Cosmological Signatures of Neutrino Seesaw Mechanism

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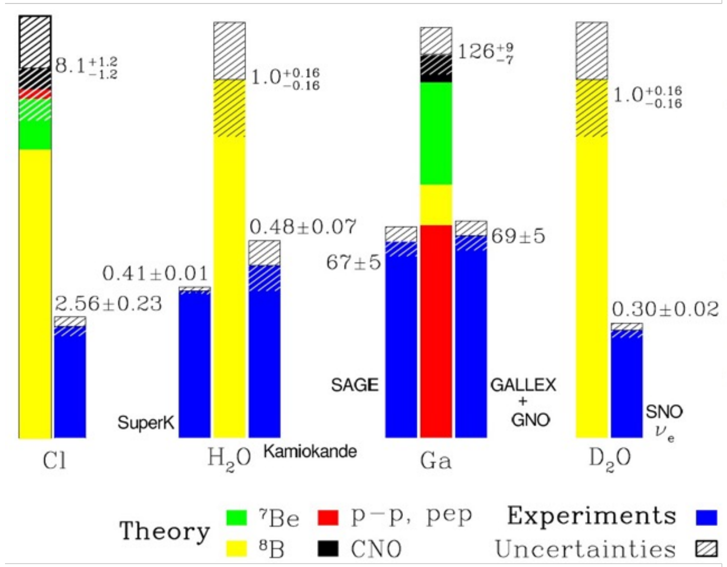
With Hongjian He, Linghao Song, Jintao You, arXiv: 2412.21045，2412.16033

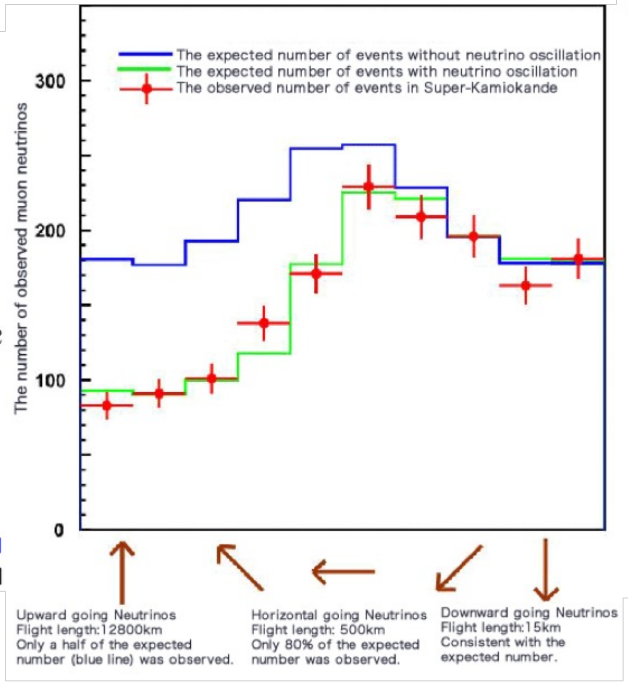
30th Mini-workshop on the frontier of LHC

