Warm Inflation in Susy models

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(work in progress)

- Inflation and dissipative dynamics
- "Warm" Susy Hybrid Inflation
- Sneutrino "Warm" Inflation

Slow Roll Inflation

$\ddot{a} > 0 \Leftrightarrow$ Accelerated expansion

A small, homogeneous and isotropic patch grows and become the observable Universe

$$H = \dot{a}/a \simeq \text{Constant} \Rightarrow a \propto e^{Ht} \qquad \text{(a=scale factor)}$$

$$\rho \simeq V(\phi) + \dot{\phi}^2 \simeq V(\phi) \simeq \text{Constant}$$

Scalar field $\qquad \dot{\phi}^2 \ll$

Flat potential $\Leftrightarrow$ Slow-roll

$(\dot{\phi}^2 \ll V)$, $(\ddot{\phi} \ll 3H\dot{\phi})$

$$\text{(a)}\ \eta = \left| \frac{V''(\phi)}{3H^2} \right| < 1 \qquad \text{(b)}\ \epsilon = \frac{1}{2M_P^2} \left(\frac{V'(\phi)}{3H^2} \right)^2 < 1$$

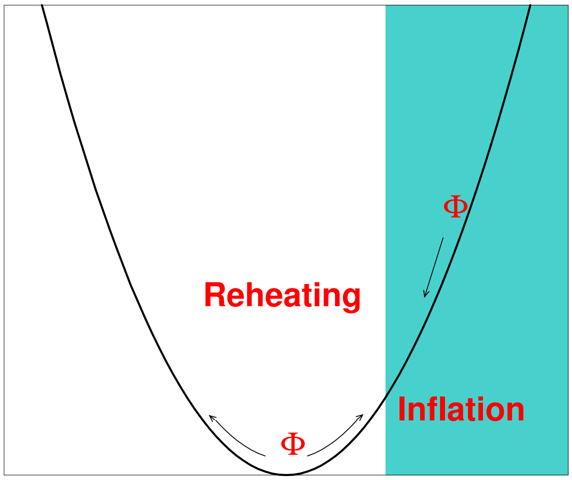
- The observable Universe should be within the horizon at the beginning of inflation: No. of e-folds $N_e \simeq 60$
- Primordial spectrum: $P_{\mathcal{R}}^{1/2} = \frac{H}{\dot{\phi}_S} \frac{H}{2\pi} = 5 \times 10^{-5}$ (COBE)
- Spectral index: $n_S - 1 = -6\epsilon_H + 2\eta_H$

$n_S = 0.93 \pm 0.03$ $\qquad (P_{\mathcal{R}} = A_0 (k/k_0)^{n_s - 1})$

- Running spectral index $\qquad (dn_S/d\ln k = -0.003 \pm 0.01\ ?)$

U. Seljak et al.: astro-ph/0407372 (WMAP+ SDSS+ SNIa)

Polynomial potentials (chaotic inflation):



$$V(\phi) = \frac{M_\phi^2}{2}\phi^2 + \cdots$$

$\hookrightarrow \phi > m_P \Rightarrow \eta,\, \epsilon < 1$

Hybrid Inflation (2 fields):

$$V = \Lambda^4 + \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda}{4}\chi^4 + \frac{1}{2}(g^2\phi^2 - \sqrt{\lambda}\Lambda^2)\chi^2$$

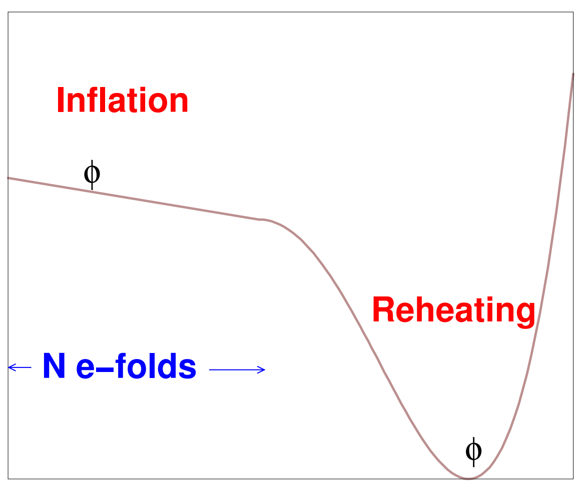
False vacuum: $\phi > \phi_c$

$\chi = 0 \Rightarrow V \simeq \Lambda^4 + \frac{m_\phi^2}{2}\phi^2$

Global minimum: $\phi < \phi_c$

$\phi = 0,\, \chi \neq 0 \Rightarrow V = 0$

$\hookrightarrow \phi < m_P$



$\hookrightarrow$ SUSY models $\leftrightarrow$ Flat directions

Dissipative Dynamics[a]

