Sneutrino Hybrid Inflation

Talk by Stefan Antusch

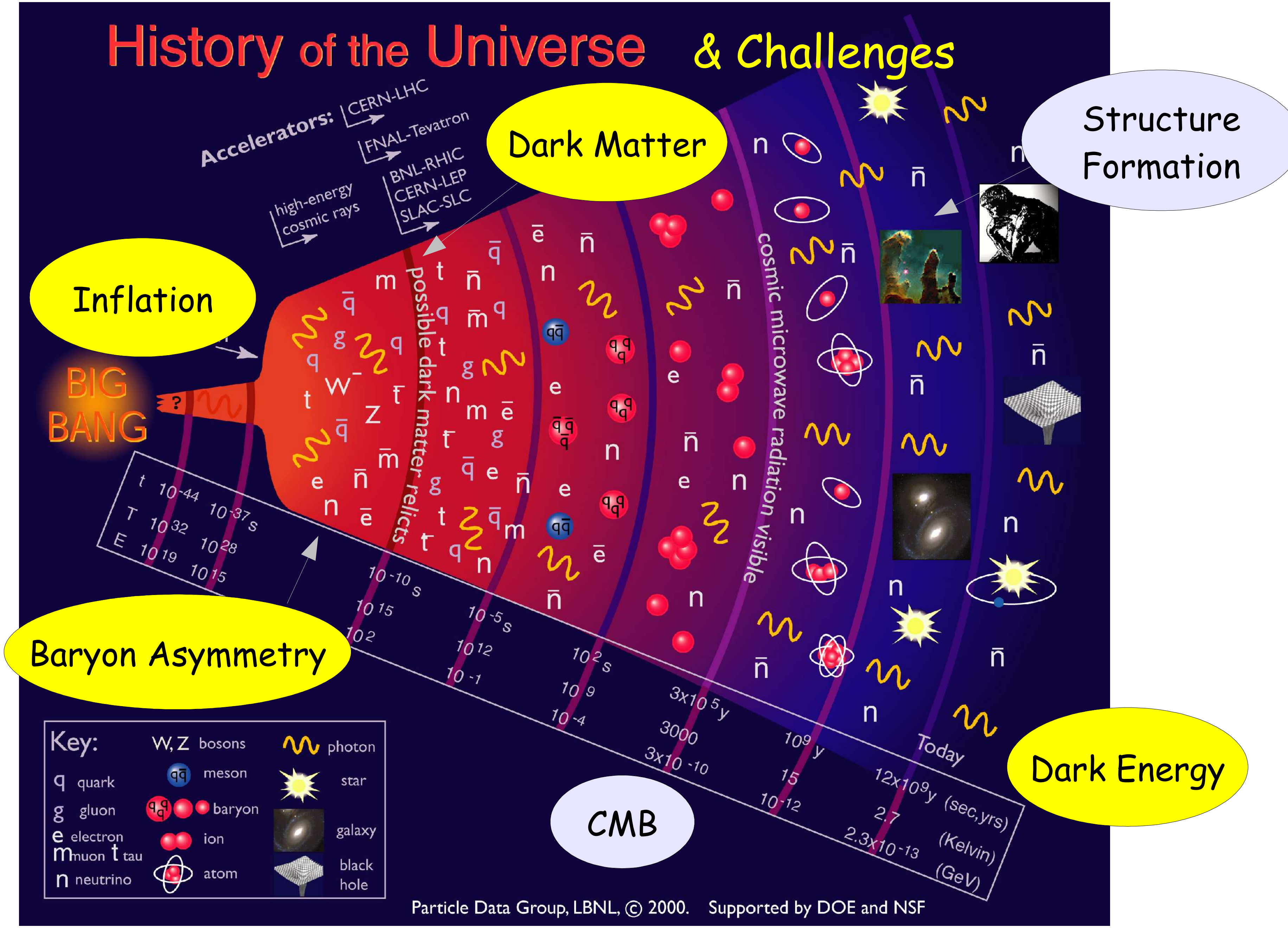
based on: 'Sneutrino Hybrid Inflation in Supergravity',
Phys.Rev. D71 (2005) 083519, (hep-ph/0411298)

