Probing the high scale seesaw at a natural cosmological Higgs collider

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With Hongjian He, Linghao Song, Jintao You, arXiv: 2412.XXXXX

The International Joint Workshop on the Standard Model and Beyond

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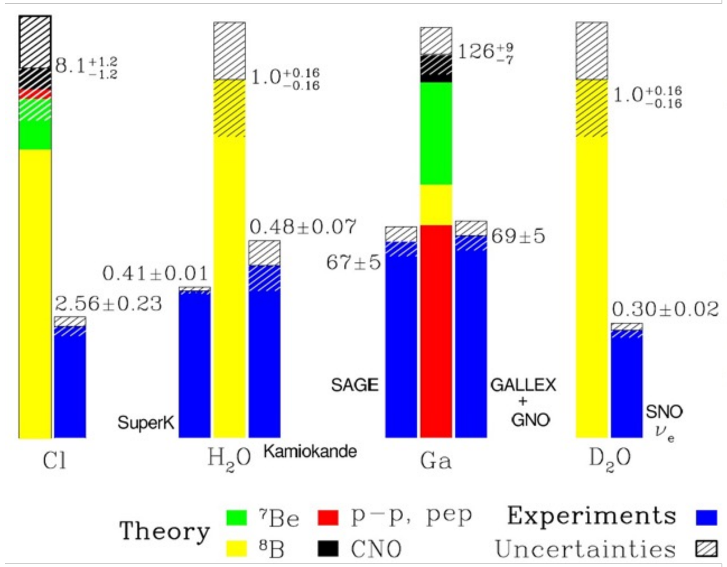
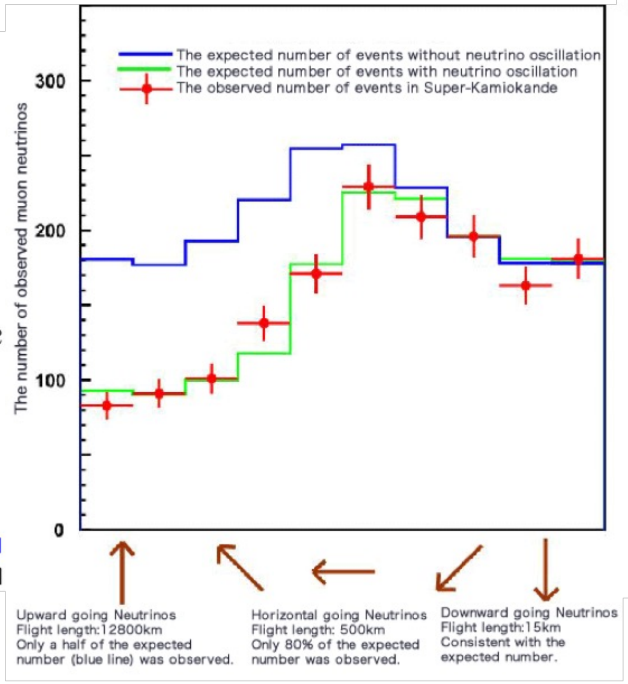
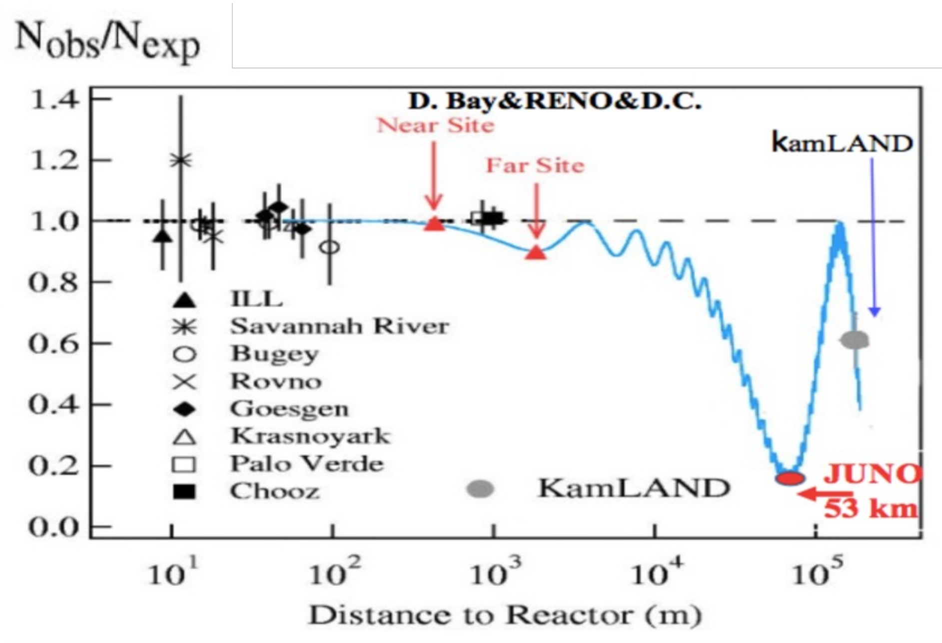
2024.12.12

Neutrino masses

Neutrino oscillation indicates massive neutrinos







Solar Neutrino oscillations

θ_{12}

Atmospheric Neutrino Oscillations

θ_{23}

Reactor Neutrino Oscillations

θ_{13}

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

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

At least one neutrino mass (0.05-0.1) eV

Seesaw mechanism

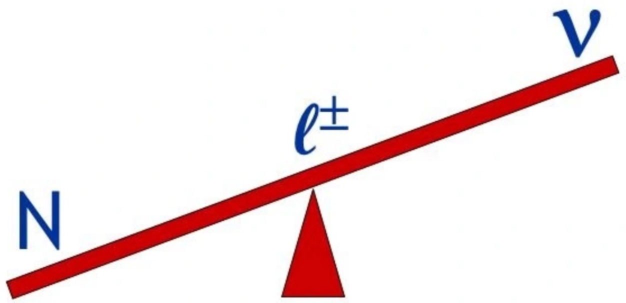
Origin of neutrino masses: seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{\rm SM} + y_\nu \tilde{H} \bar{L} N - \frac{1}{2} M_R \bar{N}^c N + h.c.$$

P. Minkowski； T. Yanagida; S. L. Glashow;
M. Gell-Mann, P. Ramond and R. Slansky

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$m_\nu \sim \frac{m_D^2}{m_R} = \frac{y_\nu^2 \langle h \rangle^2}{m_R}$$



