Cosmological non-Gaussianity from Neutrino Seesaw Mechanism

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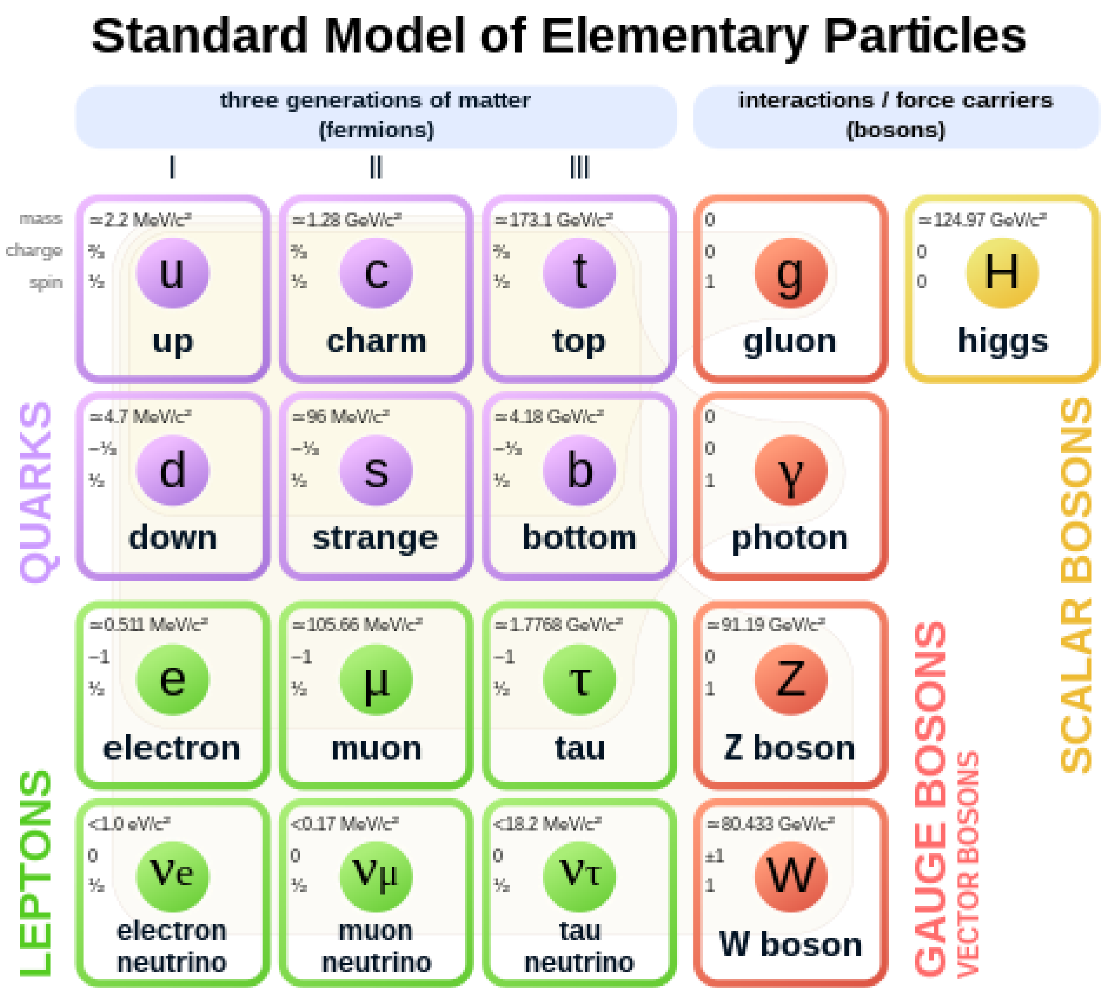
arXiv: 2412.21045，2412.16033

International Conference on the Physics of the Two Infinities

Background



$$\mathcal{L}_{\text{Yukawa}} \supset -\left[y_e \bar{e}_R \Phi^\dagger L_L + y_e^* \bar{L}_L \Phi e_R\right]$$

$$\Phi = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix},$$

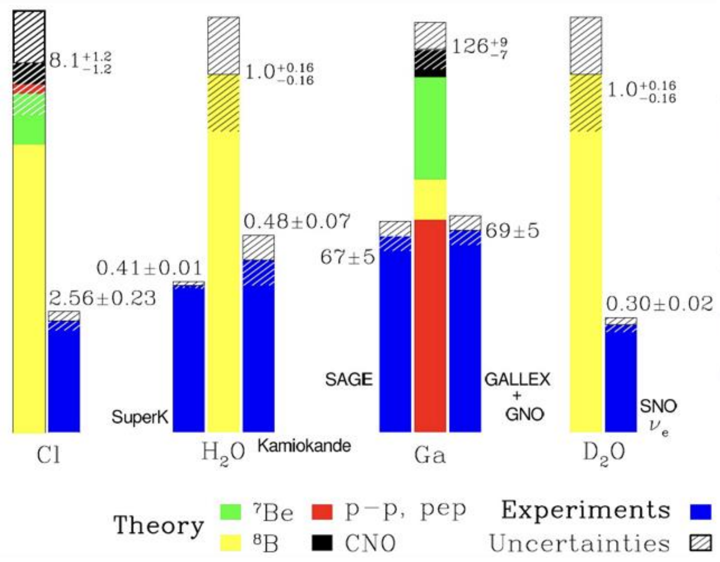
$$\Phi^\dagger L_L = \left(0, \frac{v+h}{\sqrt{2}}\right) \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L = \frac{v+h}{\sqrt{2}} e_L,$$

