Early Universe Cosmology Meets Neutrino Physics

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Based on a collaboration with S. Antusch, J. P. Baumann and P. M. Kostka

See also arxiv: 1007.0708 [hep-ph]

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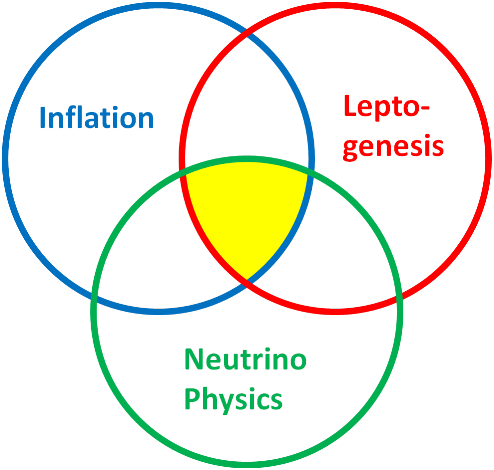
Motivation and Outline

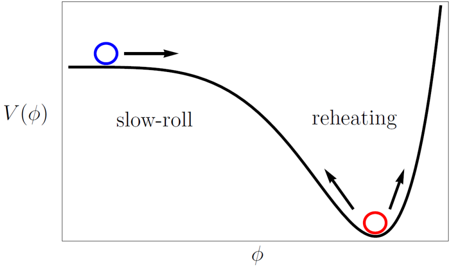


Slow-roll Inflation in a Nutshell

- Slowly rolling homogeneous scalar field
  $\rightarrow$ exponential expansion of the universe.

- 'Stretched' quantum fluctuations
  $\rightarrow$ CMB inhomogeneities, e.g. spectral index n_s.

- End of inflation: Scalar fields oscillate around the minimum of the potential



The Road to Inflationary Predictions

Particle physics framework	$\Rightarrow$	Scalar potential	$\Rightarrow$	CMB spectrum

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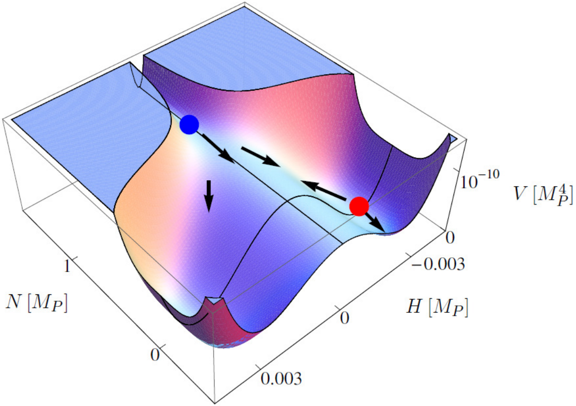
- SUSY, SUGRA
- MSSM + right-handed neutrinos (Seesaw mechanism)
- + 2 gauge singlets $\rightarrow$ Hybrid Inflation Potential

$$W = W_{\text{MSSM}} + (y_\nu)_{ij} N\, L \cdot H_u + \frac{\lambda_{ii}}{M_P} H^2 N^2 + \kappa\, S\, (H^2 - M^2) + \ldots$$

Kähler potential with shift symmetry: $N \rightarrow N + i\mu$

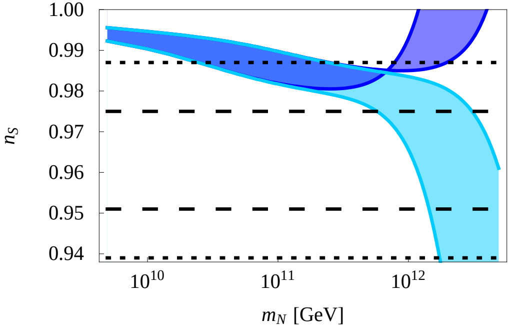
The Road to Inflationary Predictions

Particle physics framework ⇒ Scalar potential ⇒ CMB spectrum



Inflaton = Sneutrino

Particle physics framework ⇒ Scalar potential ⇒ CMB spectrum



− } SUGRA
+ } corrections

.... 95% CL
− − − 68% CL

[WMAP '09]

Dynamics at the End of Inflation

Massive scalar fields

$$\ddot{\phi} + 3\mathcal{H}\dot{\phi} + \frac{\partial V}{\partial \phi} + \Gamma_\phi \dot{\phi} = 0 \quad \phi = \{N, H\}$$

