The right-handed (s)neutrino in the Early Universe

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Motivation

Masses of the SM neutrinos

$\rightarrow$ **Seesaw mechanism**

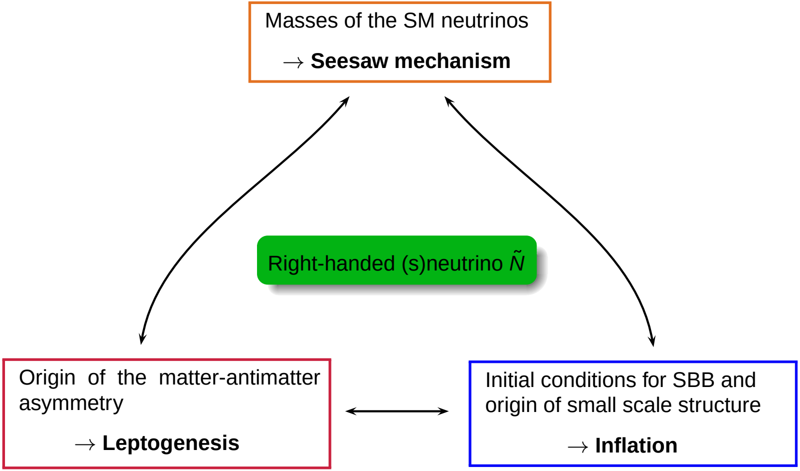
Origin of the matter-antimatter asymmetry

$\rightarrow$ **Leptogenesis**

Initial conditions for SBB and origin of small scale structure

$\rightarrow$ **Inflation**

Motivation


Masses of the SM neutrinos
→ **Seesaw mechanism**
Right-handed (s)neutrino $\tilde{N}$
Origin of the matter-antimatter asymmetry
→ **Leptogenesis**
Initial conditions for SBB and origin of small scale structure
→ **Inflation**

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$\longleftrightarrow$

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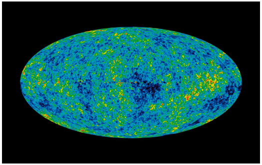
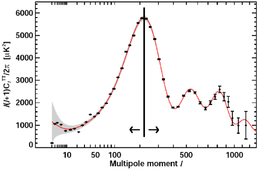
Inflation

Why Inflation

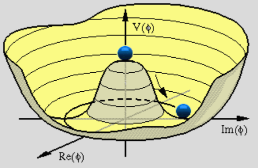
Inflation can explain ...



... why the Universe is so homogeneous and isotropic



... why the Universe is spatially flat

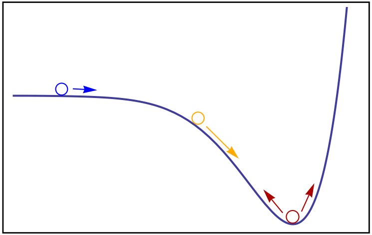


... the absence of stable topological relics

... the origin of the small scale structure

Slow-roll Inflation

- Utilize a slowly rolling scalar field that's trapped at its potential to drive inflation
- Inflation ends when the kinetic energy starts to dominated (i.e. when the slow-roll conditions get violated)
- After inflation the inflaton oscillates around the minimum of the potential $\rightsquigarrow$ reheating (see later)



Given the potential of the inflationary model, predictions can be derived that can be compared to experimental data !

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \quad , \quad \eta = M_P^2 \frac{V''}{V}$$

$$n_s \simeq 1 - 6\epsilon + 2\eta$$
$$r \simeq 16\epsilon$$

$$\langle 0|(\mathcal{R}(x,t))^2|0\rangle = \int \frac{\mathrm{d}k}{k}\mathcal{P}_\mathcal{R}(k)$$
$$n_s - 1 = \frac{1}{\mathrm{d}ln(k)}\mathrm{d}\mathcal{P}_\mathcal{R}(k)$$

$$0.939 < n_s < 0.987 \quad (95\%CL)$$
$$r < 0.24 \quad (95\%CL)$$

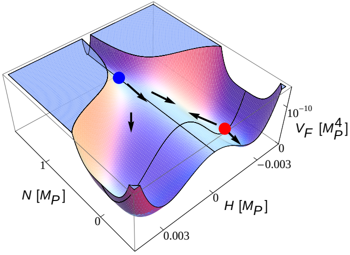
[WMAP Collaboration]

Sneutrino Tribrid Inflation

Superpotential: $W = W_{\text{MSSM}} + Y_N\, \hat{h}_a\, \varepsilon^{ab} \hat{L}_b\, \hat{N} + \frac{\lambda}{M_P} \hat{N}^2 \hat{H}^2 + \kappa \hat{S}(\hat{H}^2 - M^2)$

Kaehler Potential: $K = |\hat{S}|^2 + |\hat{H}|^2 + \frac{1}{2}(\hat{N} + \hat{N}^\dagger)^2 + \frac{\kappa_{SH}}{M_P^2} |\hat{S}|^2 |\hat{H}|^2 + K_{\text{MSSM}} + \dots$