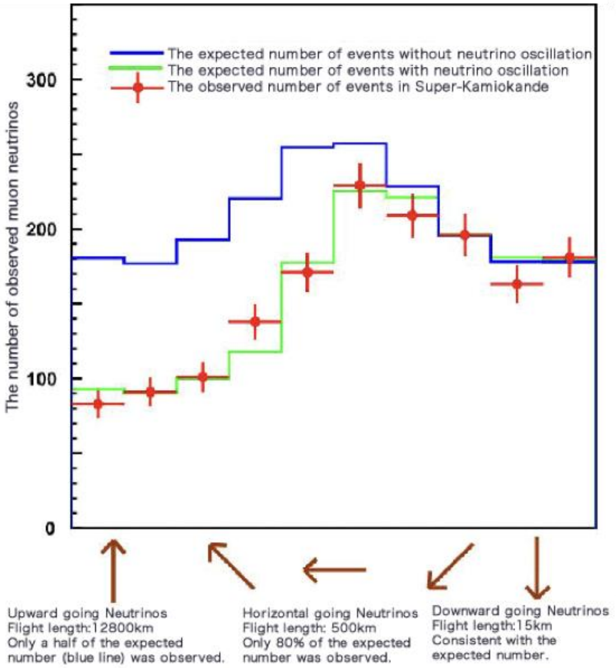
Neutrino masses

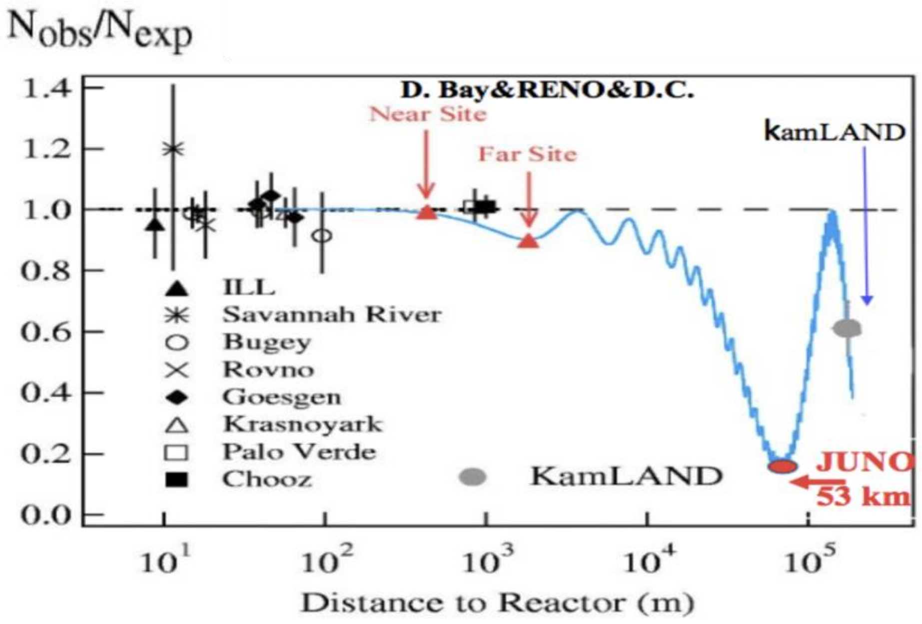
Neutrino oscillation indicates massive neutrinos

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087\,,$$
$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \mathrm{eV}^2\,.$$

JUNO 2025







Solar Neutrino oscillations

θ_{12}

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

Atmospheric Neutrino Oscillations

θ_{23}

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

Reactor Neutrino Oscillations

θ_{13}

Particle Data Group Collaboration, S. Navas et al., Review of particle physics, Phys. Rev.D 110 (2024), no. 3 030001

NuFit-6.0: updated global analysis of three-flavor neutrino oscillations, JHEP 12 (2024) 216, [arXiv:2410.05380]

Cosmological limit

Particle Data Group Collaboration, S. Navas et al., Review of particle physics, Phys. Rev.D 110 (2024), no. 3 030001

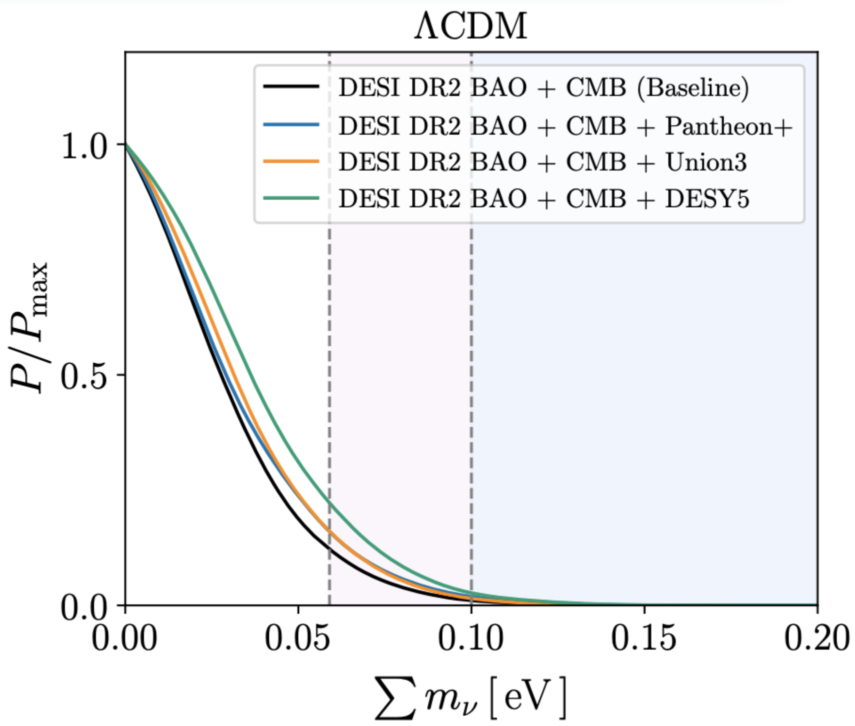
Table 26.2: Summary of $\sum m_\nu$ constraints.

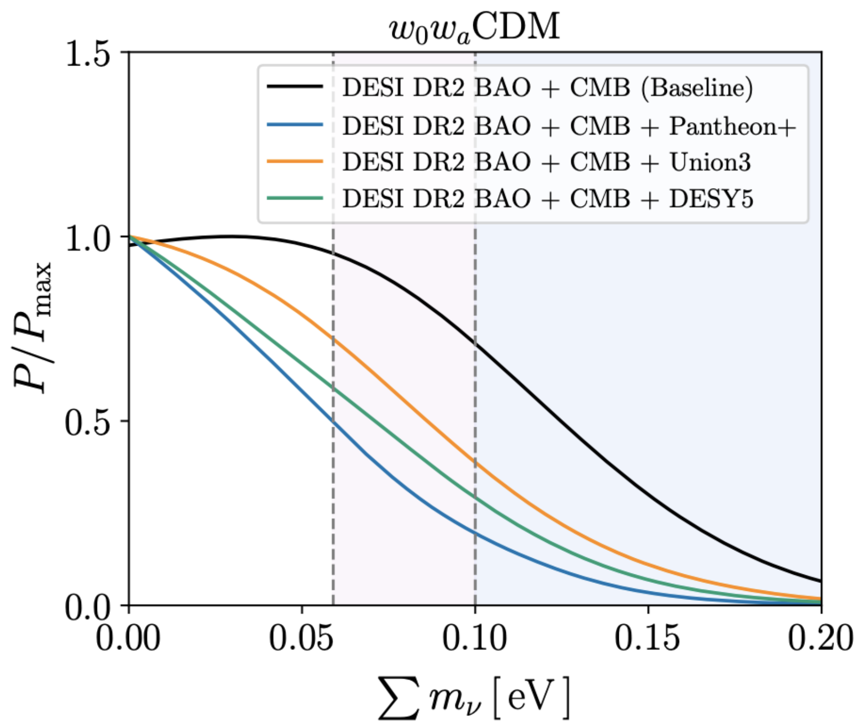
	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[24]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[24]
CMB + probes of background evolution			
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[49]
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[25]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[24]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[24]
Pl18[TT,TE,EE+lowE]+ ACT[lensing]	ΛCDM+$\sum m_\nu$	< 0.12	[50]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[49]
Pl18[TT,TE,EE+lowE+lensing] + BAO + RSD + Shape	ΛCDM+$\sum m_\nu$	< 0.082	[51]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[52]
Pl18[TT,TE,EE+lowE] + BAO + RSD + SN + DES-Y1	ΛCDM+$\sum m_\nu$	< 0.12	[49]
Pl18[TT,TE,EE+lowE] + BAO + RSD + SN + DES-Y3	ΛCDM+$\sum m_\nu$	< 0.13	[53]

Cosmological limit

W. Elbers et al., Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape, Phys. Rev. D 112 (2025), no. 8 083513, [arXiv:2503.14744].

