Right-handed neutrinos as the source of density perturbations

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Based on:

- LB and P. Creminelli , `hep-ph/0602052` – PRD **73** (2006) 103516.

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Experiments

Observations are getting more and more accurate $\rightarrow$ "Precision Cosmology"

- Amplitude of fluctuations $\sim 10^{-5}$
- Scale dependence (tilt) $\lesssim .05$
- Nature of fluctuations
  - Adiabatic? $\left| \dfrac{\delta(n_B/s)}{n_B/s} \Big/ \zeta \right| < 0.3 - 0.4 \quad @ \quad 2\sigma$ Seljak etal.
  - Gaussian? $\dfrac{\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle}{\langle \zeta_{\vec{k}} \zeta_{-\vec{k}} \rangle^{3/2}} \ll 10^{-5}$
  - Tensors? $r \lesssim .22$

- Single field slow-roll inflation $\dot{\phi}^2 \ll V(\phi)$.

$$\zeta \sim \frac{V^{3/2}}{M_P^3 V'}$$

Additional scalars

- The curvaton scenario

Lyth & Wands
Enqvist & Sloth
Moroi & Takahashi

$$\zeta \sim \frac{\delta\sigma}{\sigma_*}$$

- Inhomogeneous reheating

Dvali, Gruzinov & Zaldarriaga
Kofman

$$\zeta \sim \frac{\delta\Gamma_\phi}{\Gamma_\phi}$$

(i) *e.g.* In string theory, there exist a lot of scalars (string moduli) that could be relevant for cosmology.

(ii) They have distinctive experimental signatures in the CMB:

- Non-Gaussianity
- Correlated isocurvature perturbation
- Typically no tensors.

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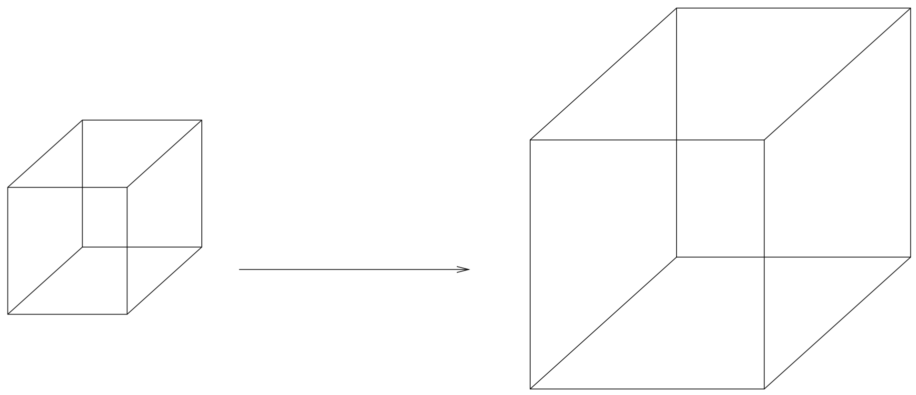
Departure from thermal equilibrium is required!



$T_1 \rightarrow a(T_1)$ $\qquad$ $T_2 < T_1 \rightarrow a(T_2)$

In thermal equilibrium, due to adiabaticity, the scale factor $a \propto 1/T$

$\Downarrow$

NO temperature perturbation can be produced.

$\Downarrow$

Departure from thermal equilibrium is required!

$\downarrow$

One can produce temperature fluctuations during baryogenesis.

Baryon Isocurvature

• Produced baryon number is conserved after baryogenesis (out-of-equilibrium) $\rightarrow$ Baryon isocurvature.

• In contrast with other types of isocurvature, e.g. CDM isocurvature, since CDM is a thermal relic $\rightarrow$ CDM ISO is erased due to thermal equilibrium.

• Baryon isocurvature is correlated with curvature perturbation since produced during the same process.

• Present limits on isocurvature are becoming more and more stringent.

We consider the SM + 3 right-handed neutrinos (Type I seesaw + leptogenesis)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_{ij}\left(\frac{\chi}{M_P}\right) L_i H N_j + M_i \left(\frac{\chi}{M_P}\right) N_i N_i + (\partial\chi)^2$$

with $M_1 > M_2 > M_1 \equiv M$. Consider as usual the decay of the lightest N.