in collaboration with:
M. Bastero-Gil, S.F. King and Q. Shafi

International Workshop:
The Dark Side of the Universe

IFT UAM CSIC

Madrid, June 2006

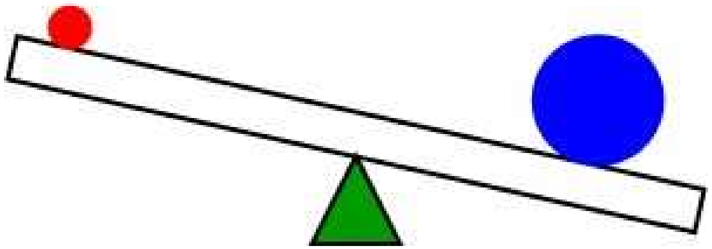


$1\ eV \approx 1.6 \times 10^{-19}\ J$

How is cosmology connected to particle physics?

Motivation

SUSY +



See-Saw Mechanism:

Right-Handed Neutrinos N_i

(MSSM singlet)

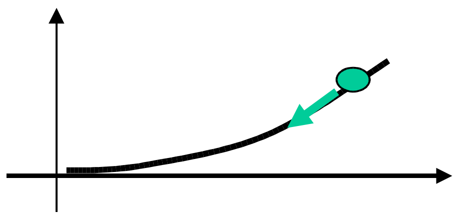
$\Rightarrow$ Sneutrinos $\tilde{N}_i$

Can (one of) the sneutrinos play the role of the inflaton?

Motivation

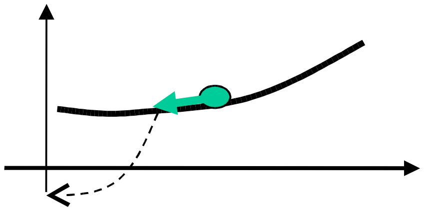
Types of (Sneutrino) Inflation?

Large field chaotic inflation:
- e.g. $V \sim m_\phi^2 \phi^2$; $m_\phi \approx 10^{13}$ GeV
- $\phi > m_P$



Chaotic Sneutrino Inflation ($V \sim \phi^2$)
Murayama, Suzuki, Yanagida, Yokoyama ('93)

Hybrid inflation:
- typically, field values << m_P
- inflation ends by 'waterfall'
- 'promising' for relating inflation to particle physics



Sneutrino Hybrid Inflation?

Content

A minimal scenario for 'Sneutrino Hybrid Inflation'

- Superpotential, Kähler potential
- The inflationary epoch, the end of inflation
- Predictions for the CMB observables

Non-thermal leptogenesis and reheating in 'Sneutrino Hybrid Inflation'

- Low reheat temperature possible

'Sneutrino Hybrid Inflation' vs. 'Chaotic Sneutrino Inflation'

- Distinguishable via predictions for CMB observables

Summary , Conclusions and Outlook

Superpotential for Sneutrino Hybrid Inflation

Waterfall field ϕ

Sneutrinos (inflaton) $\tilde{N}_i$

$$\mathcal{W} = \kappa \hat{S} \left(\frac{\hat{\phi}^4}{M'^2} - M^2 \right) + \frac{(\lambda_\nu)_{ij}}{M_*} \hat{N}_i \hat{N}_j \hat{\phi}\hat{\phi} + \ldots$$

This term fixes the vev of the waterfall field after inflation and gives vacuum energy during inflation

Gives positive square mass to the waterfall field during inflation; large right-handed neutrino masses after inflation

Fields:

- $\hat{N}_i$: Neutrino superfields, contain the sneutrinos $\tilde{N}_i$ as scalar components
- $\hat{\phi}$: Superfield which contains the waterfall field ϕ as scalar component (MSSM singlet)
- $\hat{S}$: MSSM singlet superfield, scalar component S
- ...