DESI 2025





ΛCDM: DESI DR2 BAO + CMB:

$$\sum m_\nu < 0.0642\,\text{eV} \quad (95\%),$$

w_0w_aCDM: DESI DR2 BAO + CMB + DESY5:

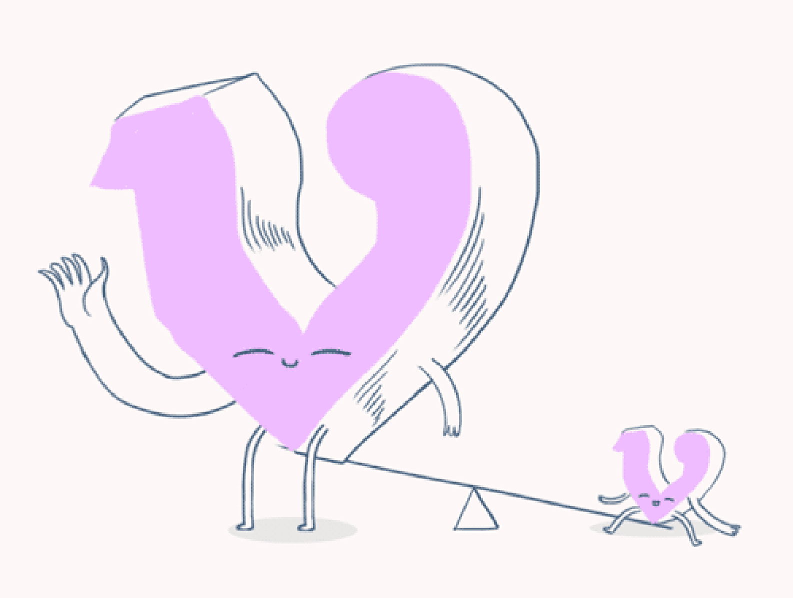
$$\begin{cases} \sum m_\nu < 0.129\,\text{eV} \\ w_0 = -0.76^{+0.12}_{-0.11} \\ w_a = -0.82^{+0.46}_{-0.48} \end{cases} \quad (95\%).$$

The heavy neutrino mass should be around 0.05 eV(IO)-0.06eV(NO)

Seesaw mechanism

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

Origin of neutrino masses: seesaw mechanism



Type I seesaw mechanism

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

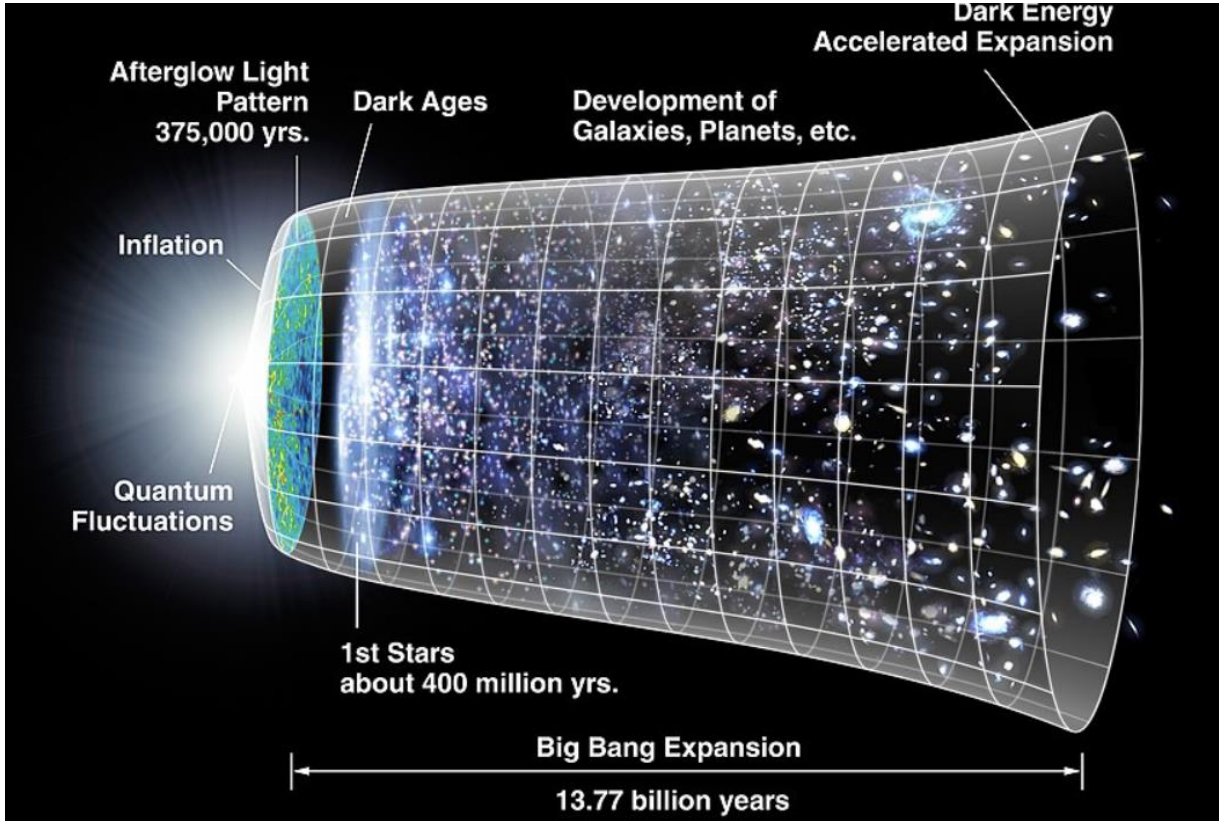
$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad m_\nu \sim \frac{m_D^2}{M_R} = \frac{y_\nu^2 \langle h \rangle^2}{2M_R}$$

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.

$$y_\nu \sim O(1) \Longrightarrow M \sim 10^{14}\mathrm{GeV}$$

How to test such high scale seesaw?