- Natural prediction of small neutrino masses
- Explain the baryon asymmetry of the universe: leptogenesis

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

Seesaw mechanism

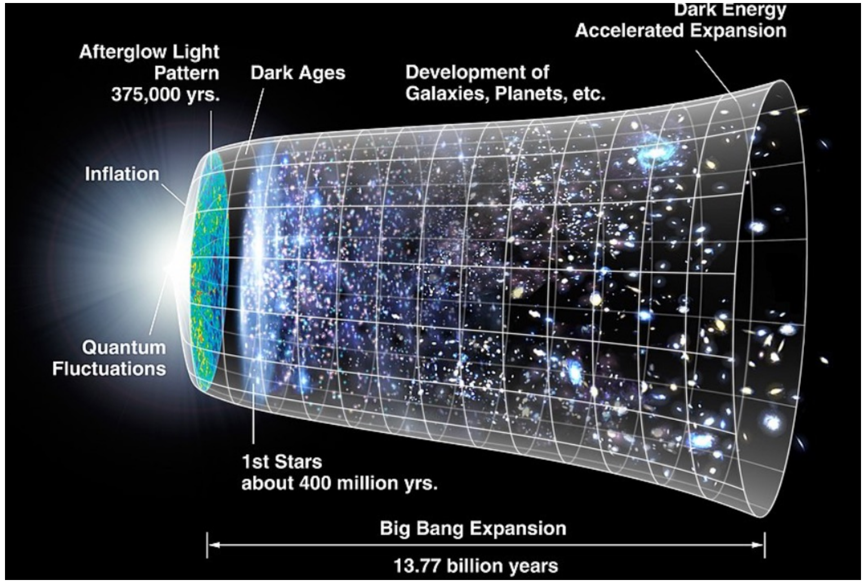
$$m_\nu \sim \frac{m_D^2}{m_R} = \frac{y_\nu^2 \langle h \rangle^2}{m_R}$$

If the Yukawa coupling is O(1)(as predicted by the GUT), the scale of M_R should be around $10^{13\text{-}14}$ GeV, which is much beyond the reach of particle experiments.

How to test such high scale seesaw?

Inflation

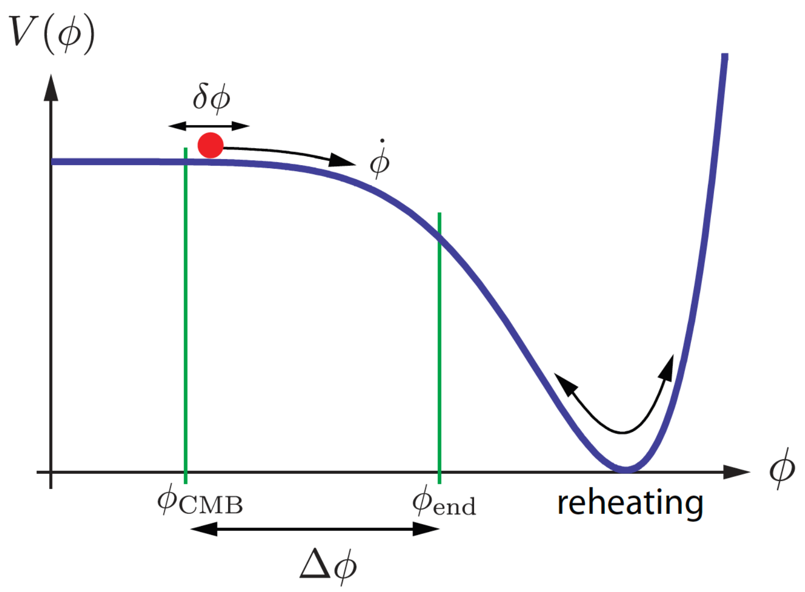
Rapid expansion of the universe in the early time



- Flatness problem
- Horizon problem
- Seeding the primordial anisotropies in CMB, finally develop into the large scale structure of our universe

Slow-roll Inflation

Inflation is driven by a scalar field (inflaton)



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

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

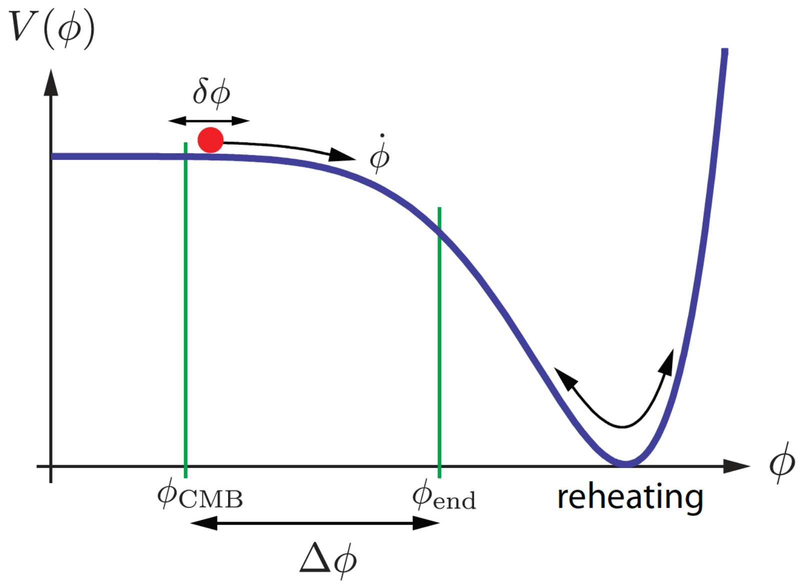
Slow roll condition

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

- **Hubble parameter is nearly constant(de Sitter universe)**
- **After inflation, inflaton oscillates at the bottom of the potential and finally decays, then reheats the universe(still no clear how it happens)**