The decay parameter

$$\frac{\Gamma(T=0)}{H(T=M)} = \frac{(Y^\dagger Y)_{11}\cdot M}{8\pi} \Big/ \left(g_*^{1/2}\frac{M^2}{M_P}\frac{2\pi^{3/2}}{\sqrt{45}}\right) \equiv \frac{\widetilde{m}_1}{1.1\times 10^{-3}{\rm eV}} \lessgtr 1,$$

where $g_* \sim 100$, controls departure from thermal equilibrium.

The baryon asymmetry is

$$\frac{n_B}{s} = -\frac{28}{79}\epsilon_{N_1}\eta(\widetilde{m}_1)\frac{n_{N_1}}{s}(T \gg M),$$

where η is the washout parameter and ϵ_{N_1} is the CP parameter $\propto {\rm Im}\left[(Y^\dagger Y)^2_{j1}\right]$.

We can parametrise curvature (temperature) fluctuations produced during RHN decay as

$$ds^2 = -dt^2 + e^{2\zeta(\vec{x})} a(t)^2 d\vec{x}^2$$

up to subleading $O\left(k/(aH)\right)$ terms. k is the comoving wavevector and H is the expansion rate.

Salopek & Bond; Maldacena; Lyth etal.

Thus

$$e^{\zeta(\vec{x})} = \frac{a(T_{\rm low})}{a(T_{\rm high})}(M,\Gamma)$$

$T_{\rm high} \equiv$ temperature before decay.
$T_{\rm low} \equiv$ temperature after decay.

In our scenario, the only relevant parameter is $\widetilde{m}_1$, so

$$e^{\zeta(\vec{x})} = \frac{a(T_{\rm low})}{a(T_{\rm high})}(\widetilde{m}_1)$$

Complete dominance limit

- At $T \gg M$, RHN are relativistic, they contribute $1/g_*$ of the plasma density

$$\rho \propto a^{-4}. \qquad \text{(RD1)}$$

- At $T \sim M$, RHN decouples from the plasma.

- From $T \simeq M/g_*$ until decay $H \sim \Gamma$, the universe is dominated by RHN's

$$\rho \sim \rho_N \propto a^{-3}. \qquad \text{(MD)}$$

- After that RHNs decay into radiation. (RD2)

$$\Downarrow$$

$$\frac{a(T_{\rm low})}{a(T_{\rm high})} \propto M^{1/3}\,\Gamma^{-1/6} \propto \widetilde{m}_1^{-1/6} \qquad \text{for} \quad \widetilde{m}_1 \ll \widetilde{m}^*/g_*^2\ .$$