Decay into light particles $\equiv$ dissipation into "radiation"

(Heuristic argument) $(\Phi(x,t) = \phi(t) + \delta\phi(x,t))$

The effective EOM for a background scalar field includes quantum corrections due to the interaction with other fields

$$\ddot{\phi} + 3H\dot{\phi} + (m_\phi^2 + \Pi_\phi)\phi = 0$$

Self-energy: $\Pi_\phi = \Pi_\phi^R + i m_\phi \Gamma_\phi$

decay rate

$\hookrightarrow \omega_\phi^2 = m_\phi^2 + \Pi_\phi = \bar{m}_\phi^2 + i\bar{m}_\phi\Gamma_\phi$ $\quad$ ($\bar{m}_\phi$ = renormalized mass)

$\hookrightarrow \phi \propto e^{\pm i w_\phi t} \simeq e^{\pm i \bar{m}_\phi t} e^{-\Gamma_\phi t/2}$

$\Gamma_\phi \Leftrightarrow$ "friction" term in the effective EOM

$$\boxed{\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + \bar{m}_\phi^2\phi = 0}$$

$\hookrightarrow$ Radiation: $\dot{\rho}_R + 4H\rho_R = \Gamma_\phi\dot{\phi}^2$

- Quantum corrections already present during inflation[b]

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[a] A. Berera and R. O. Ramos, PRD63 (2001) 103509; PLB 567 (2003) 294

[b] E. Calzetta and B. Hu, PRD, PRD ('97) 3536

• The inflaton may be too light to decay during inflation...

• Dissipative effects can be induced by the decay (Γ_χ) of some other particle coupled to ϕ ($g^2\phi^2\chi^2$) ($\Pi_\chi = \Pi_\chi^R + i m_\chi \Gamma_\chi$)

$$\ddot{\phi} + (3H + \Upsilon_\phi)\dot{\phi} + V_\phi = 0$$

$\hookrightarrow$ Dissipative coefficient:

$$\Upsilon_\phi \simeq \frac{g^4}{64\pi}\left(\frac{\Gamma_\chi}{m_\chi}\right)\frac{\phi^2}{m_\chi}$$

• Valid under the adiabatic approximation:

macroscopic (background field) motion should be slow on the scale of the microscopic (quantum) motion

$\hookrightarrow \dot{\phi}/\phi < \Gamma_\chi$, $\quad H < \Gamma_\chi$ Thermalization condition

(a) $\rho_R^{1/4}$, $\Upsilon_\phi \ll H \Rightarrow$ "Cold" inflation

(b) $\rho_R^{1/4} > H, \Upsilon_\phi < H \Rightarrow$ "Weak" dissipative regime

- Inflaton evolution unchanged: $3H\dot{\phi} \simeq -V_\phi$
- Radiation $\Rightarrow (T/H)^4 \simeq 9\frac{\Upsilon_\phi}{3H}\epsilon_H\frac{m_P^4}{V}$

Even weak dissipation can be enough to generate a thermal bath with $T > H$

$\hookrightarrow$ Quantum fluctuations affected by the presence of the thermal bath:

Vacuum fluct. Thermal fluct.

$$\frac{k^3}{2\pi^2}|\delta\phi_k|^2 \simeq \left(\frac{H}{2\pi}\right)^2 \quad \Rightarrow \quad \frac{k^3}{2\pi^2}|\delta\phi_k|^2 \propto (TH)$$

Hawking T

- Primordial spectrum: $P_{\mathcal{R}}^{1/2} \simeq \left(\frac{H}{\dot{\phi}}\right)\sqrt{TH}$

$\hookrightarrow$ Different constraints on model parameters from COBE

- Spectral index:

$$n_S - 1 = -\frac{17}{4}\epsilon_H + \frac{3}{2}\eta_H - \frac{1}{4}\beta_\Upsilon$$

$$(\beta_\Upsilon = \frac{V'}{3H^2}\frac{\Upsilon'_\phi}{\Upsilon_\phi})$$

(c) $\rho_R^{1/4}$, $\Upsilon_\phi > H \Rightarrow$ "Strong" dissipative regime

Both the inflaton evolution and the spectrum change:

$$\dot\phi \simeq -\frac{V_\phi}{3H}\frac{1}{1+r} \qquad (r = \Upsilon_\phi/(3H))$$