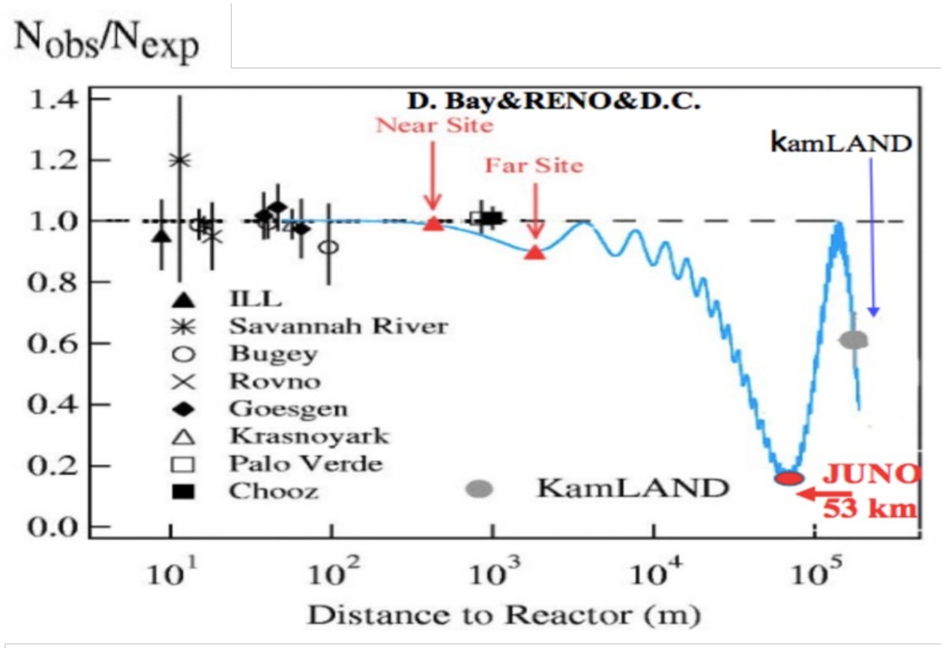
2025.5.24

Neutrino masses

Neutrino oscillation indicates massive neutrinos







Solar Neutrino oscillations

θ_{12}

Atmospheric Neutrino Oscillations

θ_{23}

Reactor Neutrino Oscillations

θ_{13}

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

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

Seesaw mechanism

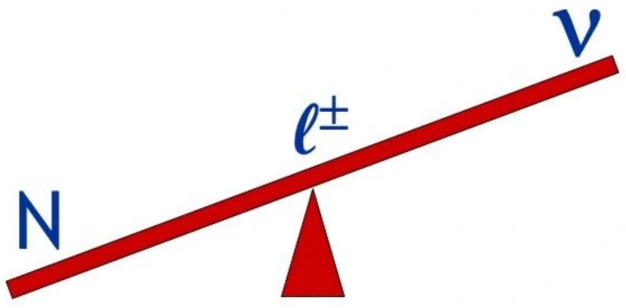
Origin of neutrino masses: seesaw mechanism

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

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

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

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



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

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

Seesaw mechanism

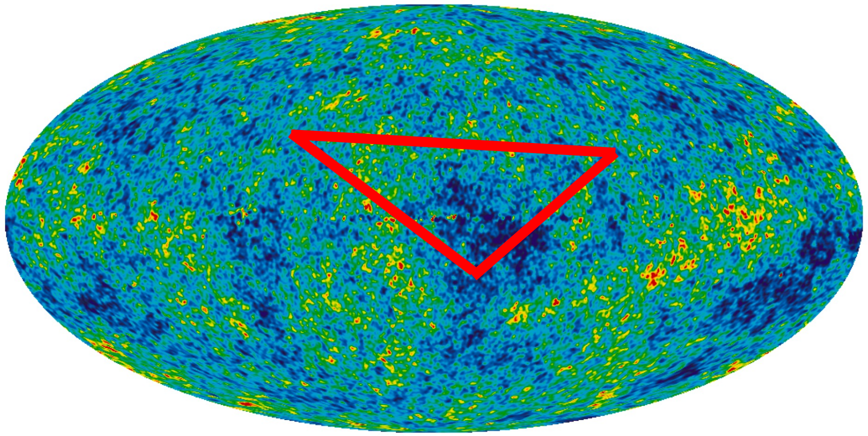
$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{y_\nu^2 \langle h \rangle^2}{2M_R}$$

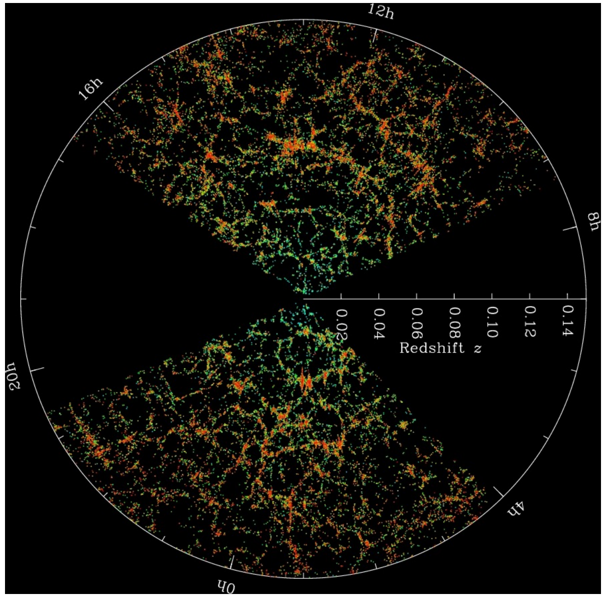
If the Yukawa coupling is O(1)(as predicted by the GUT), the seesaw scale M_R should be around $10^{13\text{-}14}$ GeV, which is much beyond the reach of particle experiments.