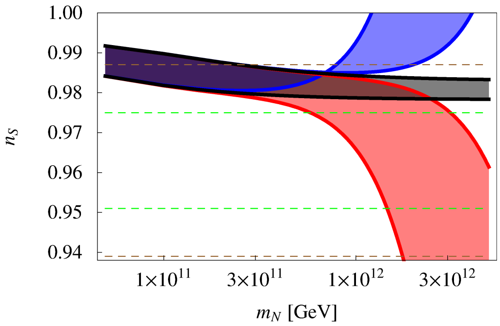
- Supersymmetric tribrid inflation model
- $V_F = e^{K/M_P^2} \left[\mathcal{D}_i W \cdot K^{i\bar{j}} \cdot \mathcal{D}_{\bar{j}} \bar{W} - 3|W|^2/M_P^2 \right]$
  $+$ loop corrections
- Includes SuperGravity effects $\rightsquigarrow \kappa_{SH}$
- **Right-handed sneutrino is the inflaton particle**
- **Mass for the right-handed neutrino is generated dynamically after the end of inflation**



Scalar F-term potential

Inflationary Predictions

- Spectral index n_s



$\kappa_{SH} = 0$, $\kappa_{SH} = 1$, $\kappa_{SH} = 2$

$10^{10}\text{GeV} \lesssim m_N \lesssim 10^{13}\text{GeV}$

- Tensor-to-scalar ratio r : $r < 0.015$

Leptogenesis

Why Baryogenesis

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.19 \pm 0.15)\, 10^{-10}$$ *[WMAP Collaboration]*

Why is there matter in the Universe but no anti-matter ???

Necessary conditions to generate a baryon asymmetry *[Sakharov 1967]*:

- Baryon number violation
  $\rightsquigarrow$ to create baryon asymmetry
- C and CP violation
  $\rightsquigarrow$ otherwise $(i \to f)$ and $(i \to f)^{C/CP}$ at the same rate
  with $\Delta B(i \to f) = -\Delta B(i \to f)^{C/CP}$
- Departure from thermal equilibrium
  $\rightsquigarrow$ otherwise $(i \leftrightarrow f)$ at the same rate, washing out any asymmetry

A Possibility : Leptogenesis

- Generate a Lepton asymmetry through the decay of heavy right-handed Majorana neutrinos $N \to LH$, $N \to \bar{L}\bar{H}$

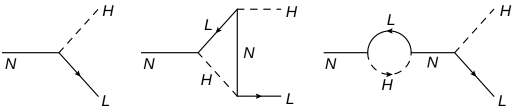
  $\rightsquigarrow$ C & CP violation, s. below

- Transfer the Lepton asymmetry to the Baryon sector (at finite temperature) through SM sphaleron processes

- Sakharov's conditions ?

  (1) B violation :
  L violation & sphaleron processes ✓

  (2) C & CP violation :



✓

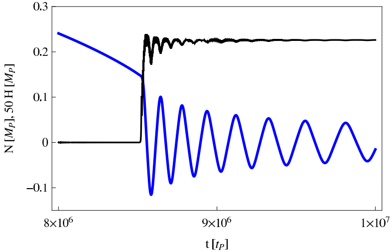
  (3) Departure from thermal equilibrium :
  Either N is produced non-thermally (as in our model),
  or N is produced thermally and decouples when $\Gamma_N \ll \mathcal{H}$ ✓

Non-thermal Leptogenesis after Inflation

Dynamics after inflation :

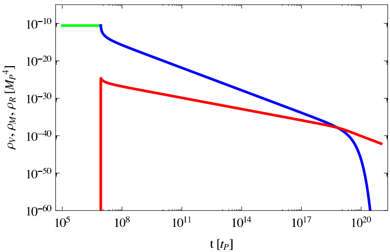
- Massive scalar fields oscillate around their minimum, damped by a decay term
- Simultaneous production of light particles, i.e. radiation

Oscillation of the scalar fields



inflaton (sneutrino) field
waterfall field

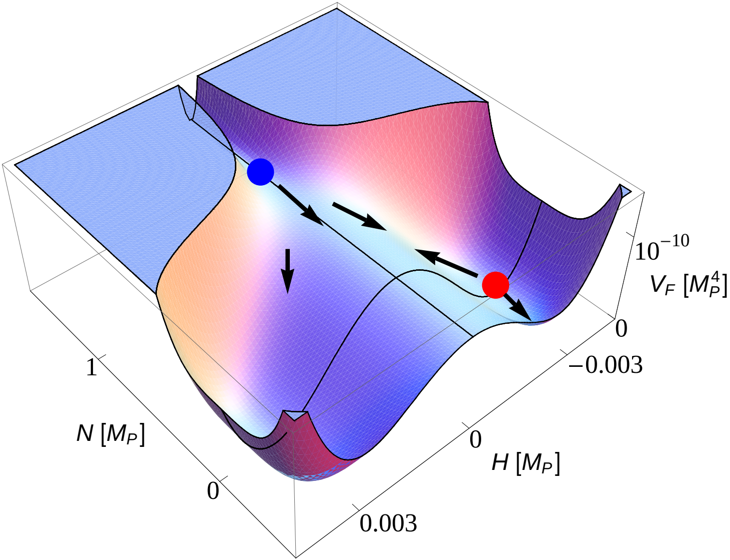
Energy densities after inflation



vacuum energy
matter
radiation

Sneutrino dominated Universe after inflation ⇝ Non-thermal leptogenesis

Dynamics after Inflation



$$W = W_{\rm MSSM} + Y_N\, \hat{h}_a\, \varepsilon^{ab} \hat{L}_b\, \hat{N} + \frac{\lambda}{M_P} \hat{N}^2 \hat{H}^2 + \kappa \hat{S}(\hat{H}^2 - M^2)$$