- Slow-roll parameters

$$\eta_\Upsilon = \frac{\eta_H}{(1+r)^2} < 1$$
$$\epsilon_\Upsilon = \frac{\epsilon_H}{(1+r)^3} < 1$$
$$\epsilon_{\Upsilon H} = \beta_\Upsilon \frac{r}{(1+r)^3} < 1$$

- The inflaton mass can be larger than H : no "eta" problem in SUGRA
- Extra friction $\Upsilon_\phi \Leftrightarrow$ slower motion of the inflaton $\Leftrightarrow \phi < m_P$
- Spectrum of field fluctuations:

$$P_{\delta\phi}^{1/2} \sim \left(\frac{\pi\Upsilon_\phi}{4H}\right)^{1/4}\left(\frac{T}{H}\right)^{1/2} H$$

- Spectral index:

$$n_S - 1 = (-\tfrac{9}{4}\epsilon_H + \tfrac{3}{2}\eta_H - \tfrac{9}{4}\beta_\Upsilon)\frac{1}{1+r}$$

Warm Susy Hybrid Inflation ?

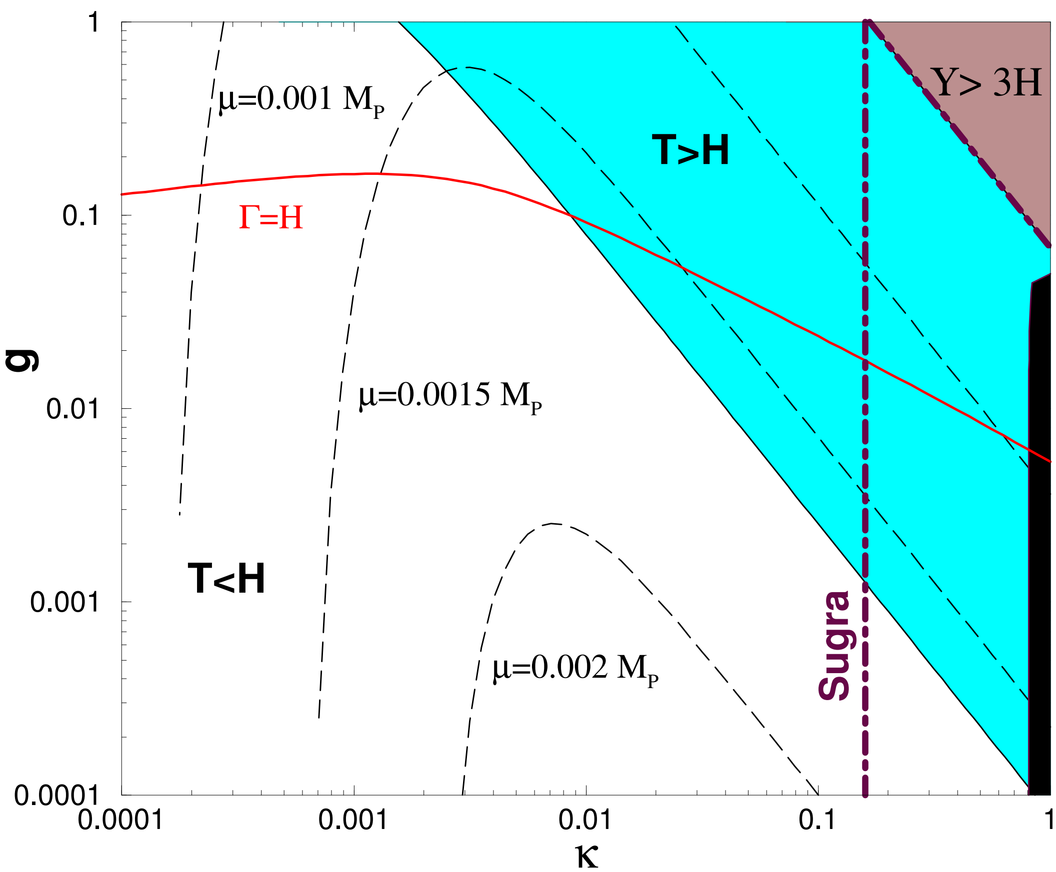
$$W = \kappa S(\Phi_1\Phi_2 - \mu^2) + g\Phi_2\Delta\bar{\Delta}$$