Boltzmann equation for light particles

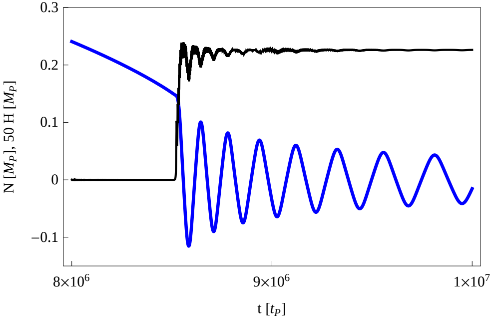
$$\dot{\rho_R} + 4\mathcal{H}\rho_R - \sum_\phi \Gamma_\phi \rho_\phi = 0$$

Friedmann equation

$$\frac{1}{3}(\sum_\phi \rho_\phi + \rho_R) = \mathcal{H}^2$$

Dynamics at the End of Inflation

- Heavy scalar fields



H field
Sneutrino field

$\Rightarrow$ Sneutrino dominated universe

- Hubble parameter

$$\mathcal{H}(t) = \Gamma_N \Rightarrow \text{Reheat temperature: } T_{RH} \sim \rho_R^{1/4}\Big|_{\rho_R = \rho_M}$$

$$\Rightarrow \text{Gravitino problem}$$

Leptogenesis

$$\frac{n_B}{n_\gamma} = (6.19 \pm 0.15) \cdot 10^{-10}$$

[Komatsu '10]

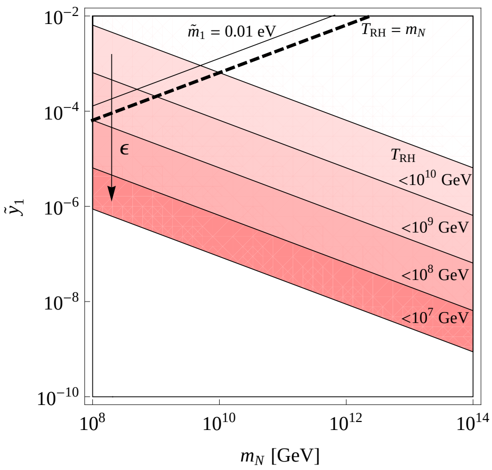
Leptogenesis:

- Generate matter asymmetry dynamically in lepton sector
- Typically via decay of heavy neutrino
- Transfer to baryon sector via SM processes (Sphalerons)

Nonthermal Leptogenesis:

- Produce (s)neutrinos nonthermally
- In our framework: universe is sneutrino dominated after inflation

Combining Reheating and Leptogenesis



- Reheating + Leptogenesis

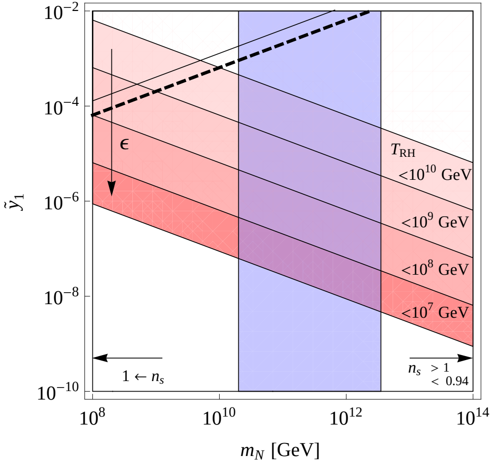
$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)_{11}}$$

$$m_N = \text{(s)neutrino mass}$$

$$\tilde{m}_1 = \tilde{y}_1^2 \, \langle H_u \rangle^2 \, / \, m_N$$

$$\epsilon < \frac{3}{8\pi} \frac{\sqrt{\Delta m_{\text{atm}}^2} m_N}{\langle H_u \rangle^2}$$

[S. Davidson, A. Ibarra '02]



- Reheating + Leptogenesis
- Inflation

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[S. Davidson, A. Ibarra '02]

Implications for Neutrino Physics

Mass of lightest right-handed neutrino

$$m_N = \mathcal{O}(10^{10} - 10^{13})\ \text{GeV}$$

Effective first generation neutrino Yukawa coupling

$$\widetilde{y}_1 = \mathcal{O}(10^{-9} - 10^{-4})$$

Mass of lightest left-handed neutrino

$$m_{\nu_1} \lesssim \mathcal{O}(10^{-4})\ \text{eV}$$

Conclusions

General Picture

Particle physics framework	$\Rightarrow$	Inflation	$\rightarrow$	CMB spectrum	$\Leftarrow$	Exp.
		Leptogenesis	$\rightarrow$	reheat temperature, matter asymmetry		