We recover the standard result

Dvali, Gruzinov, Zaldarriaga

$$\zeta = -\frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

Density perturbations: The general case

In general, one has to solve

$$
\begin{aligned}
\dot{\rho}_\gamma &+ 4H\rho_\gamma = \Gamma\rho_N \\
\dot{\rho}_N &+ 3\big(1 + w_N(T/M)\big)H\rho_N = -\Gamma\rho_N \\
H^2 &= \frac{8\pi}{3M_P^2}(\rho_N + \rho_\gamma)\ .
\end{aligned}
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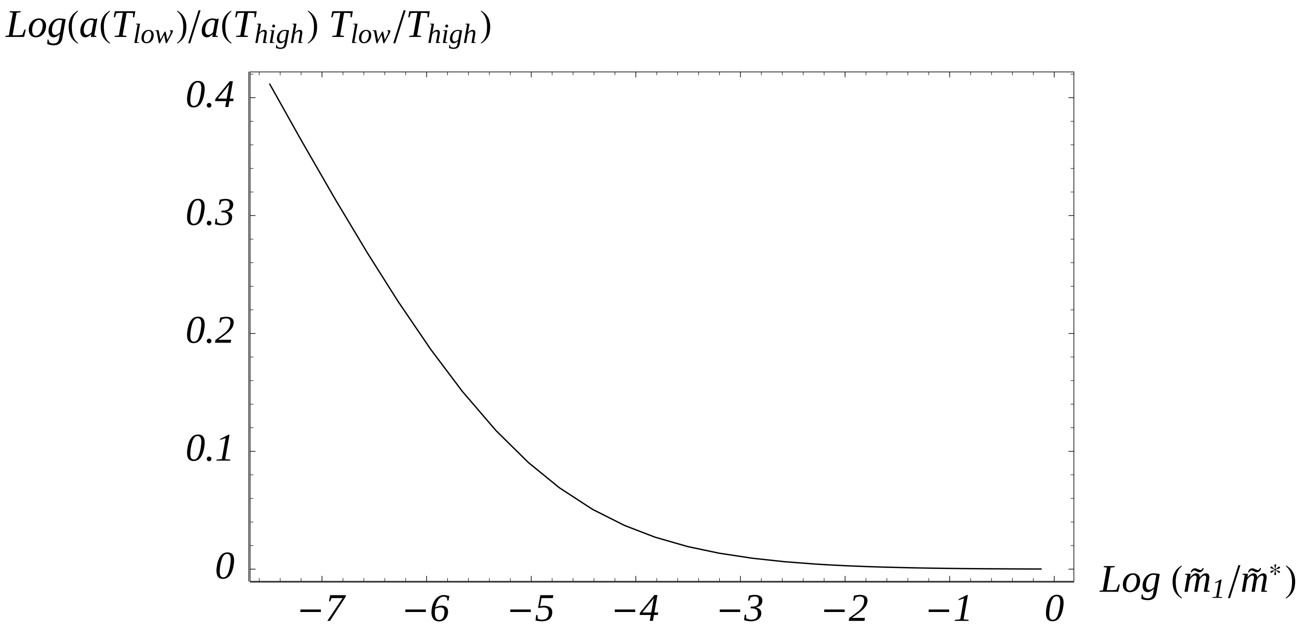

The non-linearity parameter $f_{\rm NL}$ is defined as

$$\zeta(\vec{x}) = \zeta_g(\vec{x}) - \frac{3}{5} f_{\rm NL} (\zeta_g^2(\vec{x}) - \langle \zeta_g^2(\vec{x}) \rangle)$$

In our case $\zeta = f(\log \widetilde{m}_1 / \widetilde{m}^*)$.

$$\zeta(\vec{x}) = f' \frac{\delta \widetilde{m}_1}{\widetilde{m}_1}(\vec{x}) + \frac{1}{2}(f'' - f') \left(\frac{\delta \widetilde{m}_1}{\widetilde{m}_1}(\vec{x}) \right)^2 \, ,$$

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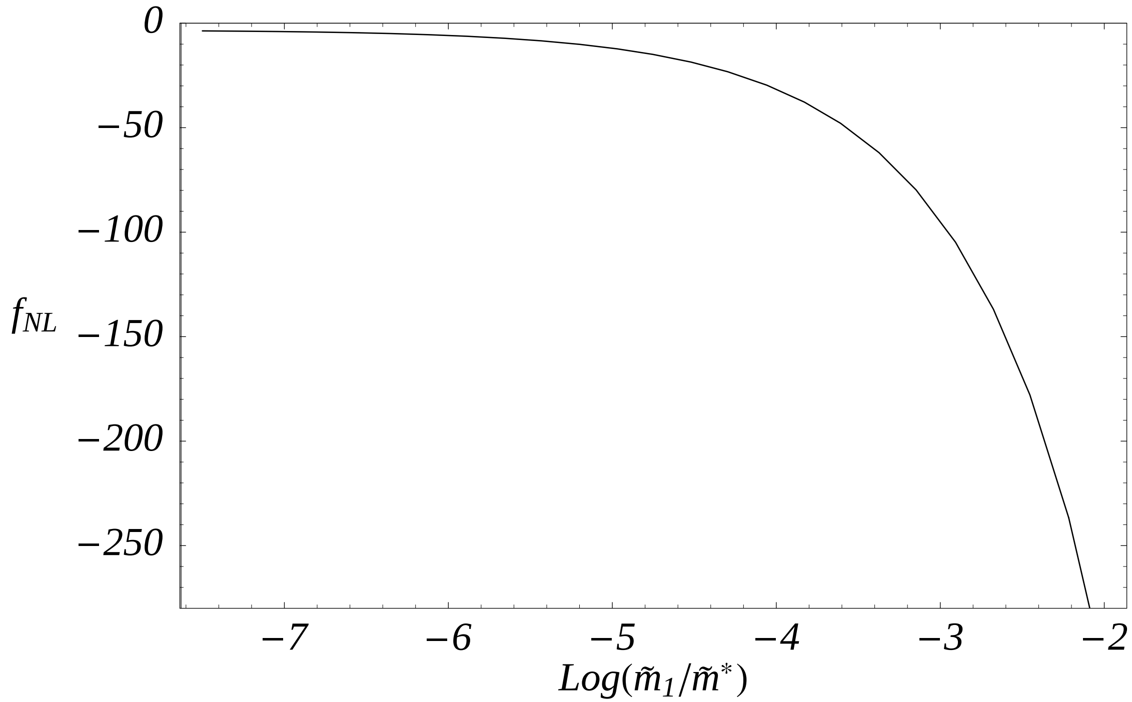
$$f_{\rm NL} = -\frac{5}{6} \frac{f'' - f'}{f'^2}$$