Scales: M, M' and M_* (most general: independent scales)

Symmetries

Note: Symmetries may be violated by higher order terms (dots in W)

$$W = \kappa \hat{S} \left(\frac{\hat{\phi}^4}{M'^2} - M^2 \right) + \frac{(\lambda_\nu)_{ij}}{M_*} \hat{N}_i \hat{N}_j \hat{\phi}\hat{\phi} + \ldots$$

Symmetries:

- Discrete symmetry Z_4: sneutrinos $\tilde{N}_i$ and ϕ have unit charge, S uncharged, ...
  - forbids direct mass term for the (s)neutrinos!
- $U(1)_R$: e.g. W and S can carry charge 1 while charge of $\tilde{N}_i$ is 1/2;
  - forbids further unwanted terms
  - under suitable conditions the $U(1)_R$ can lead to matter parity

Remark:

- Z_4-breaking after inflation: Possible domain wall networks 'blown away' when the dots in W include Z_4-violating terms (such as e.g. $S\,\phi^5/M'^3$ or even $S\,\phi^5/m_P^3$)

The Kähler Potential

for simplictiy: assume only one sneutrino $\tilde{N}$ as the inflaton)

Expansion (all fields << m_P):

Large (> H) mass for S for κ_s < -1/3!

$$\mathcal{K} = |\hat{S}|^2 + |\hat{\phi}|^2 + |\hat{N}|^2 + \kappa_S \frac{|\hat{S}|^4}{4m_{\mathrm{P}}^2} + \kappa_N \frac{|\hat{N}|^4}{4m_{\mathrm{P}}^2} + \kappa_\phi \frac{|\hat{\phi}|^4}{4m_{\mathrm{P}}^2}$$

$$+ \kappa_{S\phi} \frac{|\hat{S}|^2|\hat{\phi}|^2}{m_{\mathrm{P}}^2} + \kappa_{SN} \frac{|\hat{S}|^2|\hat{N}|^2}{m_{\mathrm{P}}^2} + \kappa_{N\phi} \frac{|\hat{N}|^2|\hat{\phi}|^2}{m_{\mathrm{P}}^2} + \dots$$

For $\kappa_{s\phi}$ - 1 > 0: negative contribution to square mass of the waterfall field

Contribution to the inflaton mass during inflation ⇒ η-problem

Contributes significantly to the scalar potential!

$$V_{\mathrm{F}} = e^{\mathcal{K}/m_{\mathrm{P}}^2} \left[K_{ij}^{-1} D_{z_i} \mathcal{W} D_{z_j^*} \mathcal{W}^* - 3 m_{\mathrm{P}}^{-2} |\mathcal{W}|^2 \right]$$

where: $$D_{z_i}\mathcal{W} := \frac{\partial \mathcal{W}}{\partial z_i} + m_{\mathrm{P}}^{-2} \frac{\partial \mathcal{K}}{\partial z_i} \mathcal{W}, \quad K_{ij} := \frac{\partial^2 \mathcal{K}}{\partial z_i \partial z_j^*}$$

$$\hat{z}_i \in \{\hat{N}, \hat{\phi}, \hat{S}, \dots\}$$

The Scalar Potential

After introducing real fields: $\tilde{N}_{\rm R} = \sqrt{2}|\tilde{N}|$, $\phi_{\rm R} = \sqrt{2}|\phi|$ and $S_{\rm R} = \sqrt{2}|S|$

$$V = \kappa^2 \left(\frac{\phi_{\rm R}^4}{4M'^2} - M^2 \right)^2 \left(1 - \beta \frac{\phi_{\rm R}^2}{2m_{\rm P}^2} + \gamma \frac{\tilde{N}_{\rm R}^2}{2m_{\rm P}^2} - \kappa_S \frac{S_{\rm R}^2}{2m_{\rm P}^2} \right) + \frac{\lambda_N^2}{2M_*^2} (\tilde{N}_{\rm R}^4 \phi_{\rm R}^2 + \tilde{N}_{\rm R}^2 \phi_{\rm R}^4) + \dots$$

RH neutrino masses after inflation (for see-saw)

where we have defined:

$$\beta := \kappa_{S\phi} - 1 \quad (> 0 \text{ for inflation to end})$$
$$\gamma := 1 - \kappa_{SN}$$

governs mass of the inflaton $\tilde{N}_R$ during inflation

During inflation: $\phi_R = S_R = 0$, $\tilde{N}_R \neq 0$

After inflation: $\tilde{N}_R = S_R = 0$, $\phi_R = (2\, M\, M')^{1/2}$

The Inflationary Epoch

During inflation: $\phi_R = S_R = 0$, $\tilde{N}_R \neq 0$:

$$V = \kappa^2 M^4 \left(1 + \gamma \frac{\tilde{N}_R^2}{2m_P^2} + \delta \frac{\tilde{N}_R^4}{4m_P^4}\right) + \ldots$$