Specific case

Sneutrino hybrid inflation

$+$

Nonthermal leptogenesis

$\Downarrow$

Constraints on neutrino physics parameters

Backup slides

framework

$$W = W_{\text{MSSM}} + (y_\nu)_{ij} N^i H_u \cdot L^j + \frac{\lambda_{ii}}{M_P} (N^i)^2 H^2 + \kappa S(H^2 - M^2) + \ldots$$

- MSSM
- Seesaw mechanism
- Heavy neutrino mass
  $m_N \sim \langle H \rangle$

framework

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[S. Antusch, M. Bastero-Gil, S. King, Q. Shafi '04]

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$$K = |S|^2 + |H|^2 + |H_u|^2 + \sum_i \frac{1}{2}(N^i + (N^i)^\dagger)^2 + \sum_j |L^j|^2 + \frac{\kappa_{SH}}{M_P^2}|S|^2|H|^2 + \ldots .$$

- η - problem resolved by shift symmetry

[S. Antusch, K. Dutta and P. Kostka '09]

Proof of Existence: W and K from Discrete Symmetries

Superfield content and imposed symmetries

	H	S	N	X	Y	Z
Z_2	-	$+$	-	$+$	$+$	$+$
Z_4	0	2	0	1	1	0
Z_6	2	0	1	4	0	5
R	1/2	0	0	0	1/2	0

$\Rightarrow$ Terms in W and K up to dimension 6

$$W = S(H^2\langle X\rangle^2 - \langle Y\rangle^2) + N^2 H^2 + \langle Y\rangle^2 S^3 + \ldots$$
$$K = (N\langle Z\rangle + N^*\langle Z\rangle^*)^2 + \ldots$$

[S. Antusch, K. Dutta and P. Kostka '09]

Inflation

Scalar potential

$$V_{\text{tree}} = e^K \left[K^{i\bar{j}} D_i W D_{\bar{j}} W^\dagger - 3|W|^2 \right] \Big|_{\Phi \to \phi}$$

$$V_{\text{loop}} = \frac{1}{64\pi^2} \text{STr} \left[\mathcal{M}^4 \left(\ln \frac{\mathcal{M}^2}{Q^2} - \frac{3}{2} \right) \right]$$

Slow-roll equation

$$3\,\mathcal{H}\,\dot{\phi} = -V' \,.$$

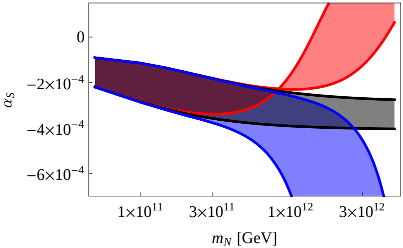
CMB observables

$$P_{\mathcal{R}}(k) \simeq P_{\mathcal{R}}(k_0) \left(\frac{k}{k_0} \right)^{n_s - 1}$$

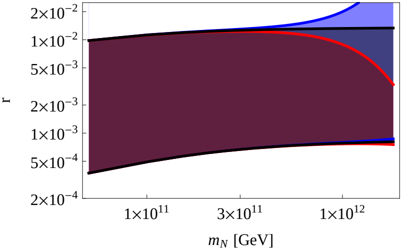
$$n_s \simeq 1 - 3 \left(\frac{V'}{V} \right)^2 + 2 \frac{V''}{V} \Big|_{\phi = \phi_e}$$

Results from Inflation II

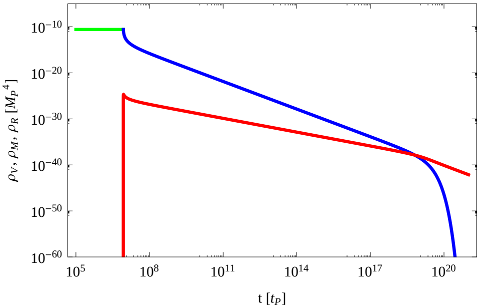
Running of spectral index α_s



Tensor-to-scalar ratio r



Dynamics at the End of Inflation: Energy Densities



Vacuum
Matter
Radiation

} energy density

$\Rightarrow$ Reheat temperature: $T_{RH} \sim \rho_R^{1/4}\big|_{\rho_R=\rho_M}$

$\Rightarrow$ Gravitino problem