How to test such high scale seesaw?

Fluctuations at CMB and LSS

宇宙早期的量子扰动





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

我们可以计算其中的两点关联函数，三点关联函数(非高斯)来检验是否有右手中微子的信号

Seesaw mechanism

Consequence of the seesaw mechanism

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

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

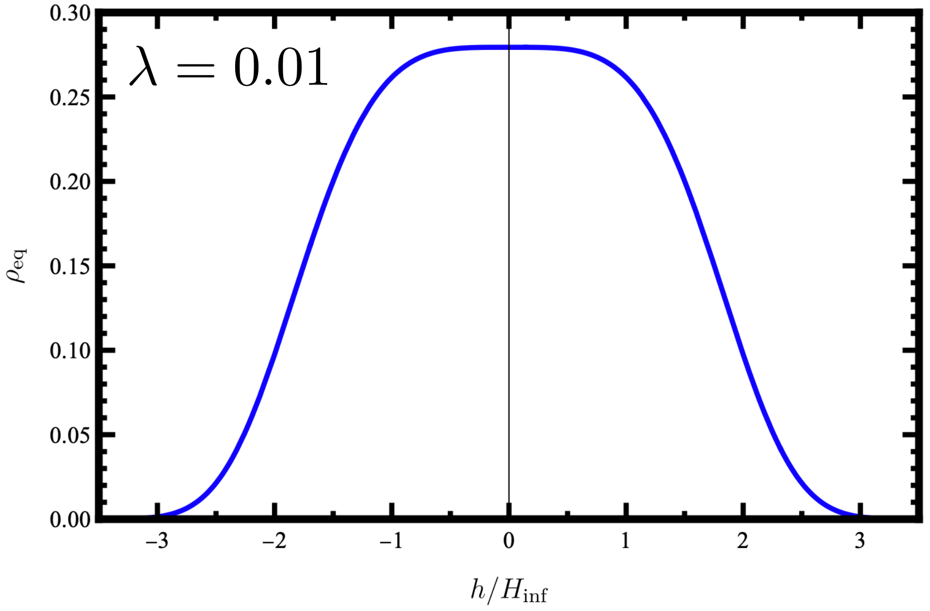
- **Light neutrino gets a mass**
- **Heavy neutrino mass are get lifted (h dependence)**

What happens to h in the early universe?

Higgs during inflation

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

- **During inflation(de-Sitter universe), Higgs gets quantum fluctuations**
- **Different part of universe Higgs field takes different value(as large as 10^{13} GeV)**



$$\rho_{\rm eq}(h) = \frac{2\lambda^{1/4}}{\Gamma(1/4)}\left(\frac{2\pi^2}{3}\right)^{1/4}\exp\left(\frac{-2\pi^2\lambda h^4}{3H_{\rm inf}^4}\right)$$

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

The right-handed neutrino mass is different in different patch of the universe

it may trigger the density fluctuation in CMB or large scale structure

A minimal model

Minimal model incorporates inflation and seesaw

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

- V(phi) is the potential for inflation is unknown but denominated by the mass term after inflation
- Derivative coupling to keep the flatness of the inflaton potential(shift-symmetry)
- 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.

Higgs modulated reheating

Considering decay rate of the inflaton is h dependent

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

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

- **Different patches of the universe reheat differently**
- **Perturbation is delta N= N- <N>, different universe has different e-fold N (from the end of inflation to the time after reheating completed)**