Slow-roll Inflation

In a de Sitter universe, scalar fields get quantum fluctuation



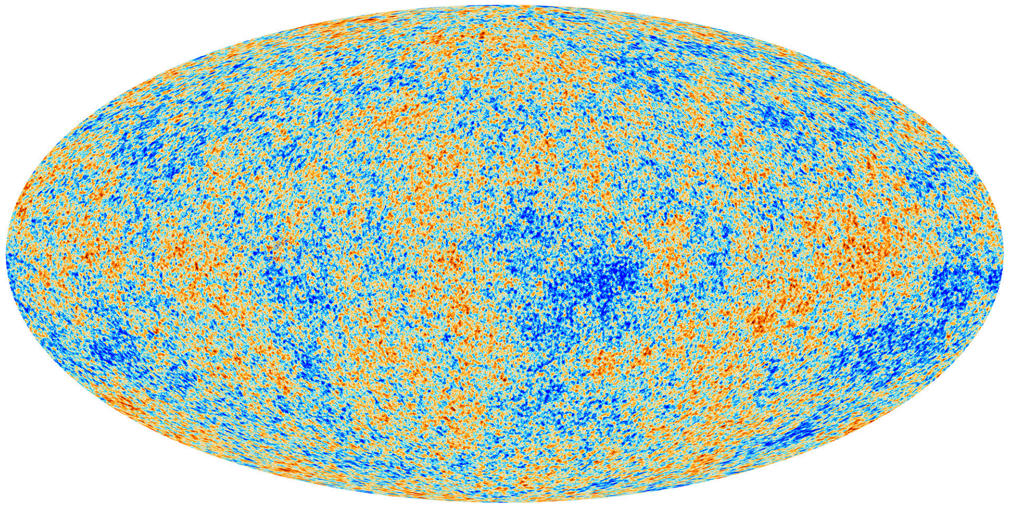
$$\delta\phi(x,\tau) = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\left[u_a(\tau,\mathbf{k})b_a(\mathbf{k}) + u_a^*(\tau,-\mathbf{k})b_a^\dagger(-\mathbf{k})\right]e^{\mathbf{ik\cdot x}}$$

Massless limit $$u_{\mathbf{k}}(\tau) = \frac{H}{\sqrt{2k^3}}\left[1+ik\tau\right]e^{-ik\tau}$$

$$\langle \delta\phi_{\mathbf{k}}\,\delta\phi_{\mathbf{k}'}\rangle = (2\pi)^3\,\delta(\mathbf{k}+\mathbf{k}')\,\frac{2\pi^2}{k^3}\left(\frac{H}{2\pi}\right)^2$$

- **Quantum fluctuation of inflaton induces CMB anisotropies(or curvature perturbations)**
- **In the single field inflation, the fluctuations should be nearly gaussian and adiabatic, close to scale invariant**

Measurements from Planck



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

$$\epsilon_V < 0.0097$$

$$\eta_V = -0.010^{+0.007}_{-0.011}$$

$$\frac{H_*}{M_{\rm Pl}} < 2.5 \times 10^{-5}$$

- **Inflaton potential should be flat enough(shift-symmetry?)**
- **Hubble scale could be as high as 10^{14} GeV(close to seesaw scale), providing a circumstance to interplay with high scale physics**

Non-Gaussianity

Non-Gaussianity is sensitive to new physics

- New physics could induce large non-Gaussianity : multi-field inflation models, modulated reheating, curvaton scenario…
- Current limit from Planck on local type f_{NL}~ O(10), future CMB observations, LiteBIRD O(1), large scale structure observations DESI O(1), SKA O(0.1), 21 cm tomography O(0.01-0.1)
- Non-Gaussianity could provide information to the new particle mass, spin, interactions: cosmological collider signals

Nima Arkani-Hamed, Juan Maldacena, arXiv:1503.08043

Xingang Chen, Yi Wang, JCAP 04 (2010) 027

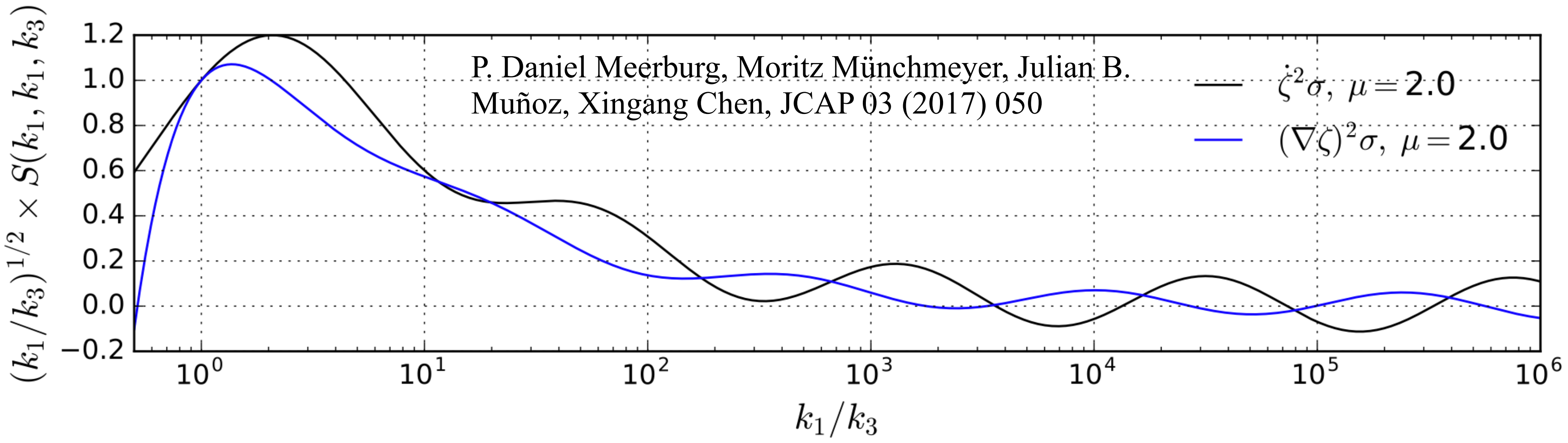
Cosmological collider signals

Bispectrum

$$\langle \zeta^3 \rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_{123}) \frac{A^2}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3) \qquad P_\zeta(k) = A/k^3$$

Massive particle coupling to the inflaton could induce

$$S_{\text{squeezed}} \propto \left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{1/2 \pm i\mu} \qquad \mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$



- **Probing new particles with mass around Hubble scale**
- **Signature would be highly suppressed when mass is large**