Inflation

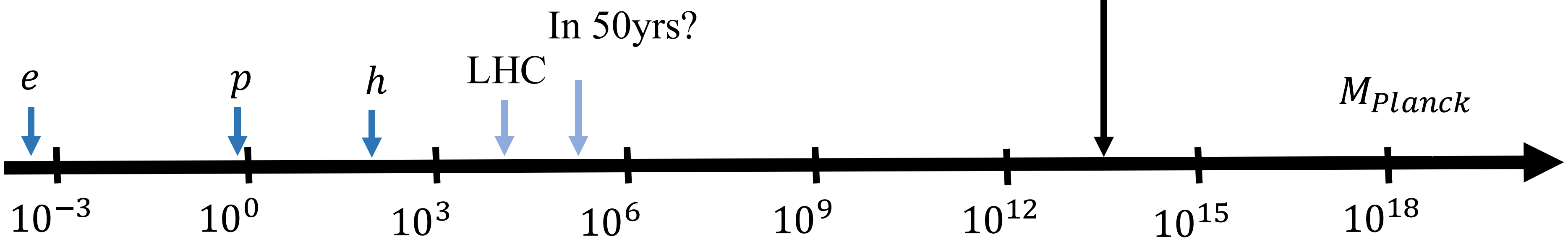


Alexei Starobinsky;
Alan Guth;
Andrei Linde

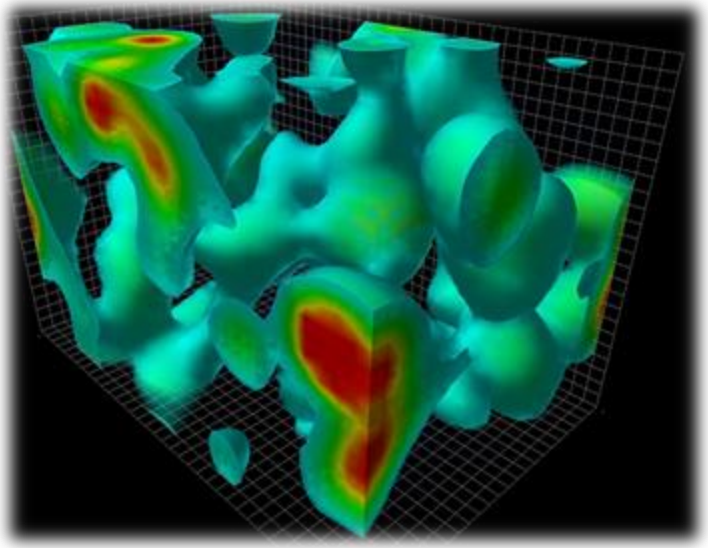
The inflationary universe

$\boldsymbol{H \sim 10^{13}\,\mathrm{GeV}}$

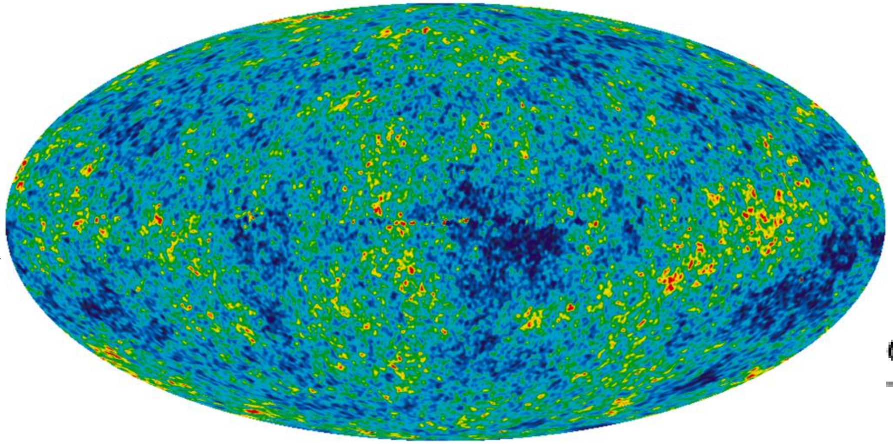
Seesaw Scale:
$M \simeq 10^{14} GeV$



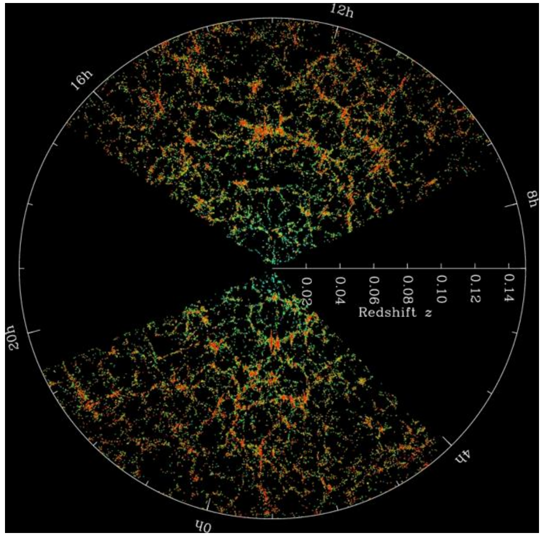
Inflation



Quantum fluctuations during the inflation



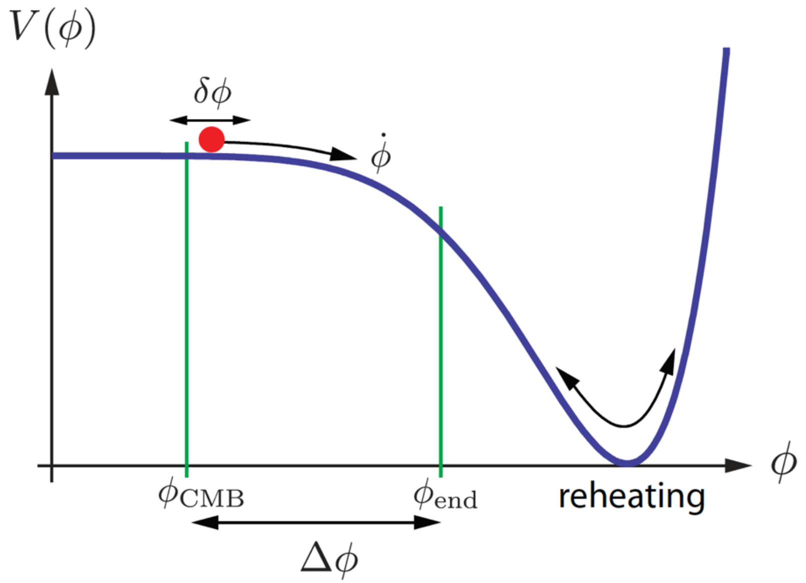
$$\frac{\delta T}{T} \sim 10^{-5}$$



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

Slow-roll Inflation

Inflaton: $\phi(x,\tau)$



- **Quantum fluctuation of inflaton induces CMB anisotropies(or curvature perturbations)**
- **The fluctuations should be nearly gaussian, adiabatic and scale invariant**

- **Slow roll condition: $\epsilon, \eta \ll 1$**

$$\epsilon \equiv -\frac{\dot{H}}{H^2}\,, \qquad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon}$$

$$\epsilon_V = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,, \qquad \eta_V = M_p^2 \frac{V''}{V}$$

$H(t) \simeq$ const. (de Sitter universe)