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

Bispectrum

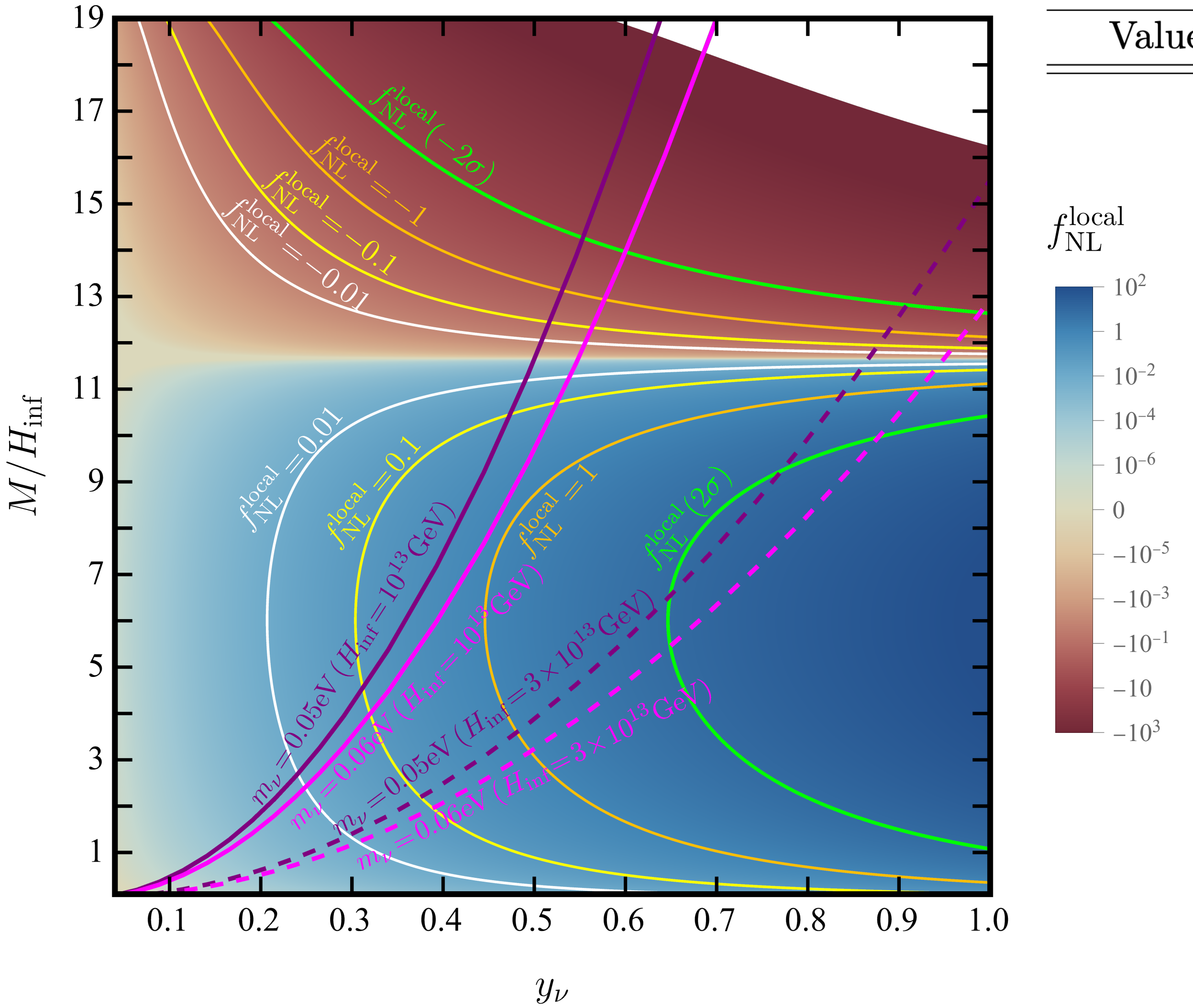
Taylor expansion of the curvature perturbation

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

Considering the three point correlation function

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

Local type non-gaussianity



Parameters	$\mathcal{P}_\zeta$	N_e	$H_{\rm inf}$	m_ϕ	Λ	λ
Values	2.1×10^{-9}	60	$(1,3)\times10^{13}\,$GeV	$40H_{\rm inf}$	$60H_{\rm inf}$	0.01

- **Colored curves indicating future searches**
- **Parameter space with Yukawa O(1) could be probed by future observations**
- **The contribution from self-interaction and non-linear term are both important**
- **Interplaying with neutrino experiments(JUNO, DUNE for neutrino ordering)**

Summary

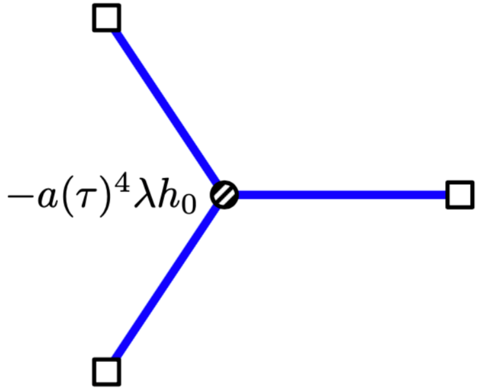
- A minimal model incorporates inflation and seesaw
- Non-Gaussianity induced by seesaw could be probed in near future CMB or large-scale structure observations

Thanks!