Δ, $\bar{\Delta}$ are massless fields during inflation

(they become massive in the global minimum)

- Φ_2 can decay into a pair of massless Δ, $\bar{\Delta}$

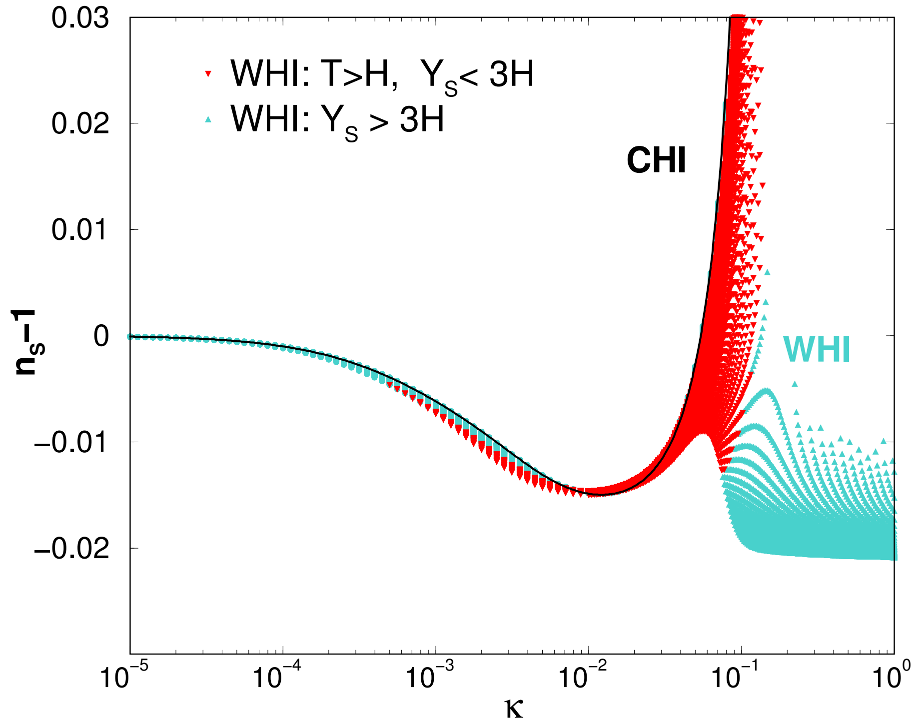
$$\hookrightarrow \frac{\Upsilon_S}{3H} \simeq \left(\frac{g}{4\pi}\right)^2 \left(\frac{\kappa}{4\pi}\right)^2 \left(\frac{m_P}{\mu}\right) \left(\frac{\phi_S}{\mu}\right)$$



Large values of κ not in conflict with observations

Weak dissipative regime	Strong dissipative regime
$g \sim O(0.1)$, $\kappa \sim O(0.03)$	$g \sim \kappa \sim O(1)$
Sugra corrections?	No sugra corrections$^{(a)}$: $\phi_S < m_P$
$\mu \approx 10^{15}$ GeV	$\mu < 10^{15}$ GeV
$n_S - 1 \sim -0.02$	$n_S - 1 \sim -0.02$
$dn_S/d\ln k \sim -2 \times 10^{-4}$	$dn_S/d\ln k \sim -4 \times 10^{-4}$

[a] A. Linde and A. Riotto, PRD56('97); V. N. Senoguz and Q. Shafi, PLB567 ('03)



- Gravitino constraint: $T_{RH} < O(10^9 - 10^7)$ GeV

M. Kawasaki et al., astro-ph/0402490

$\hookrightarrow$ To avoid the decay of the scalars ($m_S = \sqrt{2}\kappa\mu$) into Δ, $\bar{\Delta}$ fermions after inflation: $\boxed{\kappa < 2g}$

Warm Sneutrino Inflation ?

$$W = \frac{M_i}{2} N_i N_i + (h_N)_{ij} H_u L_i N_j + h_t H_u Q_3 U_3^c + \cdots$$