- **$\phi(x,\tau)$ get quantum fluctuation:**

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

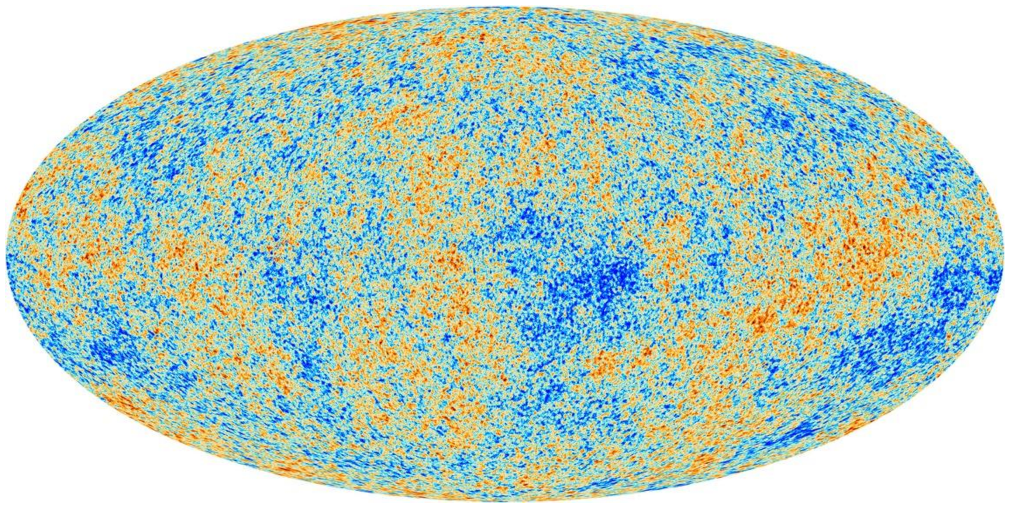
$$u_{\mathbf{k}}(\tau) = \frac{H}{\sqrt{2k^3}}\left[1 + ik\tau\right]e^{-ik\tau}$$

Curvature perturbation $\quad \zeta = -\frac{H}{\dot{\phi}}\delta\phi$

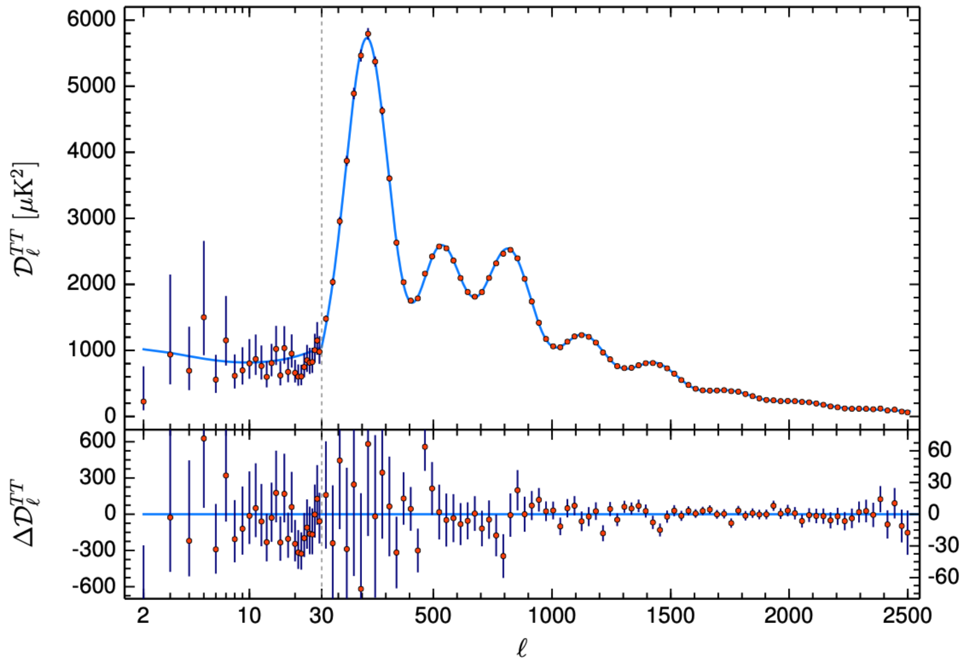
$$\langle \zeta_{\mathbf{k}}\zeta_{\mathbf{k}'}\rangle = (2\pi)^3\delta^3(\mathbf{k}+\mathbf{k}')\frac{2\pi^2}{k^3}P_\zeta(k)$$

$$P_\zeta(k) = \frac{H^4}{4\pi^2\dot{\phi}^2} = \frac{H^2}{8\pi^2\epsilon M_p^2}$$

Measurements from Planck



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



arXiv:1807.06209v4

From Planck 2018

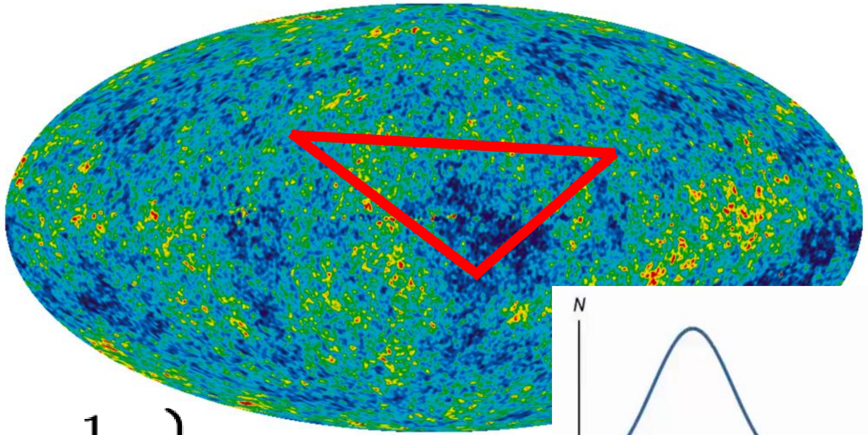
$$\epsilon_V < 0.0097$$

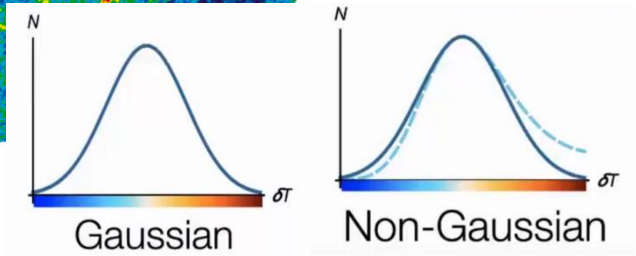
$$\eta_V = -0.010^{+0.007}_{-0.011}$$

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

- **Inflaton potential should be flat enough(shift-symmetry?)**
- **Hubble scale could be as high as 10^{13} GeV(close to seesaw scale), providing a circumstance to interplay with high scale physics**