Bispectrum

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

Steven Weinberg, Phys.Rev.D 72 (2005) 043514, Phys.Rev.D 74 (2006) 023508

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

Bispectrum

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

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

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

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

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

Bispectrum

Second term is from non-linear evolution of the Higgs

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

Local type non-gaussianity

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

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

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

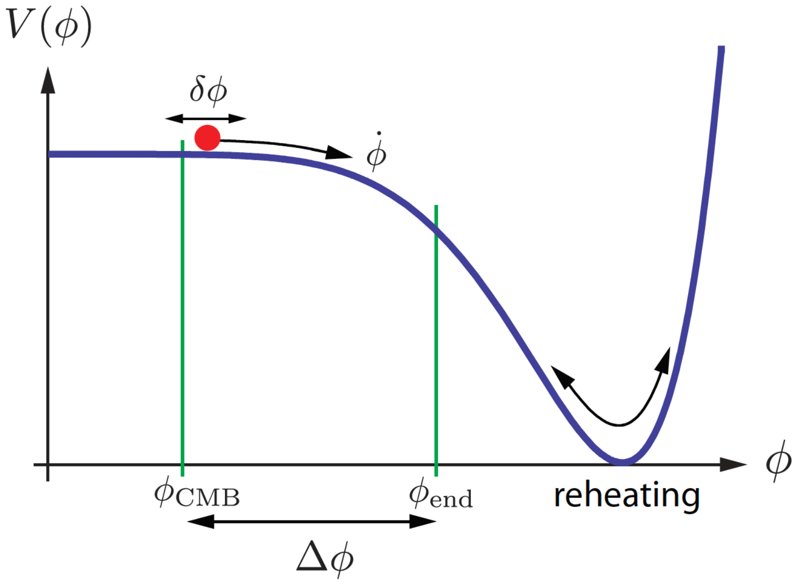
$$f_{\rm NL}^{\rm local} \sim -\frac{10}{3} \frac{z_1^3 H^3}{(2\pi)^4 \mathcal{P}_\zeta^2} \cdot \left(\frac{\lambda \bar{h}}{2H} N_e - \frac{H \cdot z_2}{4 z_1} \right)$$

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

Summary

- A minimal model incorporates inflation and seesaw
- Non-Gaussianity induced by seesaw could be probed in near future CMB or large-scale structure observations

Slow-roll Inflation



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

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

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

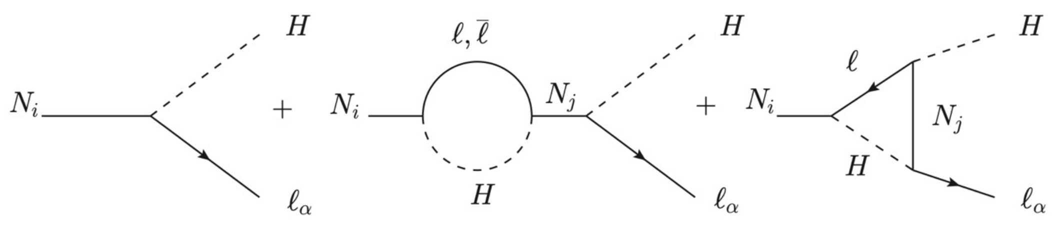
$$\Delta_{\rm t}^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}$$

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

Leptogenesis

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

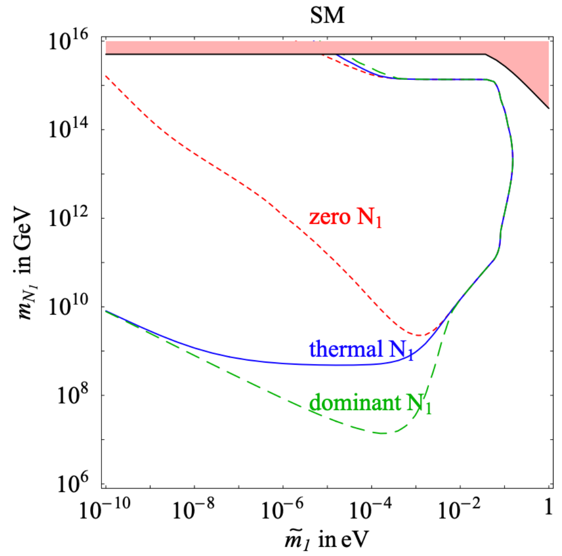
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