Dissipative channel: N_i couples to $H_u \Rightarrow H_u$ decays into tops

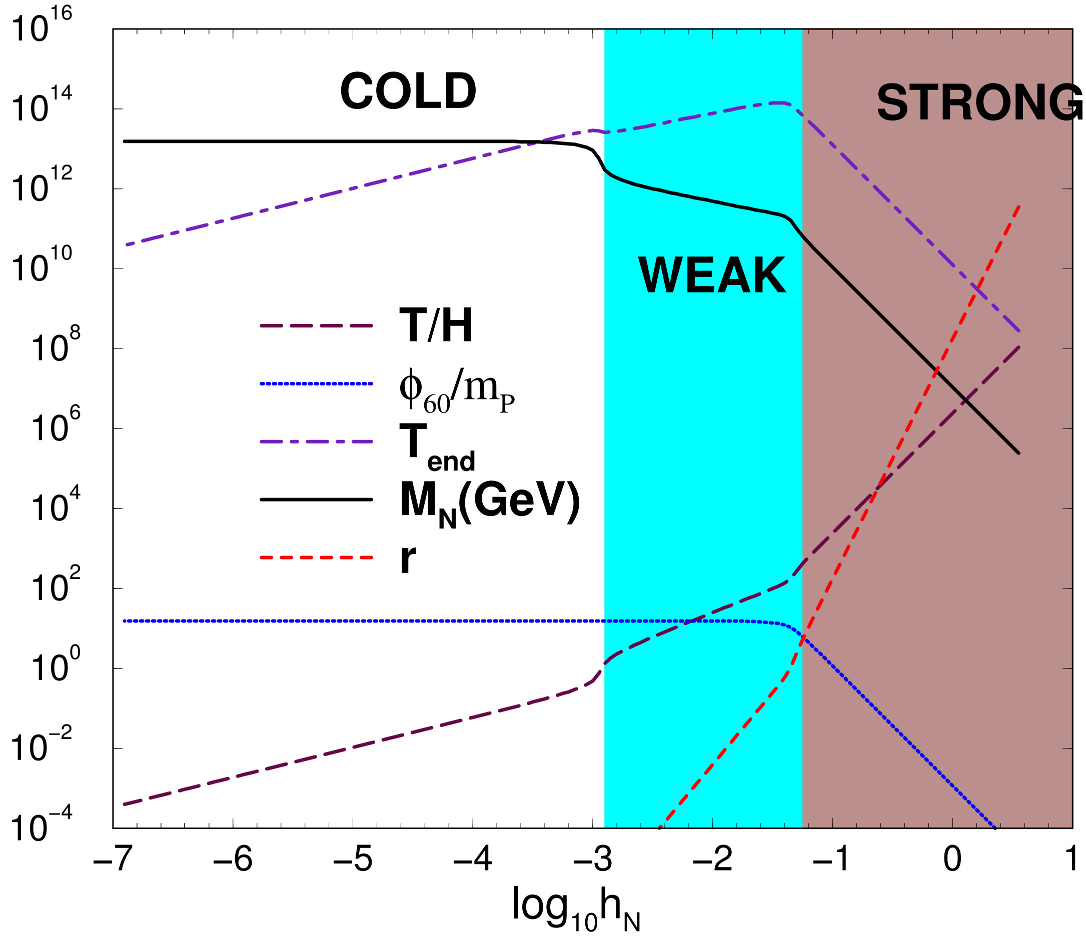
$$\frac{\Upsilon_N}{3H} \simeq \frac{\sqrt{6\pi}}{120} \left(\frac{h_N^2}{4\pi}\right)^{3/2} \left(\frac{h_t^2}{4\pi}\right) \left(\frac{m_P}{M_N}\right)$$

$(Y_t = h_t^2/(4\pi) \approx 1)$

- Cold inflation: $|h_N| < 10^{-3}$, $\phi_N > m_P$

$M_N \simeq 2 \times 10^{13}$ GeV (COBE)