(with: $\delta = \frac{1}{2} + \kappa_{SN}^2 - \kappa_{SN}\kappa_N + \frac{5}{4}\kappa_N + \ldots$)

WMAP ('06): $n_s \approx 0.95 \pm 0.02$

($\gamma = 1 - \kappa_{SN} \approx 0.025 \pm 0.01$ from data*)

Slow roll parameters:

$$\epsilon := \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2 \approx \gamma^2 \frac{\tilde{N}_R^2}{2m_P^2}$$

$$\eta := m_P^2 \left(\frac{V''}{V}\right) \approx \gamma$$

η-problem

$$\xi := m_P^4 \left(\frac{V' V'''}{V^2}\right) \approx 6\delta\gamma \frac{\tilde{N}_R^2}{m_P^2}$$

$\Rightarrow$

$$n_s \simeq 1 - 6\epsilon + 2\eta \approx 1 + 2\gamma$$

$$r \simeq 16\epsilon \approx \gamma^2 \frac{8\,\tilde{N}_{Re}^2}{m_P^2} << \gamma^2$$

Prediction: small!

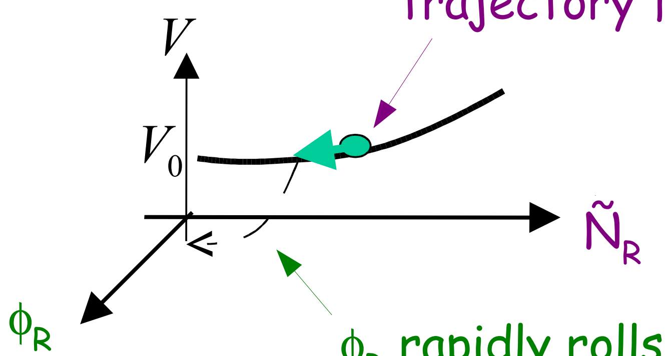
$$\frac{d n_s}{d \ln k} \simeq 16\epsilon\eta - 24\epsilon^2 - 2\xi \approx -\gamma \frac{12\delta\,\tilde{N}_{Re}^2}{m_P^2}$$

Primordial density fluctuations: $P_{\mathcal{R}}^{1/2} \simeq \frac{1}{\sqrt{2\varepsilon}}\left(\frac{H}{2\pi m_P}\right) \approx \frac{\kappa}{2\sqrt{3}\,\gamma\,\pi}\frac{M^2}{m_P\,\tilde{N}_{Re}}$

COBE: $P_{\mathcal{R}}^{1/2} \approx 5 \times 10^{-5}$

*) neglecting the contribution from 1-loop eff. potential

The End of Inflation



- Inflation ends (by 2nd order phase transition) when the waterfall field ϕ_R develops tachyonic instability:

$$m^2_{\phi_R} = \lambda_N^2 \frac{\tilde{N}_R^4}{M_*^2} - \beta \frac{\kappa^2 M^4}{m_P^2} < 0$$

- This defines the 'critical' value of the inflaton field:

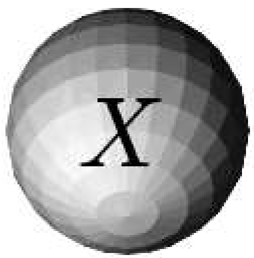
$$\tilde{N}_{Rc}^2 = \sqrt{\beta}\,\frac{\kappa}{\lambda_N}\,\frac{M^2 M_*}{m_P}$$

- Observable inflation starts (for N = 50 ... 70 e-folds of observable inflation) at $\tilde{N}_{Re}$ given by:

$$\tilde{N}_{Re} \approx \tilde{N}_{Rc}\, e^{\gamma N}$$

The Baryon Asymmetry of our Universe

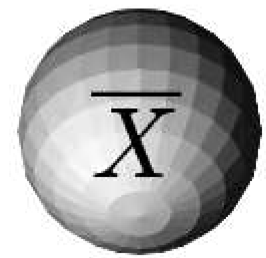
In the very early universe: equal number of particles and anti-particles:



matter

Symmetry

⟷



anti-matter

Observation today: $n_B/n_\gamma \approx 6 \cdot 10^{-10}$

matter

Baryon Asymmetry

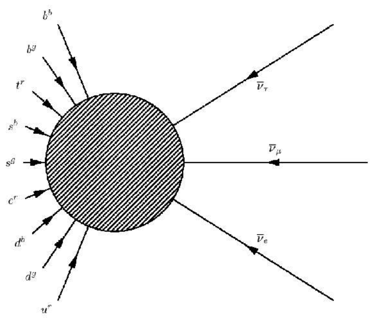
⟷

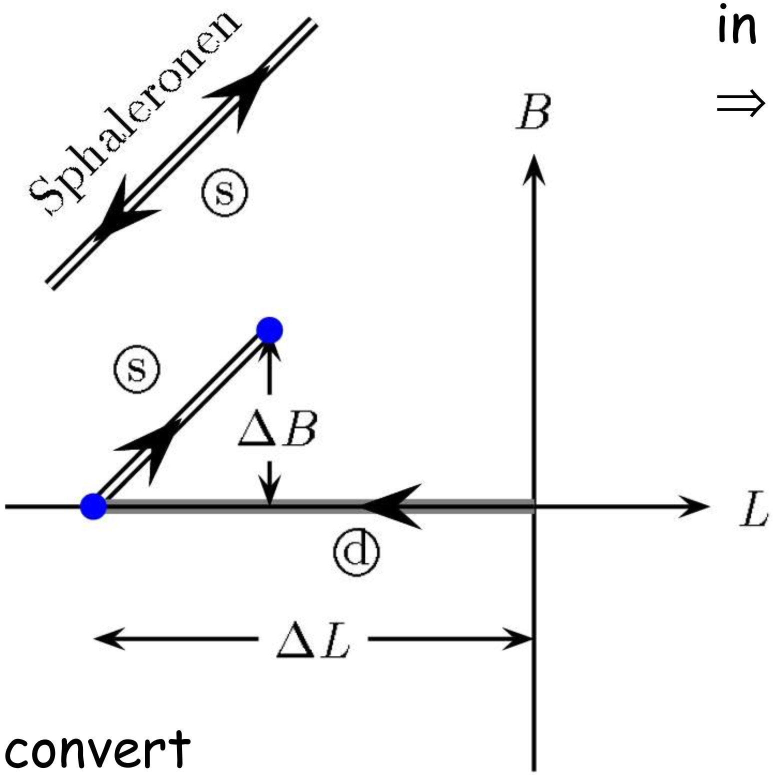
?

anti-matter

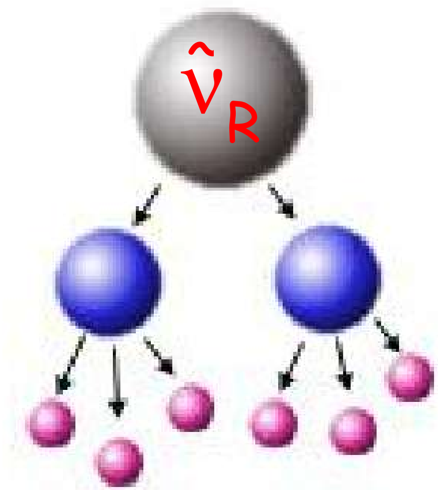
Baryogenesis via Leptogenesis

Fukugita, Yanagida ('86)





Step 1:
Out-of-equilibrium decay of $\tilde{\nu}_R$
in the early universe
$\Rightarrow$ lepton asymmetry ΔL



Step 2:
Sphalerons partly convert
the lepton asymmetry into
a baryon asymmetry ΔB
(B – L conserved!)

After Inflation: Reheating and Leptogenesis

After inflation: $\tilde{N}_{Ri} = S_R = 0$, $\phi_R = (2\,M\,M')^{1/2}$

- Masses of RH neutrinos (and sneutrino):

$\phi_R = (2\,M\,M')^{1/2}$

$$\frac{(\lambda_N)_{ij}}{M_*} \hat{N}_i \hat{N}_j \hat{\phi} \hat{\bar{\phi}} \longrightarrow M_{\mathrm{R}1} = 2(\lambda_N)_{11} M' M / M_*$$

