Inflation & Leptogenesis in a Particle Physics Context

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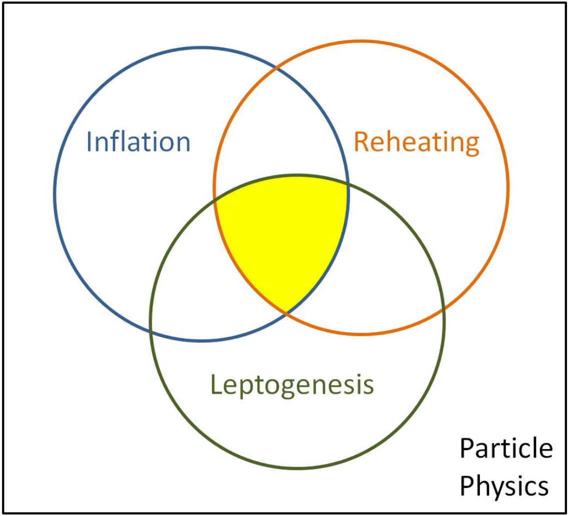
Based on a collaboration with S. Antusch, J.P. Baumann and P.M. Kostka

See also arxiv: 1007.0708

Young Scientists Workshop Ringberg, 28.7.2010

Motivation



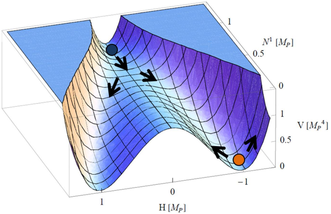
Outline

1. Introduction
   - (Inflation)
   - Reheating
   - Leptogenesis
2. An Interesting Scenario
   - Sneutrino Hybrid Inflation
   - Nonthermal Leptogenesis
   - Results
3. Conclusion

Outline

Recapitulation: Essentials of Inflation

- Slowly rolling classical scalar field
  → exponential expansion of the universe.
- 'Stretched' quantum fluctuations
  → CMB inhomogeneities, e.g. spectral index n_s.
- End of inflation:
  Scalar fields oscillate around the minimum of the potential



The next step: Dynamics after the End of Inflation

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

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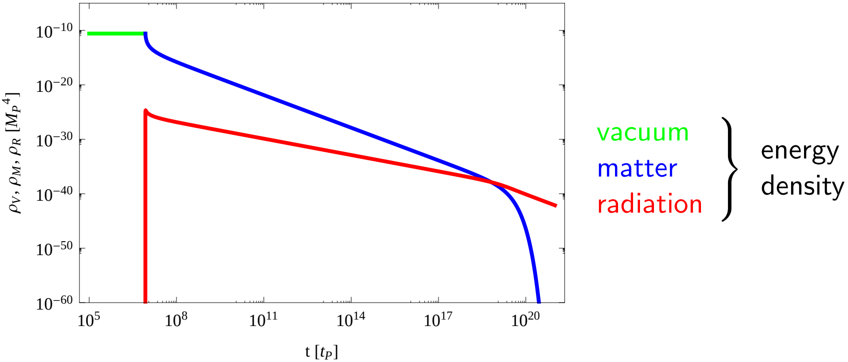

- Reheat temperature: $T_{RH} \sim \rho_R^{1/4}\big|_{\rho_R = \rho_M}$ ($\rightarrow$ gravitino problem)

Why do we need Leptogenesis?

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

WMAP 7 year survey
[Komatsu 2010]

- Why is this number not zero, i.e. why are we here?
  (At the end of inflation: $\frac{n_B - n_{\bar{B}}}{n_\gamma} = 0$)

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Leptogenesis:

- Generate asymmetry dynamically in lepton sector, possibly during reheating
- Transfer to baryon sector via SM processes (Sphalerons)

The Sakharov Conditions

Baryon asymmetry can be generated dynamically in the early universe, if [Sakharov '67]:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Found in the SM, but: not enough!

Introducing a New Particle

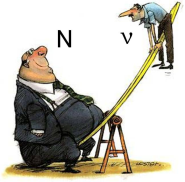
- Standard Model: Why is the neutrino ν so light?
- Possible new physics:

ν carries no charge

$\rightarrow$ Can be Majorana particle
(particle = antiparticle)

$\rightarrow$ New terms in $\mathcal{L}$:
massive right handed neutrino N

$\rightarrow$ Seesaw mechanism:
Can explain small mass for ν



$\Rightarrow$ Decay of N can generate sufficient amount of asymmetry!