Non-Gaussianity





Non-Gaussianity is sensitive to new physics

$$\langle \Phi_{\mathbf{k}_1} \Phi_{\mathbf{k}_2} \Phi_{\mathbf{k}_3} \rangle'_{\text{local}} = 2A^2 f_{\text{NL}}^{\text{local}} \left\{ \frac{1}{k_1^3 k_2^3} + \frac{1}{k_2^3 k_3^3} + \frac{1}{k_3^3 k_1^3} \right\}$$

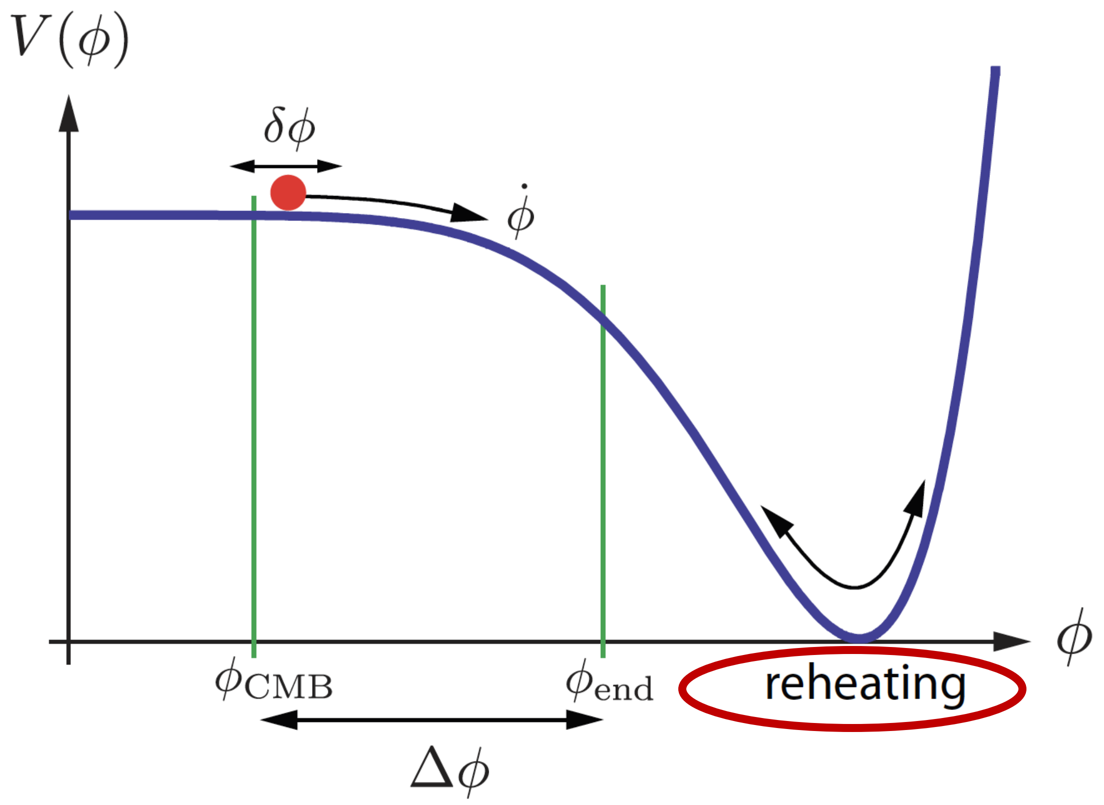
- **Current limit from Planck 2018: f_{NL}~ O(10)**

Shape	Independent	Lensing subtracted
	SMICA *T*	
Local	6.7 ± 5.6	−0.5 ± 5.6
Equilateral	4 ± 67	5 ± 67
Orthogonal	−38 ± 37	−15 ± 37
	SMICA *T*+*E*	
Local	4.1 ± 5.1	−0.9 ± 5.1
Equilateral	−25 ± 47	−26 ± 47
Orthogonal	−47 ± 24	−38 ± 24

Planck 2018 results. IX. Constraints on primordial non-Gaussianity, Astron. Astrophys. 641 (2020) A9, [arXiv:1905.05697].

- **future CMB observations (CMB-S4 , LiteBIRD ...), large scale structure observations (DESI, Euclid...) O(1), 21 cm tomography O(0.01-0.1)**

Reheating



- **After inflation, inflaton oscillates at the bottom of the potential and finally decays into SM particles, then reheats the universe(still no clear how it occurs)**

A minimal model

Minimal model incorporates inflation and seesaw

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

After inflation, the inflaton decays into the neutrinos and thus reheating the universe.

- **Both light and heavy neutrino mass are h dependent**

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

- **Decay rate of the inflaton is "h" dependent:**

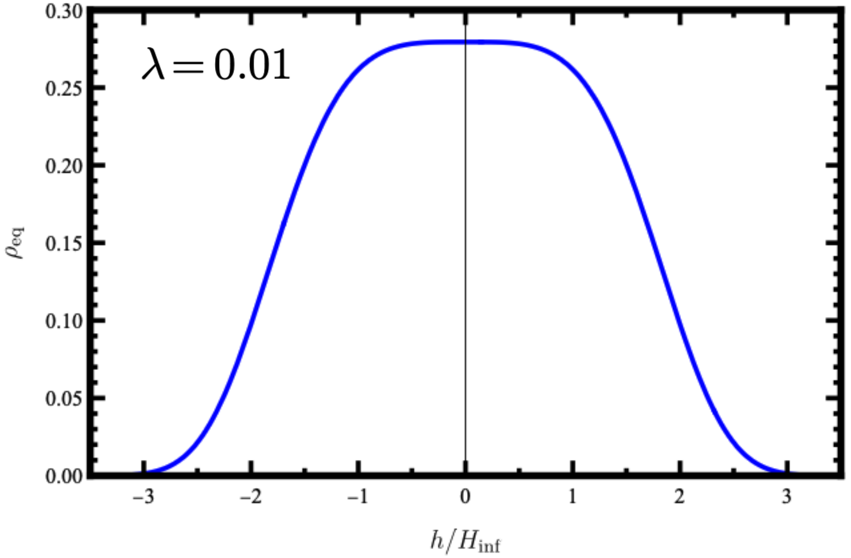
$$\Gamma \simeq \frac{m_\phi M^2}{4\pi\Lambda^2}\left[1 + \frac{1}{4}\left(\frac{y_\nu h}{M}\right)^2\right]$$

What happens to h in the early universe?