The model

Minimal model incorporates inflation and seesaw

$$\Delta\mathcal{L} = \sqrt{-g}\Big\{ -\frac{1}{2}(\partial_\mu\phi)^2 - V(\phi) + i\overline{N}_{\rm R}\partial\!\!\!/ N_{\rm R} + \frac{1}{\Lambda}\partial_\mu\phi\overline{N}_{\rm R}\gamma^\mu\gamma^5 N_{\rm R} + \Big[-\frac{1}{2}M\overline{N^c_{\rm R}}N_{\rm R} - y_\nu\,\bar{\ell}_{\rm L}\tilde{\mathbb{H}}N_{\rm R} + \text{ H.c.}\Big]\Big\}\,,$$

- **Derivative coupling to keep the flatness of the inflaton potential(shift-symmetry)**
- **Lambda > 60 Hubble to keep unitarity**
- **Inflaton coupling with SM fermions does not change the following discussions**
- **After inflation, inflaton oscillates at the bottom of the potential until decays into heavy neutrinos(mphi > 2 mN). The heavy neutrinos quickly decay into SM particles and reheat the universe**

The model

Consequence of the seesaw mechanism

$$\mathcal{L} \supset \frac{1}{2}\bar{\psi}_L \mathbf{M}_\nu \psi_R + \text{h.c.}, \qquad \mathbf{M}_\nu = \begin{pmatrix} 0 & \frac{y_\nu h}{\sqrt{2}} \\ \frac{y_\nu h}{\sqrt{2}} & M \end{pmatrix}$$

$$m_\nu \simeq -\frac{y_\nu^2 h^2}{2M}, \qquad M_N \simeq M + \frac{y_\nu^2 h^2}{2M}$$

- **Light neutrino gets a mass**
- **Heavy neutrino mass are get lifted (h dependent)**

Decay rate of the inflaton:

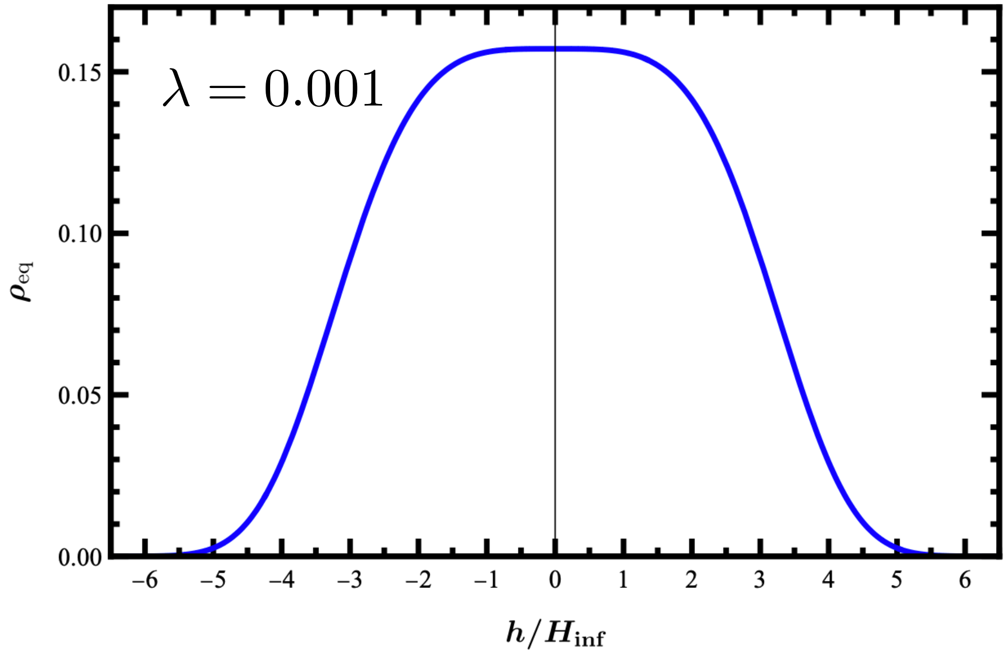
$$\Gamma \simeq \frac{1}{8\pi\Lambda^2} m_\phi M^2 \left[1 + \left(\frac{y_\nu h}{M}\right)^2 + \mathcal{O}\left(\left(\frac{y_\nu h}{M}\right)^4\right)\right]$$

What happens to h in the early universe?

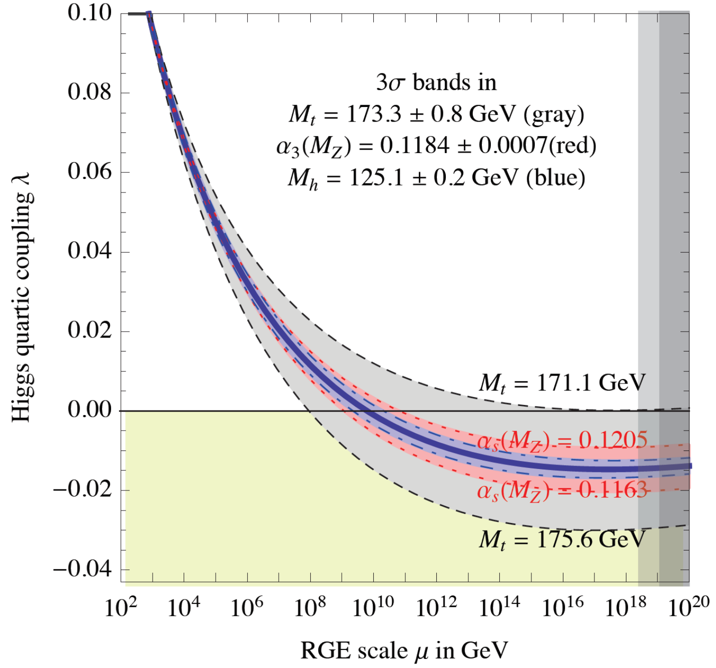
Higgs during inflation

- During inflation(de-Sitter universe), Higgs also gets quantum fluctuations
- If inflation lasts long enough, these fluctuations reach a equilibrium state
- Different part of universe Higgs field takes different value

Alexei A. Starobinsky, Jun'ichi Yokoyama, Phys.Rev.D 50 (1994) 6357-6368



$$\bar{h} = \sqrt{\langle h^2 \rangle} = \left[\int_{-\infty}^{+\infty} \mathrm{d}h\, h^2 \rho_{\rm eq}(h)\right]^{1/2} \simeq 0.363 \left(\frac{H_{\rm inf}}{\lambda^{1/4}}\right)$$