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

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

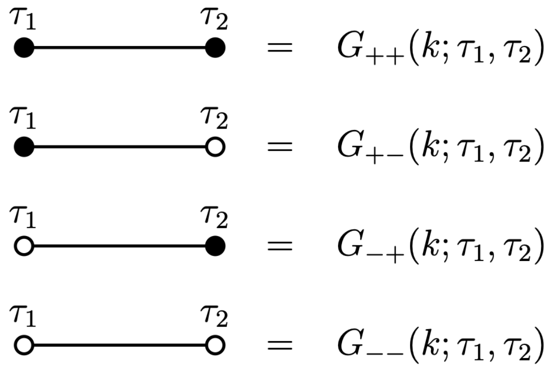
$$Q(\tau) \equiv \varphi^{A_1}(\tau, \mathbf{x}_1) \cdots \varphi^{A_N}(\tau, \mathbf{x}_N)$$

$$\langle Q(\tau) \rangle = \langle \Omega | \bar{F}(\tau, \tau_0) Q_I(\tau) F(\tau, \tau_0) | \Omega \rangle$$

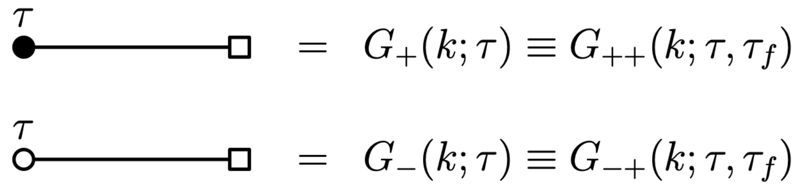
$$F(\tau, \tau_0) = \mathrm{T} \exp \left(-\mathrm{i} \int_{\tau_0}^{\tau} \mathrm{d}\tau_1 \, H_I(\tau_1) \right),$$
$$\bar{F}(\tau, \tau_0) = \bar{\mathrm{T}} \exp \left(\mathrm{i} \int_{\tau_0}^{\tau} \mathrm{d}\tau_1 \, H_I(\tau_1) \right),$$

S-K formalism

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



$$
G_{>}(k;\tau_1,\tau_2)\equiv u(\tau_1,k)u^*(\tau_2,k)
$$
$$
G_{<}(k;\tau_1,\tau_2)\equiv u^*(\tau_1,k)u(\tau_2,k)
$$



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

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

S-K formalism

Bulk-to-Boundary propagator

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

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

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

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

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

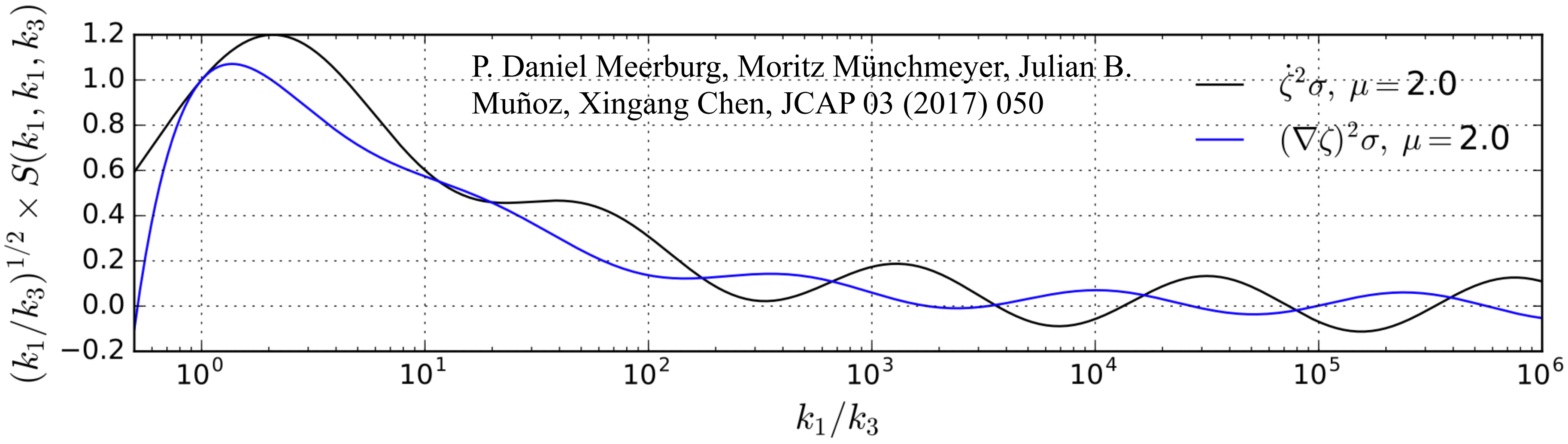
$$G_{-}\left(\mathbf{k},\tau\right) \simeq \frac{H^2}{2k^3}\left[1 + ik\tau\right] e^{-ik\tau}$$