H. Murayama, S. Suzuki, T. Yanagida, J. Yokoyama, PRL 70 ('93) 1912; J. Ellis, M. Raidal, T. Yanagida, PLB 581 (04) 9



- Strong dissipative regime: $|h_N| > 0.1$

$$r > O(100) \Rightarrow \phi_N < m_P$$

$$|h_N| \simeq 0.1 \left(\frac{10^{10}\, GeV}{M_N} \right)^{1/3} \qquad \text{(COBE)}$$

$$n_S - 1 \simeq -0.025 \qquad dn_S/d\ln k \simeq -O(10^{-4})$$

$$10^8\, GeV \leq T_{end} \leq 10^{13}\, GeV$$

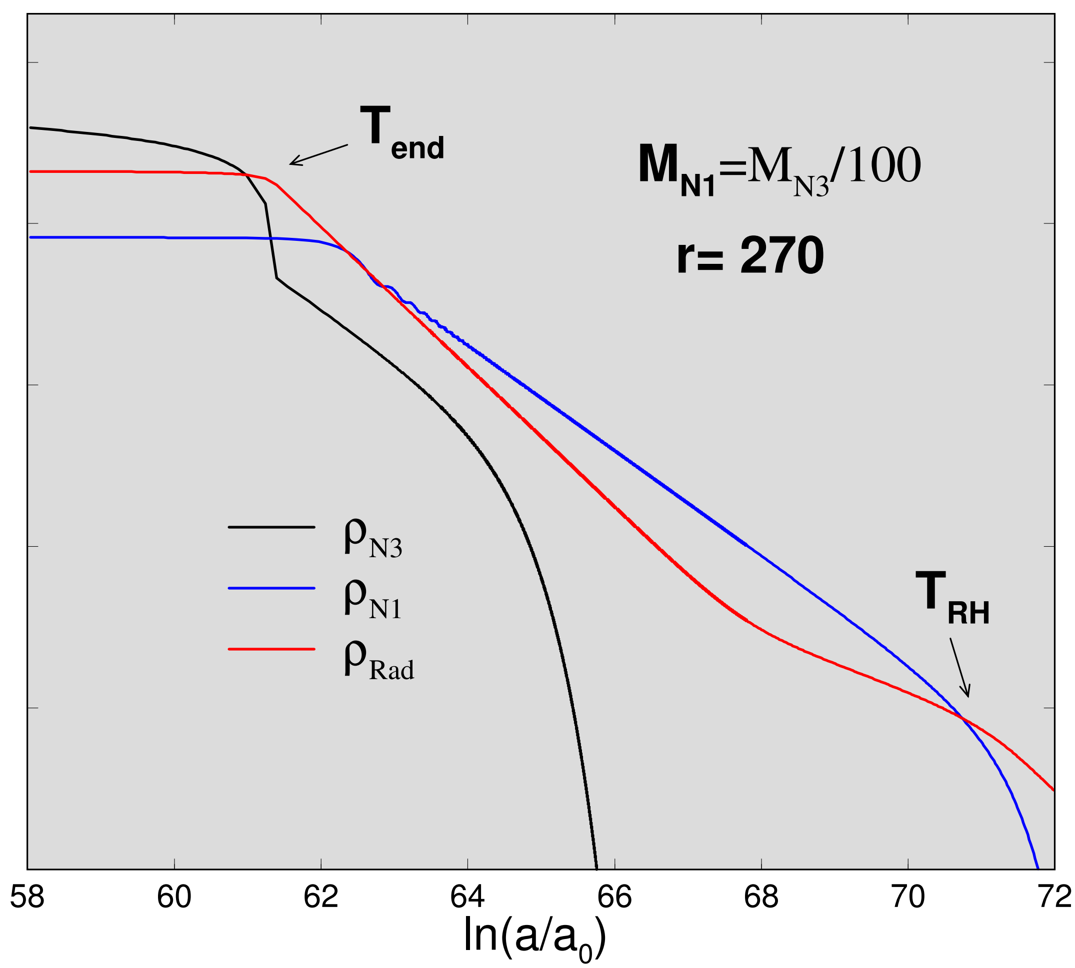
$\hookrightarrow$ problems with gravitinos ? $\quad T_{end} \simeq T_{RH} > 10^9 - 10^7$ GeV ?