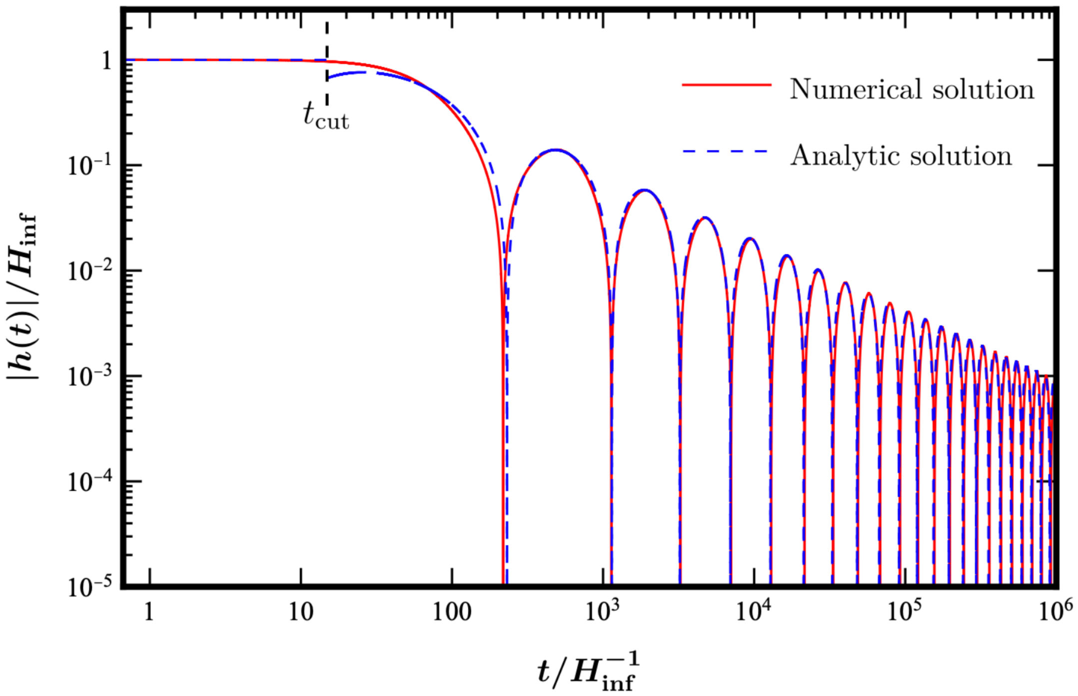


D. Buttazzo, et al arXiv:1307.3536

Higgs after inflation

Inflaton oscillates at the bottom potential. If the potential is dominated by the mass term, the Universe is matter-dominated

$$\ddot{h}(t) + \frac{2}{t}\dot{h}(t) + \lambda h^3(t) = 0$$



$$h(t) = \begin{cases} h_{\rm inf}\,, & t \le t_{\rm cut} \\ A H_{\rm inf}\left(\frac{h_{\rm inf}}{H_{\rm inf}\lambda}\right)^{\frac{1}{3}} (H_{\rm inf}\, t)^{-\frac{2}{3}} \cos\left(\lambda^{\frac{1}{6}} |h_{\rm inf}|^{\frac{1}{3}} \omega t^{\frac{1}{3}} + \theta\right), & t > t_{\rm cut} \end{cases}$$

$$t_{\rm cut} = \frac{\sqrt{2}}{3\sqrt{\lambda}\, h_{\rm inf}}$$

$$\begin{aligned} A &= 2^{1/3} 3^{-2/3} 5^{1/4} \simeq 0.9 \\ \omega &= \frac{\Gamma^2(3/4)}{\sqrt{\pi}} 2^{1/3} 3^{1/3} 5^{1/4} \simeq 2.3 \\ \theta &= -3^{-1/3} 2^{1/6} \omega - \arctan 2 \simeq -2.9 \end{aligned}$$

Higgs modulated reheating

Decay rate of the inflaton is h dependent

$$\Gamma \simeq \frac{1}{8\pi\Lambda^2} m_\phi M^2 \left[1 + \left(\frac{y_\nu h}{M}\right)^2 + \mathcal{O}\left(\left(\frac{y_\nu h}{M}\right)^4\right)\right]$$

Gia Dvali, Andrei Gruzinov, Matias Zaldarriaga,
Phys.Rev. D69 (2004) 023505

- **Different patches of the universe reheat differently (modulated reheating)**
- **The curvature perturbation is generated by Higgs field**
- **Delta N formalism (from the end of inflation to the time after reheating completed)**

$$\zeta_h(t, \mathbf{x}) = \delta N(t, \mathbf{x}) = N(t, \mathbf{x}) - \langle N(t, \mathbf{x}) \rangle$$

Higgs modulated reheating

Equation of state: $\dot{\rho} + 3H(1+\omega)\rho = 0 \qquad 3H^2 M_p^2 = \rho$

From matter-dominated universe to radiation dominated universe

$$N(\mathbf{x}) = -\frac{1}{3}\ln\frac{\rho_{\rm reh}\big(h(\mathbf{x})\big)}{\rho_{\rm inf}} - \frac{1}{4}\ln\frac{\rho_f}{\rho_{\rm reh}\big(h(\mathbf{x})\big)}$$

Reheating occurs $H_{\rm reh} = \Gamma_{\rm reh}$

Curvature perturbation in terms of the decay rate

$$\begin{aligned}\zeta_h(t > t_{\rm reh}, \mathbf{x}) &= \delta N(\mathbf{x}) = N(\mathbf{x}) - \langle N(\mathbf{x})\rangle \\ &= -\frac{1}{6}\Big[\ln(\Gamma_{\rm reh}) - \langle \ln(\Gamma_{\rm reh})\rangle\Big]\end{aligned}$$

Higgs modulated reheating

Curvature perturbation contains two parts

$$\zeta = \zeta_\phi + \zeta_h$$

$$\mathcal{P}_\zeta^{(\phi)} = \left(\frac{H}{\dot{\phi}}\right)^2 \mathcal{P}_\phi = \left(\frac{H}{\dot{\phi}}\right)^2 \frac{H^2}{4\pi^2}$$