- Suppose (in the following):
  - Sneutrino $\tilde{N}_1$ is the inflaton
  - $\tilde{N}_1$ dominates reheating and leptogenesis (i.e. ϕ decays earlier than $\tilde{N}_1$, $\phi \rightarrow \tilde{N}_2$ or $\tilde{N}_3$)

- $\tilde{N}_1$ decays via its MSSM Yukawa coupling: $(Y_\nu)_{i1} \hat{L}_i \hat{H}_{\mathrm{u}} \hat{N}_1$

- Decay into lepton and Higgs with a decay width $\Gamma_{N_1} = M_{\mathrm{R}1} (Y_\nu^\dagger Y_\nu)_{11} / (4\pi)$

- Estimate for T_{RH}:

$$T_{\mathrm{RH}} \approx (90/(228.75\pi^2))^{1/4} \sqrt{\Gamma_{N_1} m_{\mathrm{P}}}$$

G. Lazarides, Q. Shafi ('91)
H. Murayama, T. Yanagida ('94)
K. Hamaguchi, T. Yanagida, H. Murayama, ('02), ...

Non-Thermal Leptogenesis

G. Lazarides, Q. Shafi ('91)
H. Murayama, T. Yanagida ('94)
K. Hamaguchi, T. Yanagida, H. Murayama, ('02), ...

(Supposed: $\tilde{N}_1$ dominates reheating and leptogenesis)

B.A. Campbell, S. Davidson, K.A. Olive ('93)

- Estimate for generated baryon-to-photon ratio:

$$\frac{n_B}{n_\gamma} = -\epsilon \frac{T_{RH}}{M_{R1}}$$

(non-thermal leptogenesis: $T_{RH} \ll M_R$, out-of thermal equillibrium)

- Decay asymmetry bound in the (type I) see-saw mechanism (hierarchical m_ν):

K. Hamaguchi, H. Murayama, T. Yanagida ('01);
S. Davidson, A. Ibarra ('02)

$$|\varepsilon| \lesssim \frac{3}{8\pi} \sqrt{\Delta m^2_{31}} M_{R1} / v_u^2$$

- Consequence: Lower bound on the reheat temperature $T_{RH} \gtrsim 10^6$ GeV

- Numerical example:

Consistent values are e.g.:
$M = 10^{15}$ GeV,
$M' = 10^{16}$ GeV,
$M_* = 10^{17}$ GeV,
$\gamma = \beta = 10^{-2}$, $\kappa = 10^{-1}$,
$(\lambda_N)_{33} = O(1)$, $\tilde{N}_{Re} = 10^{16}$ GeV

desirable w.r.t. gravitino constraints in some supergravity models

$M_{R1} = 10^8$ GeV and $(Y_\nu)_{i1} \sim 10^{-6} \Rightarrow T_{RH} \approx 10^6$ GeV