Outline

Recent Work

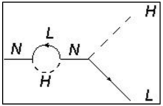
Superpotential

$$W = W_{\text{MSSM}} + (y_\nu)_{ij} \hat{N}^i \hat{h}_a \epsilon^{ab} \hat{L}^j_b + \frac{\lambda_{ii}}{M_P} (\hat{N}^i)^2 \hat{H}^2 + \kappa S(\hat{H}^2 - M^2) + \ldots$$

\+

Kähler potential

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



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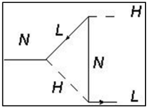

$$V_F = e^K \left[K^{i\bar{j}} D_i W D_{\bar{j}} W^* - 3|W|^2 \right] \Big|_{\Phi \to \phi},$$

$$(M_F)_{ij} = e^{K/2} (W_{ij} + K_{ij} W + K_i W_j + K_j W_i + K_i K_j W - K^{k\bar{l}} K_{ij\bar{l}} D_k W) \Big|_{\Phi \to \phi}.$$

$$(m_H^{(S)})^2 = 2\kappa^2 M^2 \left[x - 1 + \left(\frac{M}{M_P} \right)^2 (1 - \kappa_{SH})/2 \right],$$

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$$(m_H^{(F)})^2 = 2\kappa^2 M^2 x,$$

$$(m_{h_a}^{(S)})^2 = (m_{h_a}^{(P)})^2 = \kappa^2 \frac{M^4}{M_P^2} + \frac{1}{2} N^2 \sum_j |y_{1j}|^2,$$

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Dynamics

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

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

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

$$\dot{n}_{L-\bar{L}} + 3\mathcal{H}\, n_{L-\bar{L}} = \sum_\phi \epsilon_\phi \Gamma_\phi \frac{\rho_\phi}{m_\phi}$$

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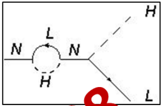

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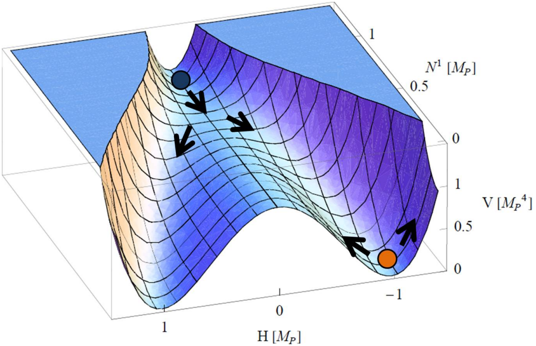
Sneutrino Hybrid Inflation

- Supersymmetric hybrid inflation model
- Scalar potential (include 1-loop corrections)

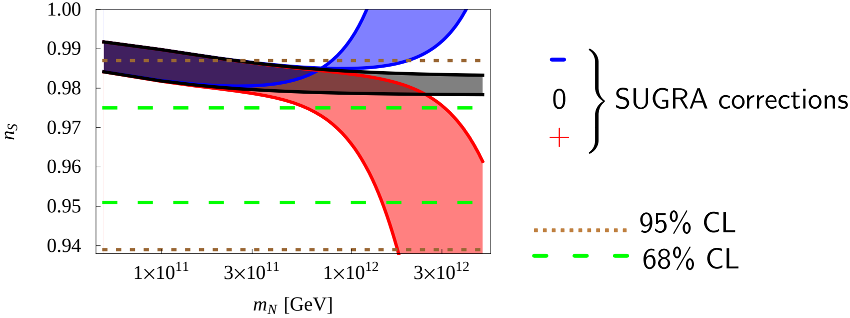


Inflaton = lightest right handed sneutrino

- Right handed neutrino masses generated dynamically at 'waterfall' ending inflation
- Include supergravity (SUGRA)

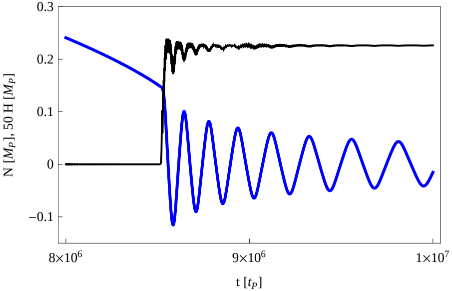
Results from Inflation

The spectral index n_s and the (s)neutrino mass m_N:



