis

Type II seesaw

$M \sim 10^{13}\ \mathrm{GeV}$

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



At least two triplet Higgs are needed to generate the baryon asymmetry

Or one triplet Higgs + right-handed neutrino

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

Affleck-Dine mechanism for Non-SUSY models

1 neutral scalar + 3 colored scalars

$$V_\Phi = \epsilon_{abd}\left(\lambda''\,\phi^*\,\Phi_1^a\Phi_2^b\Phi_3^d + y_1\Phi_1^a\,\bar{u}_R^b d_R^{c,d} + y_2\Phi_2^a\,\bar{u}_R^b d_R^{c,d} + y_3\Phi_3^a\,\bar{d}_R^b d_R^{c,d}\right) + \mathrm{H.c.}$$

Couple to quarks

$$V = m_\phi^2|\phi|^2 + \lambda|\phi|^4 + i\lambda'(\phi^4 - \phi^{*4})$$

U(1)B breaking term

Baryogenesis from Affleck-Dine mechanism

Equation of motion in an expansion of universe

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

$$\ddot{\phi}_I + 3H\dot{\phi}_I + \left[m^2 + 12\lambda\phi_R\phi_I + \frac{3|\phi|^4}{M^2} \right] \phi_I \quad = \quad 4\lambda\phi_R^3$$

H > m, phi frozen

H < m, phi oscillates $\phi = \phi_0/(mt)\sin(mt)$ for a matter dominated universe

$$\dot{n}_B + 3Hn_B = \mathrm{Im}\left(\phi \frac{\partial V}{\partial \phi}\right) \qquad n_B \sim \frac{n c_n \phi_0^n}{m^3 t^2}$$

Baryon number is maximally generated when H ~ m

Baryogenesis from Affleck-Dine mechanism

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

small U(1) breaking term

$$V(\phi) = m^2|\phi|^2 + (c_n \phi^n + h.c.)$$

$$n_B = 2Q\mathrm{Im}[\phi^* \dot{\phi}] = Q\rho_\phi^2 \dot{\theta} \qquad \phi = \frac{1}{\sqrt{2}}\rho_\phi e^{i\theta}$$

Equation of motion in an expansion of universe

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

H > m, phi fixed
H < m, phi oscillates

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

Baryon number is maximally generated when H ~ m

Affleck-Dine inflation

Combining the idea of inflation and baryogenesis

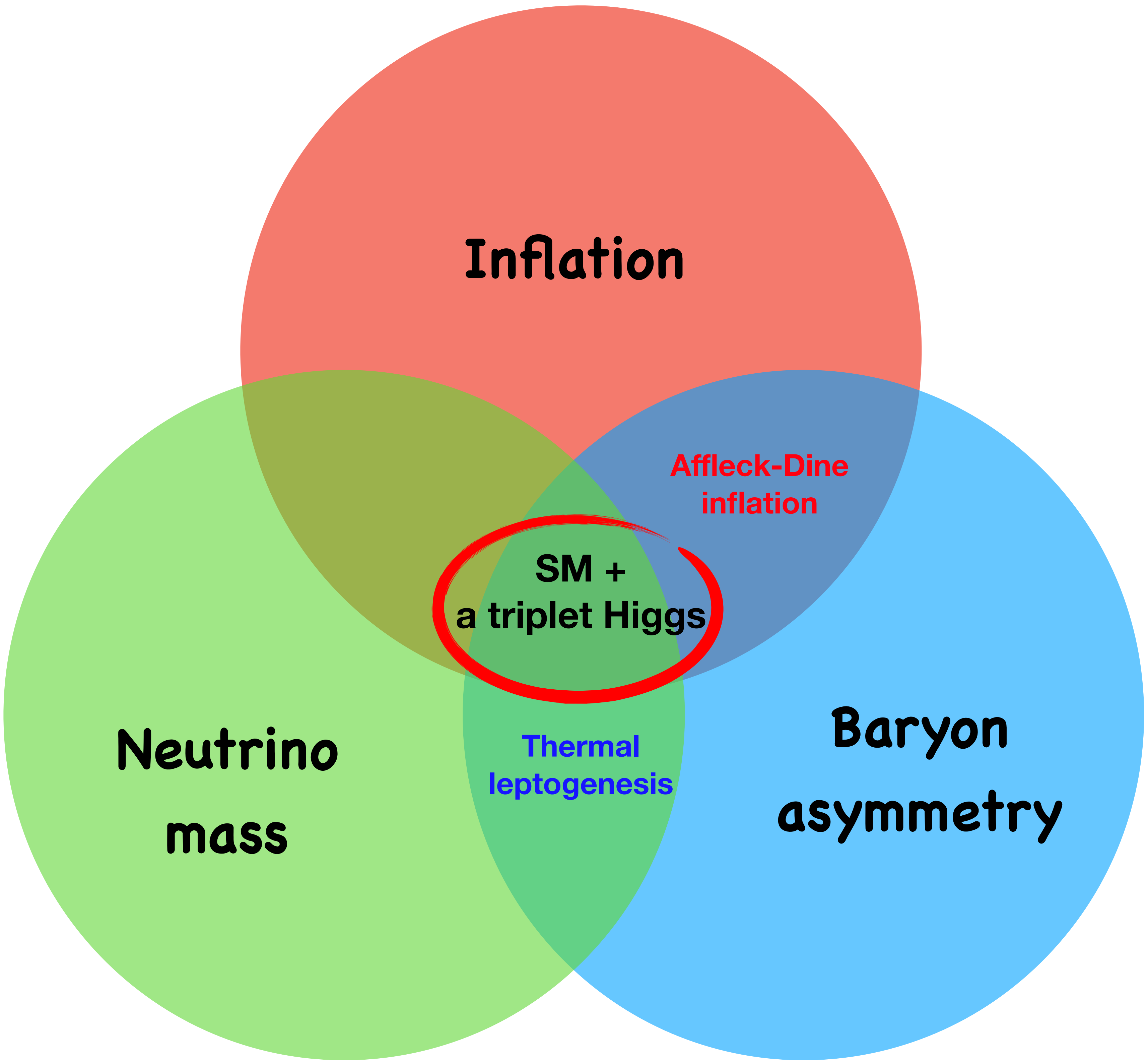
Non-SUSY: just adding the non-minimal coupling(non-SUSY)

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

Model is complicated and many new fields are needed

SUSY: adding non-canonical Kinetic term

Model might be simple, but SUSY is needed


Inflation
Affleck-Dine
inflation
SM +
a triplet Higgs
Neutrino
mass
Thermal
leptogenesis
Baryon
asymmetry