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

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



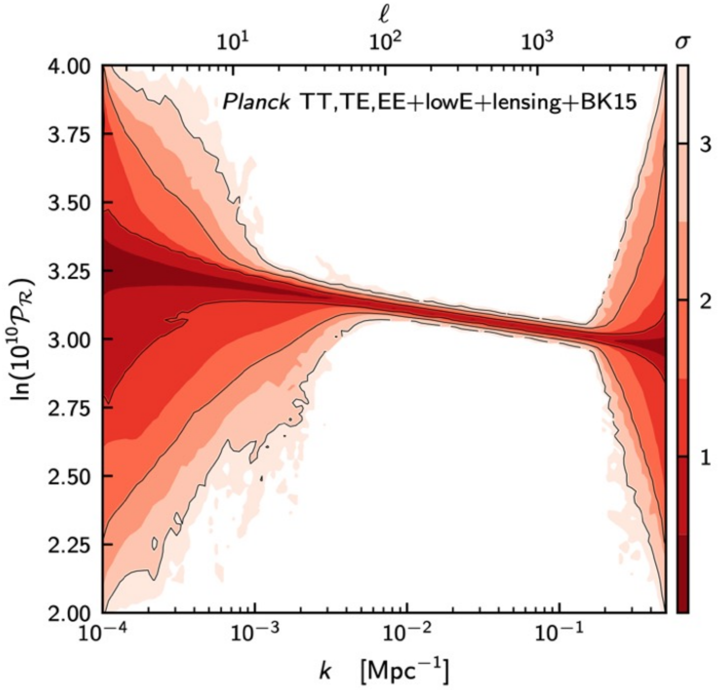
Slow-roll Inflation

标量扰动

$$\Delta_s^2(k) \approx \frac{1}{24\pi^2}\frac{V}{M_{pl}^4}\frac{1}{\epsilon_v}\bigg|_{k=aH} \qquad \epsilon_v(\phi) \equiv \frac{M_{pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \eta_v(\phi) \equiv M_{pl}^2\frac{V_{,\phi\phi}}{V}$$

$$n_s - 1 \equiv \frac{d\ln\Delta_s^2}{d\ln k} = 2\eta_v - 6\epsilon_v$$

$n_s \simeq 0.965$ **n_s=1 scale invariant**



张量扰动

$$\Delta_t^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{pl}^4}\bigg|_{k=aH} \qquad r \equiv \frac{\Delta_t^2}{\Delta_s^2} = 16\epsilon_v$$

Higgs modulated reheating

$$\zeta_h = -\frac{1}{6}\left[\ln(\Gamma_{\rm reh}) - \langle \ln(\Gamma_{\rm reh})\rangle\right]$$

$$\uparrow$$

$$\Gamma_{\rm reh} = \Gamma\big(h(t_{\rm reh})\big)$$

$$\uparrow$$

$$h(t_{\rm reh}) = h(h_{\rm inf}, t_{\rm reh})$$

$$h(t) = A\left(\frac{h_{\rm inf}}{\lambda}\right)^{\frac{1}{3}} t^{-\frac{2}{3}} \cos\left(\lambda^{\frac{1}{6}} h_{\rm inf}^{\frac{1}{3}} \omega t^{\frac{1}{3}} + \theta\right)$$

n-point correlation function of zeta changes into n-point correlation function of hinf

Higgs modulated reheating

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

From matter-dominated universe to radiation dominated universe

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

Reheating occurs $H_{\text{reh}} = \Gamma_{\text{reh}}$ $\quad 3H^2M_p^2 = \rho$

Curvature perturbation in terms of the decay rate

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