Experimental limit Creminelli etal.

$-27 < f_{\rm NL} < 121$ @ 95% C.L.

$\widetilde{m}_1 < 10^{-6}$ eV $\Rightarrow m_1 < 10^{-6}$ eV

Correlated Baryon Isocurvature

Non-Gaussianity constraint the RHN to be very out-of-equilibrium. Wash-out can be neglected.

The simplest case, where ϵ_{N_1} is constant

$$\frac{\delta(n_B/s)}{n_B/s} = -\frac{\delta s}{s} = -3\frac{\delta T}{T} = -3\zeta \qquad \text{RULED OUT}$$

In general

$$\frac{\delta(n_B/s)}{n_B/s}\Big/\zeta = -3 + \frac{\delta\epsilon_{N_1}/\epsilon_{N_1}}{\zeta} \qquad \text{Can be} \lesssim .3$$

- More generally, one can consider all the three RHN to produce both n_B/s and ζ. Baryon number is washed out by the lightest RHN decay (at least partially) but ζ is not.

- More flavor dependence in $\chi - N_i$ couplings.

Example: N_2 is way out-of-equilibrium $\rightarrow \zeta$ and N_1 is close to equilibrium and produces baryon isocurvature.

Dynamics of the scalar χ

So far, we assumed that the scalar is just frozen. However, its coupling to the plasma will produce a back-reaction.

- $M(\chi/M_P)NN \to \ddot{\phi} + 3H\dot{\chi} + \frac{M'}{M_P}T^3 = 0 \Rightarrow \Delta\chi \sim \frac{M'}{M}\frac{MT^3}{H^2 M_P^2}M_P.$

During RHN domination: $\Delta\chi > \frac{M'}{M}M_P > M_P$! given the constraints on GWs.

- $Y(\chi/M_P)LHN \to \ddot{\chi} + 3H\dot{\chi} + \frac{Y'Y}{M_P}T^4 = 0 \Rightarrow \Delta\chi \sim \frac{Y'}{Y}\frac{Y^2T^4}{H^2 M_P^2}M_P$

The displacement $\Delta\chi \ll M_P$ for small Yukawas.

- χ will start oscillating when $m_\chi > H$. It must decay before dominating (moduli problem): very model dependent.

CONCLUSIONS

- Modulated RHN decay as the source of density perturbations.
- Adiabatic perturbations related to $\delta\widetilde{m}_1/\widetilde{m}_1$.
- Signatures: Non-Gaussianity + baryon isocurvature.
- Limits on NG requires N_1 to decay very out-of-equilibrium $\widetilde{m}_1 < 10^{-6}$ eV.
- Baryon Isocurvature $\sim$ adiabatic $\rightarrow$ we must see something in the new data.
- Evolution of the scalar: under control if only Yukawas are modulated.
- Is it possible that χ is still around? (light) can it behave as a chameleon?

Khoury & Weltman