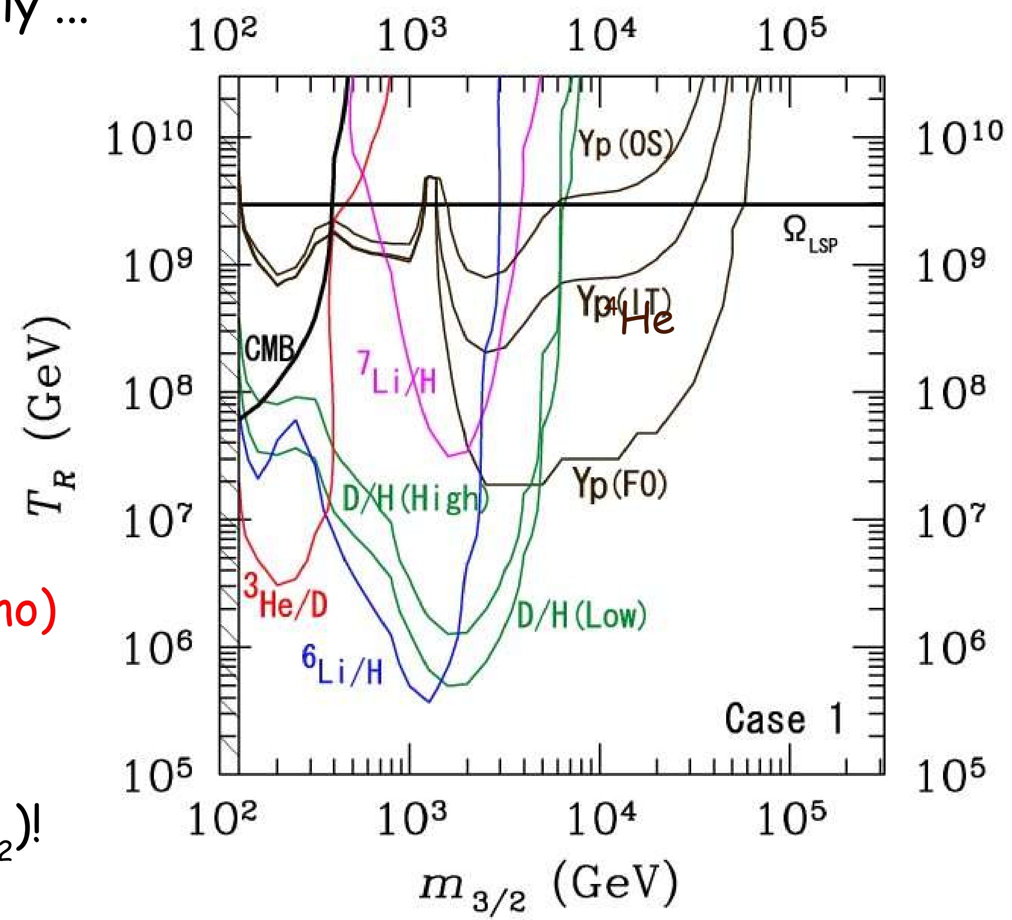
~ first family quark Yukawa couplings

Gravitino Problems and Bounds on T_{RH}

Khlopov, Linde ('84), Ellis, Kim, Nanopoulos ('84)
Ellis, Nanopoulos, Sarkar ('85), Moroi, Muryama, Yamaguchi ('93), ...

Two types of potential gravitino problems:
after reheating, gravitinos produced thermally ...

- BBN gravitino problem:
  late gravitino decays (if unstable)
  $\Rightarrow$ constraints on reheating T_{RH},
  depending on $m_{3/2}$!



Example – specific supergravity model- from:
Kohri, Moroi, Yotsuyanagi ('05)

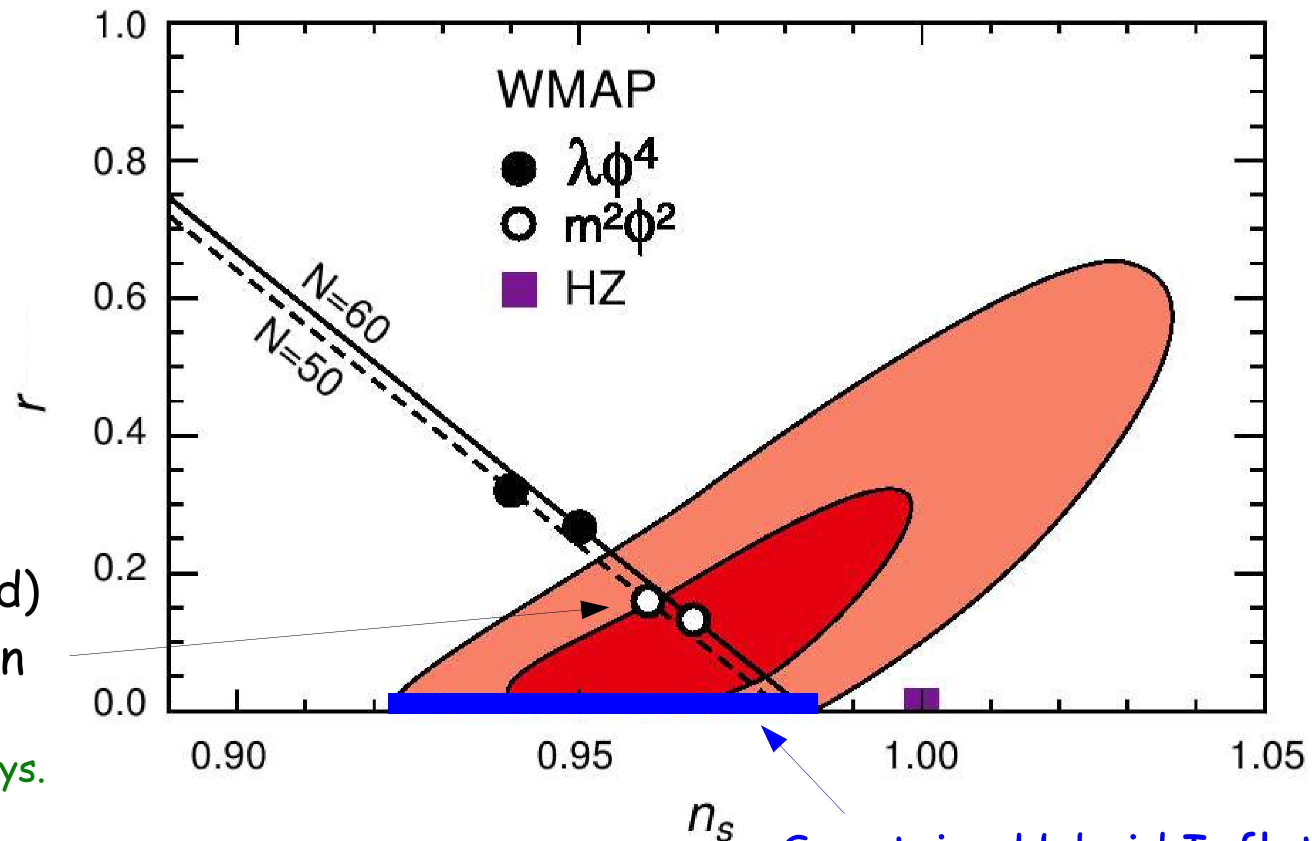
- Gravitino decay $\Rightarrow$ LSP (assumed a neutralino) produced non-thermally
  $\Rightarrow$ constraints on reheating T_{RH} in order not to overproduce DM (independent of $m_{3/2}$)!