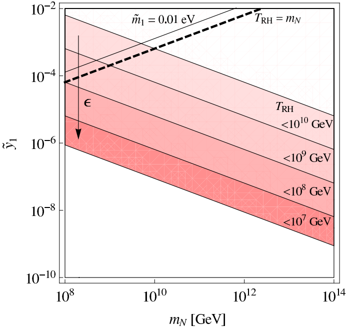
$$\tilde{N} \to L\,\tilde{h}\,,\, \tilde{L}\,h$$

$$m_N = \frac{2\lambda}{M_P} M^2 \qquad \tilde{H} \to N_3 N_3 \quad N_3 \to L\,h\,,\, \tilde{L}\,\tilde{h}$$

$$\tilde{y}_1 = Y_N$$

$$T_{RH} \sim Y_N \sqrt{m_N M_P}$$

$$\Delta n_B \sim \epsilon Y_N \sqrt{\frac{M_P}{m_N}}$$



Seesaw

Recap: Seesaw (Type I)

How can the lightness of the SM neutrinos be explained in a natural and economical way?
$\rightarrow$ **Seesaw mechanism**

Only extension to the SM : Right-handed neutrino N

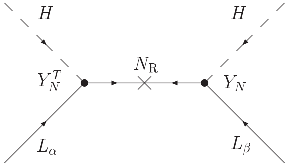
- Singlet under the SM gauge group $\rightsquigarrow$
  allowed to have a large Majorana mass $\mathcal{L} \supset -\frac{1}{2} M \bar{N} N^c + h.c.$
- Add Yukawa coupling to the left-handed Lepton-doublet with $Y_N \simeq \mathcal{O}(Y_e)$
  $\mathcal{L} \supset -Y_N^* \bar{L}\, \varepsilon H^* N + h.c.$

After integrating out the heavy right-handed neutrino (in the low energy limit, i.e. the SM) we generate a mass term for the active neutrino:

$$m_\nu \simeq -\frac{1}{2} \frac{Y_N^2 v^2}{M}$$

E.g. for $M \simeq 10^{12}$ GeV and $Y_N \simeq 10^{-6}$ we get:
$m_\nu \simeq 3 \cdot 10^{-9}$ eV.

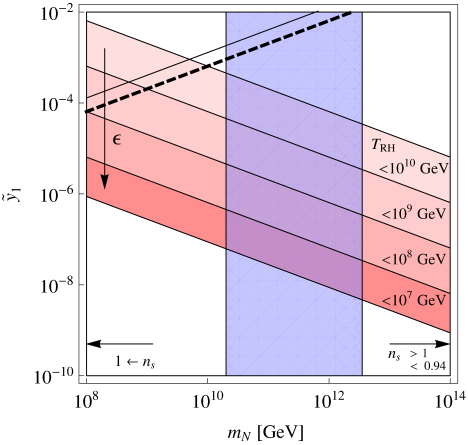
A generalization to 3 families is straightforward.



Type I Seesaw

Conclusions

Combining Inflation & Leptogenesis

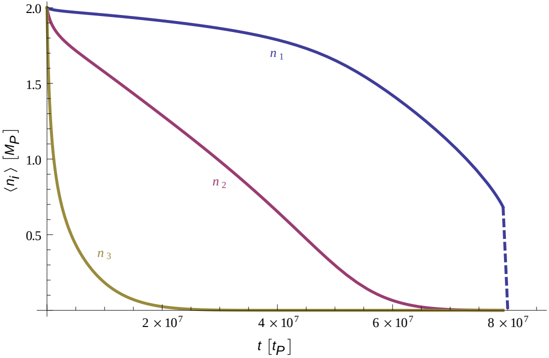


- $m_N = \mathcal{O}(10^{10} - 10^{13})$ GeV
- $Y_N = \mathcal{O}(10^{-9} - 10^{-4})$
- $m_\nu < \mathcal{O}(10^{-4})$ eV

Conclusions

- The right-handed (s)neutrino plays a crucial role in solving some of the outstanding questions of Early Universe Cosmology
- It can provide a link to (low-energy) particle physics
- Combining Inflation and Leptogenesis in one model helps to constrain the allowed parameter space
- We found a model which successfully describes inflation and leptogenesis for a parameter range compatible with low energy neutrino physics
- In this model the right-handed sneutrino is the inflaton, which makes leptogenesis very effective

One-Generation Model ?



$\kappa = 0.5$

$M = 0.0033\, M_P$

$\lambda_1 = 0.005$
$\lambda_2 = 0.05$
$\lambda_3 = 0.5$