Taylor expansion of the curvature perturbations

$$\zeta_h(\mathbf{x}) = -\frac{1}{6}\left[\frac{\Gamma_0'}{\Gamma_0}\delta h_{\mathrm{inf}}(\mathbf{x}) + \frac{\Gamma_0\Gamma_0'' - \Gamma_0'\Gamma_0'}{2\Gamma_0^2}\delta h_{\mathrm{inf}}^2(\mathbf{x})\right] \equiv z_1 \delta h_{\mathrm{inf}}(\mathbf{x}) + \frac{1}{2} z_2 \delta h_{\mathrm{inf}}^2(\mathbf{x})$$

$$\mathcal{P}_\zeta^{(h)} = z_1^2 \mathcal{P}_{\delta h} = z_1^2 \frac{H^2}{4\pi^2}$$

$$R = \left(\frac{\mathcal{P}_\zeta^{(h)}}{\mathcal{P}_\zeta}\right)^{1/2} = |z_1| \left(\frac{\mathcal{P}_{\delta h}}{\mathcal{P}_\zeta}\right)^{1/2}$$

R should be less than 1

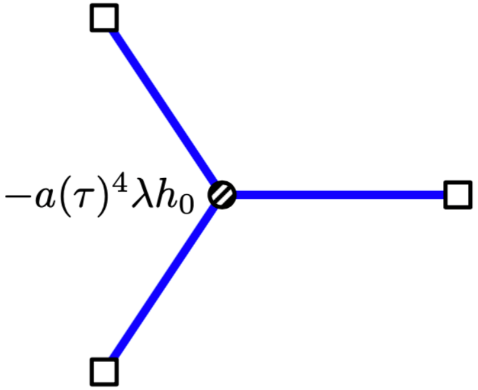
Bispectrum

Considering the three point correlation function

$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle_h = z_1^3 \langle \delta h_{\mathbf{k_1}} \delta h_{\mathbf{k_2}} \delta h_{\mathbf{k_3}} \rangle + z_1^2 z_2 \langle \delta h^4 \rangle_{2\mathrm{nd}} (\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$$

First term is from Higgs self-coupling

$$z_1^3 \langle \delta h_{\mathbf{k_1}} \delta h_{\mathbf{k_2}} \delta h_{\mathbf{k_3}} \rangle$$



Calculated by in-in formalism/Schwinger-Keldysh formalism

Xingang Chen, Yi Wang, Zhong-Zhi Xianyu, JCAP 1712 (2017) 006

Bispectrum

$$\langle \delta h_{\mathbf{k_1}} \delta h_{\mathbf{k_2}} \delta h_{\mathbf{k_3}} \rangle' = 12\lambda\bar{h}\mathrm{Im}\left(\int_{-\infty}^{\tau_f} a^4 \prod_{i=1}^{3} G_+(\mathbf{k}_i, \tau)\, d\tau\right)$$

$$\mathrm{Im}\left(\int_{-\infty}^{\tau_f} a^4 \prod_{i=1}^{3} G_+(\mathbf{k}_i, \tau)\, d\tau\right)$$

$$= \mathrm{Im}\int_{-\infty}^{\tau_f} \frac{d\tau}{(H\tau)^4} \cdot \frac{H^6}{8k_1^3k_2^3k_3^3}\left(\prod_{i=1}^{3}(1 - ik_i\tau)\right) e^{i(k_1+k_2+k_3)\tau}$$

$$N_e = \log(\frac{a_{\mathrm{end}}}{a_k}) = \log(\frac{-\frac{1}{H\tau_f}}{\frac{k_t}{H}}) = -\log(k_t|\tau_f|) \sim 60$$

$$= \frac{H^2}{24k_1^3k_2^3k_3^3} \cdot \left\{(k_1^3 + k_2^3 + k_3^3)[\log(k_t|\tau_f|) + \gamma - \frac{4}{3}] + k_1k_2k_3 - \sum_{a\neq b} k_a^2 k_b\right\}$$

Bispectrum

Second term is from non-linear evolution of the Higgs

$$
\begin{aligned}
& z_1^2 z_2 \langle \delta h^4 \rangle_{\mathrm{2nd}}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3}) \\
&= \frac{1}{2} z_1^2 z_2 \int \frac{\mathrm{d}^3\mathbf{k_0}}{(2\pi)^3} \langle \delta h(\mathbf{k_1}) \delta h(\mathbf{k_2}) \delta h(\mathbf{k_0}) \delta h(\mathbf{k_3} - \mathbf{k_0}) \rangle + 2 \quad \mathrm{perm} \\
&= \frac{1}{2} z_1^2 z_2 \left[\int \frac{\mathrm{d}^3\mathbf{k_0}}{(2\pi)^3} \langle \delta h(\mathbf{k_1}) \delta h(\mathbf{k_0}) \rangle \langle \delta h(\mathbf{k_2}) \delta h(\mathbf{k_3} - \mathbf{k_0}) \rangle + (\mathbf{k_1} \leftrightarrow \mathbf{k_2}) \right] + 2 \ \mathrm{perm} \\
&= \frac{1}{2} z_1^2 z_2 \left[\int \frac{\mathrm{d}^3\mathbf{k_0}}{(2\pi)^3} (2\pi)^3 \delta^3 (\mathbf{k_1} + \mathbf{k_0}) \frac{H^2}{2k_1^3} \right. \\
& \qquad \left. \times (2\pi)^3 \delta^3 (\mathbf{k_2} + \mathbf{k_3} - \mathbf{k_0}) \frac{H^2}{2k_2^3} + (\mathbf{k_1} \leftrightarrow \mathbf{k_2}) \right] + 2 \ \mathrm{perm} \\
&= (2\pi)^3 \delta^3 (\mathbf{k_1} + \mathbf{k_2} + \mathbf{k_3}) z_1^2 z_2 \left(\frac{H^2}{2k_1^3} \cdot \frac{H^2}{2k_2^3} + 2 \ \mathrm{perm} \right) .
\end{aligned}
$$

Local type non-gaussianity

The local type non-gaussianity which is defined by Bardeen Potential $\Phi \equiv \frac{3}{5}\zeta$