Lowering the post-inflation Temperature

- $M_{N3}, |h_{N3}| \geq 0.1 \Rightarrow$ Inflaton
- $M_{N1} \ll M_{N3}, |h_{N1}| \ll 1 \Rightarrow$ Dominates after inflation

$$M_{N1} \leq M_{N3}/\sqrt{(}2r) \Rightarrow \eta_1 \simeq 2(M_{N1}/M_{N3})^2(m_P/\phi_{N3})^2 < 1$$

$$(\phi_{N1} \sim \phi_{N3} < m_P)$$



$$T_{RH} \simeq 0.4\sqrt{\Gamma_1 m_P} \Rightarrow |h_{N1}| \simeq 10^{-6} \times \left(\frac{T_{RH}}{10^6\, GeV}\right)\left(\frac{10^8\, GeV}{M_{N1}}\right)$$

Non-thermal Leptogenesis[a]

- Out-of-equilibrium ($M_{N1} < T_{RH}$) decay during "reheating" :

$$\frac{n_L}{s}|_{RH} \simeq |\epsilon_1| \frac{3T_{RH}}{4M_{N1}}$$

(ϵ_1=CP Asymmetry param.)

$$|\epsilon_1| \simeq \frac{3}{8\pi(h_N^\dagger h_N)_{11}} \sum_{i\neq 1} Im[(h_N^\dagger h_N)_{1i}]^2 \frac{M_{N1}}{M_{Ni}}$$
$$\leq \frac{3}{8\pi}\sqrt{\Delta m_A^2}\frac{M_{N1}}{v_u^2} \simeq 2\times 10^{-8}\left(\frac{M_{N1}}{10^8\, GeV}\right) ,$$

$\sqrt{\Delta m_A^2} \simeq 0.05$ eV, atmospheric neutrino mass

$\hookrightarrow$
$$\boxed{\frac{n_B}{s}\Big|_{RH} \leq 5\times 10^{-11}\frac{T_{RH}}{10^6\, GeV}}$$

$(n_B/s \simeq (8.7\pm 0.4)\times 10^{-11})$

$\hookrightarrow$ Non-thermal lept. + $T_{RH} < 10^7 - 10^6$ GeV $\Rightarrow$ $\boxed{|h_{N3}| \leq 0.24}$

$\hookrightarrow$ Other possibilities? Larger ϵ_1?[b] non-thermal?..-

(a) H. Murayama, S. Suzuki, T. Yanagida, J. Yokoyama, PRL 70 ('93) 1912; J. Ellis, M. Raidal, T. Yanagida, PLB 581 (04) 9

(b) M. Raidal, A. Strumia and K. Turzynski, hep-ph/0408015

Summary

• Dissipative effects due to decaying fields can be relevant during inflation, and modify inflationary predictions

$$(3H + \Upsilon_\phi)\dot{\phi} \simeq -V' \qquad\qquad \rho_R \simeq \frac{\Upsilon_\phi}{3H}\dot{\phi}^2$$

• Υ_ϕ due to either the decay of the inflaton, or that of another field coupled to the inflaton

Cold	Weak dissip.	Strong dissip.
$\Upsilon_\phi \ll 3H$	$\Upsilon_\phi < 3H$	$\Upsilon_\phi > 3H$
$T \ll H$	$T > H$	$T > H$
		no "eta" problem
		$\phi < m_P$
	$P_{\mathcal{R}}^{1/2} \simeq \frac{H}{\dot{\phi}}\sqrt{TH}$	$P_{\mathcal{R}}^{1/2} \simeq \frac{H}{\dot{\phi}}\left(\frac{\Upsilon_\phi}{3H}\right)^{1/4}\sqrt{TH}$

• Strong dissipation requires large values of the couplings, that may be in conflict with having $T_{RH} < O(10^9)$ GeV

Examples

(A) Susy (GUT) hybrid inflation, with an extra pair of fields $(\kappa < 2g)$

(a) Cold hybrid inflation: $g,\ \kappa \sim O(10^{-3})$

(b) "Weak" dissipation : $g,\ \kappa \sim O(0.1)$

(c) "Strong" dissipation : $g,\ \kappa \sim O(1)$

$\hookrightarrow$ Spectral index consistent with observations

(B) Sneutrino inflation: MSSM + 3 RH neutrinos

(a) Cold inflation: $|h_N| < 10^{-3}$, $M_N \simeq 2 \times 10^{13}$ GeV, $\phi_N > m_P$

(b) "Weak" dissipation : $10^{-3} < |h_N| < 10^{-1}$, $10^{10}\,GeV < M_N < 2 \times 10^{13}$ GeV, $\phi_N > m_P$

(c) "Strong" dissipation : $|h_N| > 10^{-1}$, $M_N < 10^{10}$ GeV, $\phi_N < m_P$

$\hookrightarrow$ Another lighter and weakly coupled RH sneutrino can dominate after inflation: T_{RH}, leptogenesis, etc...