Reheating and Nonthermal Leptogenesis

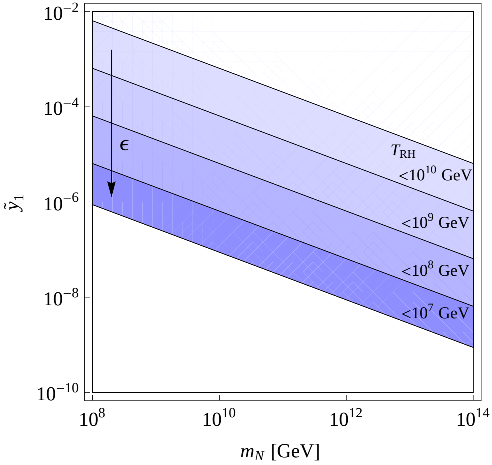
- Dynamics of the scalar fields after inflation



waterfall field
sneutrino field

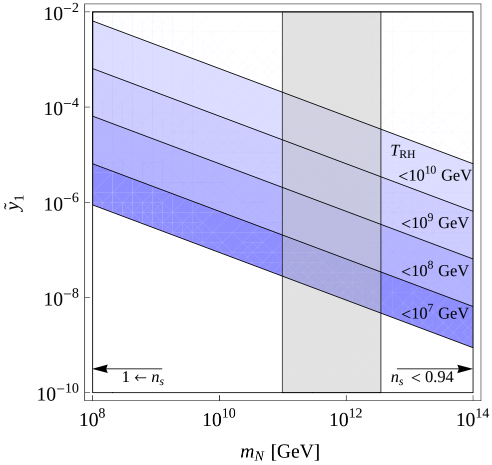
- Sneutrino dominated universe → nonthermal leptogenesis

Results from Reheating/Leptogenesis



$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)}$$
$$m_N = \text{(s)neutrino mass}$$
$$\epsilon = \text{CP violation}$$

Combining Inflation, Reheating and Leptogenesis



Inflation&Leptogenesis ✓
Predictive ✓

Implications for Particle Physics

- Mass of lightest right handed (s)neutrino:
  $m_N = \mathcal{O}(10^{10} - 10^{12})$ GeV
- Mass of lightest left handed neutrino:
  $m_{\nu_1} = \mathcal{O}(10^{-17} - 10^{-4})$ eV
- Effective first generation neutrino Yukawa coupling:
  $\widetilde{y}_1 = \mathcal{O}(10^{-9} - 10^{-4})$

Outline

Conclusion and Outlook

Particle physics model	⇒				⇐ Exp.
		Inflation	→	CMB spectrum	
		Reheating	→	reheat temperature	
		Leptogenesis	→	matter asymmetry	

⇒ Constraints on particle physics parameters

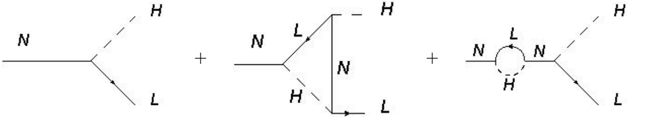
The End

Thank You

Leptogenesis: An Example

$N \to H\,L, \;\; N \to \bar{H}\,\bar{L}$

1. $\not{B}$: $\not{L}$ (N is Majorana) + Sphalerons ✓
2. $\not{C}$, $\not{CP}$:



✓

3. ~~thermal equilibrium~~: if $m_N \gg T_{\text{universe}}$ ✓

Nonthermal and thermal scenario possible

Superpotential and Kähler Potential

Superpotential

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Kähler potential

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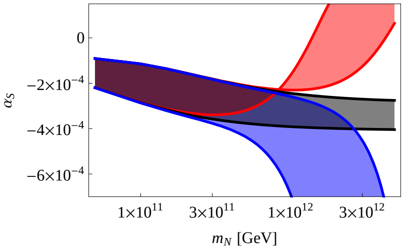
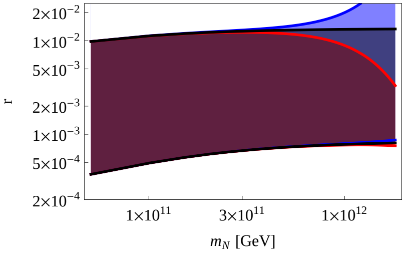
Results from Inflation II

Running of spectral index α_s



Tensor-to-scalar ratio r



Quantitative Analysis

- Massive scalar fields:

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

- Boltzmann equation for light particles:

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

- Friedmann equation:

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

- Boltzmann equation for lepton asymmetry

$$\dot{n}_{L-\bar{L}} + 3\,\mathcal{H}\,n_{L-\bar{L}} = \sum_\phi \epsilon_\phi \Gamma_\phi \frac{\rho_\phi}{m_\phi}$$