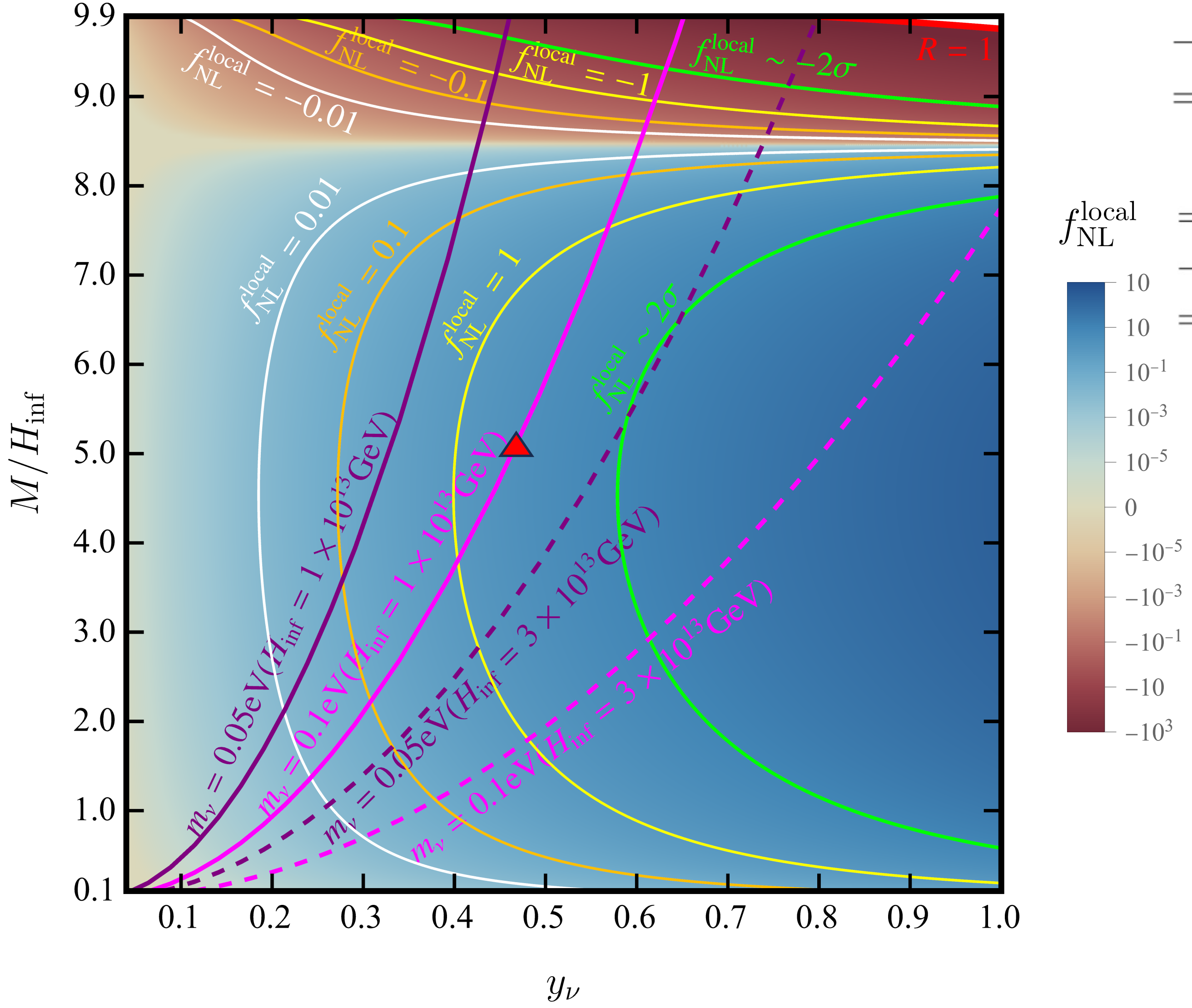
$$\langle \Phi_{\mathbf{k_1}} \Phi_{\mathbf{k_2}} \Phi_{\mathbf{k_3}} \rangle'_{\mathrm{local}} = 2A^2 f_{\mathrm{NL}}^{\mathrm{local}} \left\{ \frac{1}{k_1^3 k_2^3} + \frac{1}{k_2^3 k_3^3} + \frac{1}{k_3^3 k_1^3} \right\}$$

In the limit $k_1 \sim k_2 >> k_3$, we find

$$f_{\mathrm{NL}}^{\mathrm{local}} \sim -\frac{10}{3} \frac{z_1^3 H^3}{(2\pi)^4 \mathcal{P}_\zeta^2} \cdot \left(\frac{\lambda \bar{h}}{2H} N_e - \frac{H \cdot z_2}{4 z_1} \right)$$

$$f_{\mathrm{NL}}^{\mathrm{local}} = -0.9 \pm 5.1 \quad (68\% \text{ C.L., Planck 2018})$$

Local type non-gaussianity



Parameters	$\mathcal{P}_\zeta$	H	m_ϕ	Λ	λ
Values	2.1×10^{-9}	10^{13} GeV	$20H$	$60H$	0.001

R=0.1

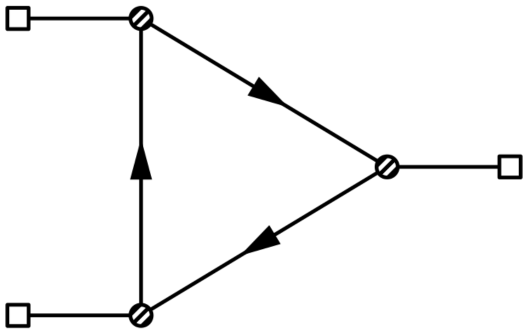
Source	Higgs Self-interaction	Non-linear Modulated Term
$f_{\rm NL}^{\rm local}$	2.3	1.5

- **Parameter space with Yukawa O(1) could be probed by future observations**
- **The contribution from self-interaction and non-linear term are comparable**
- **Interplaying with neutrino experiments**

A cosmological Higgs collider

Any particles coupling to Higgs would induce cosmological collider signals ,

W， Z, top quark… (mass around H during inflation)