Higgs during inflation

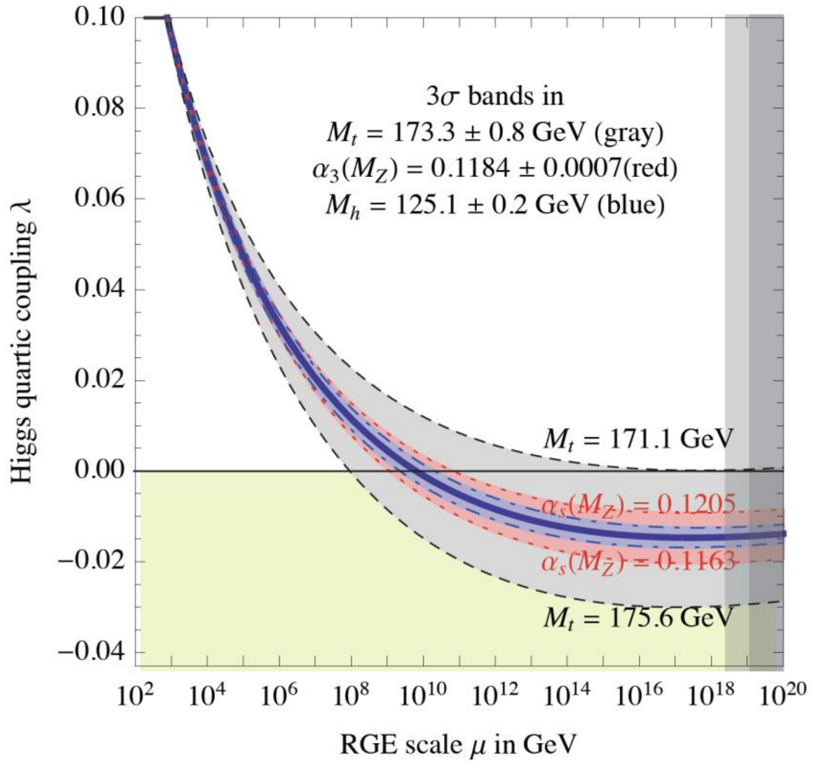
- During inflation(de-Sitter universe), Higgs also gets quantum fluctuations
- If inflation lasts long enough, super-horizon fluctuations reach a equilibrium state

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



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

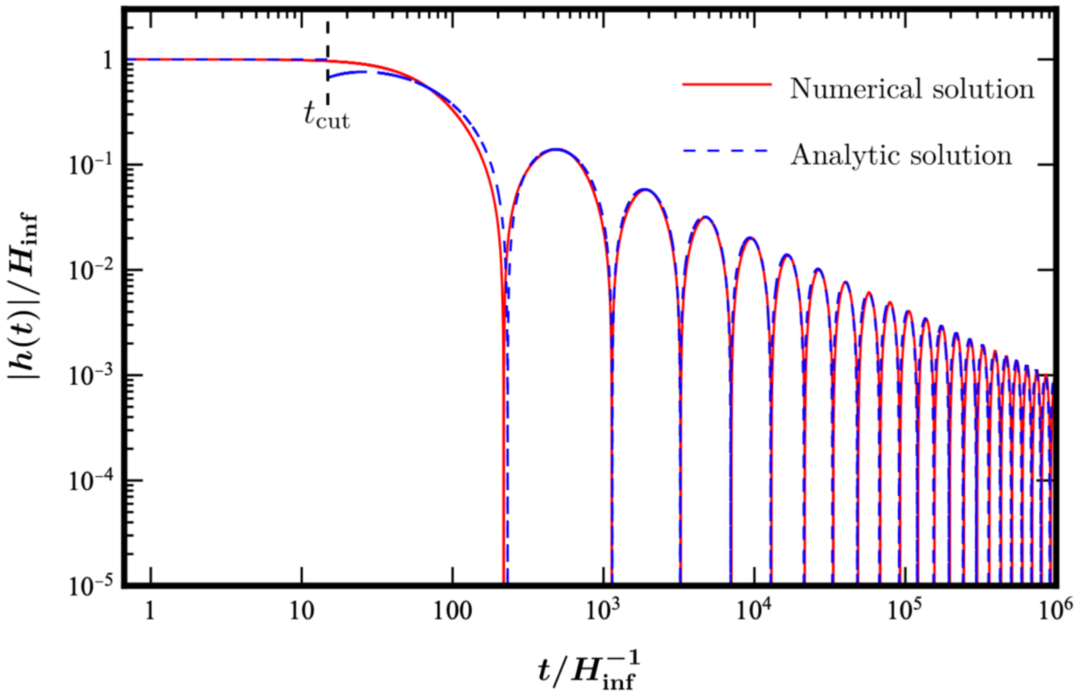
D. Buttazzo, et al arXiv:1307.3536



Higgs after inflation

Inflaton oscillates at the bottom potential. If the inflaton potential is dominated by the mass term, the Universe is matter-dominated: $w = 0,\ a \sim t^{2/3}$

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



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

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

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

Higgs value would oscillate and decrease

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

$$N(\mathbf{x}) = -\frac{1}{3(1+w_1)}\ln\frac{\rho_{\rm reh}(h(\mathbf{x}))}{\rho_{\rm inf}} - \frac{1}{3(1+w_2)}\ln\frac{\rho_f}{\rho_{\rm reh}(h(\mathbf{x}))} = -\frac{1}{6}\ln(\Gamma_{\rm reh})$$

$$w_1 = 0$$

$$w_2 = \frac{1}{3}$$

$$\zeta_h(\delta h_{\rm inf}(\mathbf{x})) = \delta N(\delta h_{\rm inf}(\mathbf{x})) = N'\delta h_{\rm inf} + \frac{1}{2}N''(\delta h_{\rm inf})^2 + \cdots\cdots$$

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

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

$$\Gamma_0' = \left.\frac{d\Gamma_{\rm reh}}{dh_{\rm inf}}\right|_{h_{\rm inf}(\mathbf{x})=\bar h} = \left.\frac{d\Gamma_{\rm reh}}{dh_{\rm reh}}\frac{\partial h_{\rm reh}}{\partial h_{\rm inf}}\right|_{h_{\rm inf}(\mathbf{x})=\bar h},$$

$$\Gamma_0'' = \left.\frac{d^2\Gamma_{\rm reh}}{dh_{\rm inf}^2}\right|_{h_{\rm inf}(\mathbf{x})=\bar h} = \left.\frac{d^2\Gamma_{\rm reh}}{dh_{\rm reh}^2}\left(\frac{\partial h_{\rm reh}}{\partial h_{\rm inf}}\right)^2\right|_{h_{\rm inf}(\mathbf{x})=\bar h} + \left.\frac{d\Gamma_{\rm reh}}{dh_{\rm reh}}\left(\frac{\partial^2 h_{\rm reh}}{\partial h_{\rm inf}^2}\right)\right|_{h_{\rm inf}(\mathbf{x})=\bar h}$$

$$\mathcal{P}_\zeta^{(h)} = z_1^2 \mathcal{P}_{\delta h} = z_1^2 \frac{H^2}{4\pi^2} \qquad R = \left(\frac{\mathcal{P}_\zeta^{(h)}}{\mathcal{P}_\zeta}\right)^{1/2} = |z_1|\left(\frac{\mathcal{P}_{\delta h}}{\mathcal{P}_\zeta}\right)^{1/2}$$

R should be less than 1

Bispectrum of ζ

$$\zeta_h = z_1 \delta h + \frac{1}{2} z_2 \delta h^2$$

Considering the three point correlation function

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle_h = z_1^3 \langle \delta h_{\mathbf{k}_1} \delta h_{\mathbf{k}_2} \delta h_{\mathbf{k}_3} \rangle + z_1^2 z_2 \langle \delta h^4 \rangle (\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