has to be $\lesssim 0.13$ WMAP

nonth.:
$$\Delta\Omega_{\rm LSP} h^2 \simeq 0.054 \times \left(\frac{m_{\chi_1^0}}{100\ {\rm GeV}}\right)\left(\frac{T_{\rm R}}{10^{10}\ {\rm GeV}}\right)$$

neutralino mass ~ 100 GeV $\Rightarrow$
$T_{RH} \lesssim 2 \cdot 10^{10}$ GeV (estimate)

Hybrid vs. Chaotic Sneutrino Inflation



Chaotic (large field) Sneutrino Inflation

Murayama, Suzuki, Yanagida, Yokoyama, Phys. Rev. Lett. 70:1912-1915 (1993); Ellis, Raidal, Yanagida, Phys. Lett. B581 (2004) 9-18

Sneutrino Hybrid Inflation

S.A., M. Bastero-Gil, S.F. King, Q. Shafi, Phys.Rev. D71 (2005) 083519, (hep-ph/0411298)

Predictions for the tensor-to-scalar ratio $r = A_t/A_s$ will allow to distinguish between 'Hybrid Sneutrino Inflation' and 'Chaotic Sneutrino Inflation'.

Other implementations: Bastero-Gil, Berera ('05), Kadota, Yokoyama ('05)

Summary, Conclusions and Outlook

Sneutrino Inflation:

- Motivation: SUSY + see-saw -> singlet sneutrino is a candidate for the inflation
- 'Chaotic Sneutrino Inflation' Murayama, Suzuki, Yanagida, Yokoyama ('93)
- 'Sneutrino Hybrid Inflation' S.A., M. Bastero-Gil, S.F. King, Q. Shafi ('04)

Generic Features of Sneutrino Hybrid Inflation

- Baryogenesis via non-thermal leptogenesis (decay of $\tilde{N}$-inflaton after inflation)
- Low T_{RH} (~ 10^6 GeV) with first generation Yukawa couplings $(Y_\nu)_{i1} \sim 10^{-6}$
- Prediction: small tensor-to-scalar ratio $r = A_t/A_s$ (c.f. chaotic with $V \sim \phi^2$: $r = 0.16$)
- $\tilde{N}_1$ inflation: M_{R1} decoupled from the see-saw mechanism (as in Sequential Dominance)

Open Questions/Outlook

- Explicit form of the Kähler potential?
- 'Sneutrino Hybrid Inflation' in Unified Theories?