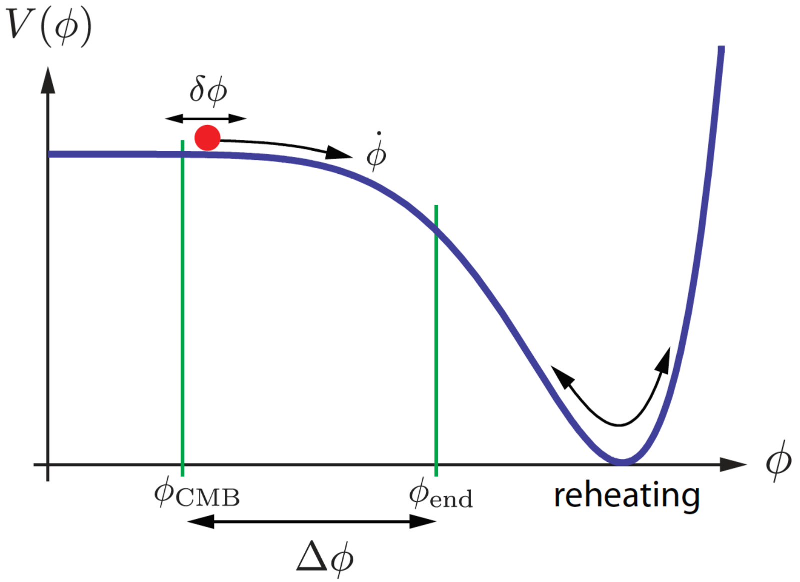
A (Natural) cosmological Higgs collider, signals need to be studied…

Summary

- We propose a minimal model incorporating inflation and seesaw
- The predicted local non-Gaussianity could be probed in near future CMB or large-scale structure observations
- It also provides a framework of cosmological Higgs collider (particles coupling to Higgs boson could be detected)

Thanks!

Slow-roll Inflation



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

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

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

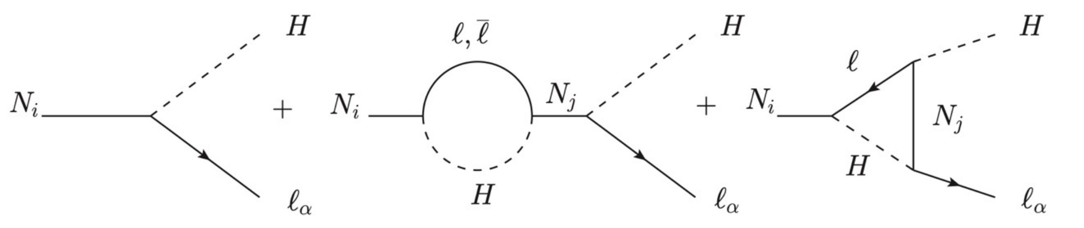
$$\Delta_{\rm t}^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}$$

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

Leptogenesis

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

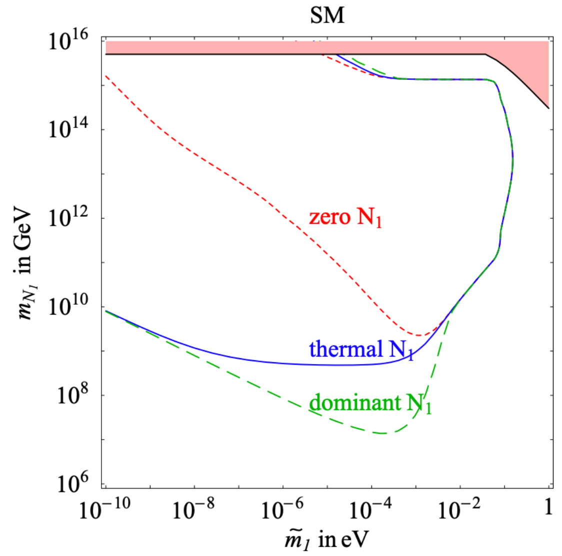
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



$$\epsilon_{i\alpha} = \frac{\gamma\left(N_i \to \ell_\alpha H\right) - \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}{\sum_\alpha \gamma\left(N_i \to \ell_\alpha H\right) + \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}$$

$$n_B = \frac{28}{79}(\mathcal{B} - \mathcal{L})_i$$

G.F. Giudice, et al,
Nucl.Phys.B 685 (2004) 89-149



Mass of the right-handed neutrino should heavier than 10^7 GeV

S-K formalism

$$\Box u_{\mathbf{k}} = \ddot{u_{\mathbf{k}}} + 3H\dot{u}_{\mathbf{k}} + \frac{\mathbf{k}^2}{a^2(t)} u_{\mathbf{k}} = 0$$

$$u_{\mathbf{k}}(\tau) = \frac{H}{\sqrt{2k^3}} \left[1 + ik\tau\right] e^{-ik\tau}$$

$$\begin{cases} G_{++}(\mathbf{k}; \tau_1, \tau_2) & \equiv G_{>}(\mathbf{k}; \tau_1, \tau_2)\, \theta(\tau_1 - \tau_2) + G_{<}(\mathbf{k}; \tau_1, \tau_2)\, \theta(\tau_2 - \tau_1) \\ G_{+-}(\mathbf{k}; \tau_1, \tau_2) & \equiv G_{<}(\mathbf{k}; \tau_1, \tau_2) \\ G_{-+}(\mathbf{k}; \tau_1, \tau_2) & \equiv G_{>}(\mathbf{k}; \tau_1, \tau_2) \\ G_{--}(\mathbf{k}; \tau_1, \tau_2) & \equiv G_{<}(\mathbf{k}; \tau_1, \tau_2)\, \theta(\tau_1 - \tau_2) + G_{>}(\mathbf{k}; \tau_1, \tau_2)\, \theta(\tau_2 - \tau_1) \end{cases}$$

S-K formalism

Bulk-to-Boundary propagator

$$G_{\pm}(\mathbf{k}, \tau) \equiv G_{\pm+}\left(\mathbf{k}; \tau, \tau_f\right)$$

$$= G_{+}(\mathbf{k}, \tau)$$

$$= G_{-}(\mathbf{k}, \tau)$$

$$= G_{+}(\mathbf{k}, \tau) + G_{-}(\mathbf{k}, \tau)$$

$$G_{+}(\mathbf{k}, \tau) = \frac{H^2}{2k^3}\left[1 - ik(\tau - \tau_f) + k^2\tau\tau_f\right] e^{ik(\tau-\tau_f)} \simeq \frac{H^2}{2k^3}\left[1 - ik\tau\right] e^{ik\tau}$$

$$G_{-}(\mathbf{k}, \tau) \simeq \frac{H^2}{2k^3}\left[1 + ik\tau\right] e^{-ik\tau}$$