Higgs self-coupling

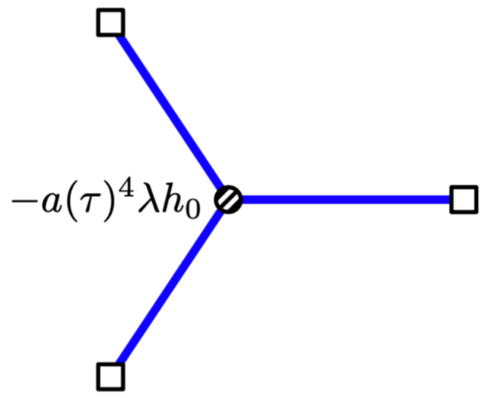
$$\Delta \mathcal{L} = -\sqrt{-g}\,[(\lambda \bar{h}) \delta h^3]$$

Non-linear Evolution

$$\frac{1}{2} z_2 \delta h^2$$

Bispectrum of ζ

First term is from Higgs self-coupling (in-in formalism/Schwinger-Keldysh formalism)



$$\langle \delta h_{\mathbf{k}_1}\delta h_{\mathbf{k}_2}\delta h_{\mathbf{k}_3}\rangle' = \frac{1}{2}\lambda\bar{h}H^2\left\{\left(\frac{1}{k_1^3k_2^3}+2\,\text{perm.}\right)\left(-N_e+\gamma-\frac{4}{3}\right) + \frac{1}{k_1^2k_2^2k_3^2}-\left(\frac{1}{k_1k_2^2k_3^3}+5\,\text{perm.}\right)\right\},$$

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

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

Second term is from non-linear evolution of the Higgs

$$z_1^2z_2\langle\delta h^4\rangle(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = (2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)z_1^2z_2\left[\frac{H^4}{4k_1^3k_2^3}+(2\,\text{perm.})\right].$$

Local type non-Gaussianity

The local type non-Gaussianity(NG) which is defined by Bardeen Poten$\Phi \equiv \frac{3}{5}\zeta$

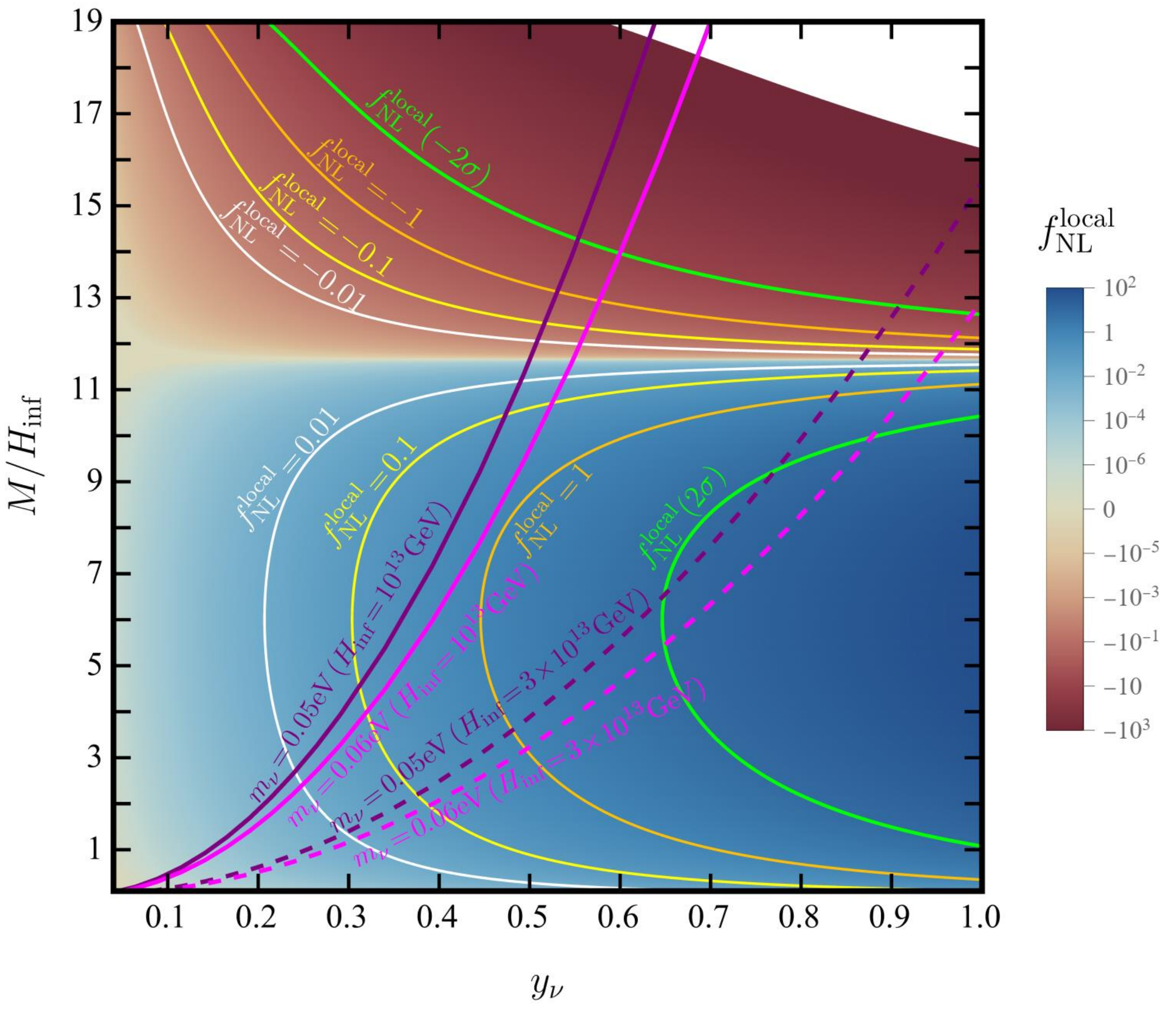
$$\langle \Phi_{\mathbf{k_1}} \Phi_{\mathbf{k_2}} \Phi_{\mathbf{k_3}} \rangle'_{\text{local}} = 2A^2 f_{\text{NL}}^{\text{local}} \left\{ \frac{1}{k_1^3 k_2^3} + \frac{1}{k_2^3 k_3^3} + \frac{1}{k_3^3 k_1^3} \right\}$$

The local NG from our scenario is

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

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

Local type non-gaussianity



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

- **Colored curves indicating future searches**
- **Parameter space with Yukawa O(1) could be probed by future observations**
- **H and neutrino masses are relevant**
- **Interplaying with neutrino experiments(JUNO, DUNE for neutrino ordering)**

Summary

- **High Scale inflation could be a good platform to probe new physics**
- **We propose a minimal model incorporating inflation and seesaw**
- **Seesaw generated non-Gaussianity could be probed in near future CMB or large-scale structure observations**

Thanks!