Higgs thermal inflation and low energy supersymmetry

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Outline

Minimal Hybrid Inflationary Supersymmetric Standard Model

- Low energy MSSM (with massive neutrinos)
- F-term hybrid inflation $T_{\rm rh} \sim 10^{15}$ GeV
- Dynamical explanation of μ-term and RH neutrino masses
- Second period of Higgs-driven “thermal” inflation $T_{\rm rh} \sim 10^{9}$ GeV
- Reduced amount of F-term inflation: $n_s \simeq 0.976$
- Dark matter (neutralino from gravitino decays/freeze-out, or gravitino)
- Leptogenesis from RH neutrino decays (if $M_{N_1} \lesssim 10^9$ GeV)
- Baryogenesis (if electroweak phase transition is 1st order)
- Cosmic strings, $G\mu_{\rm cs} \simeq 10^{-7}$, consistent with CMB

Fields and symmetries

- (ν)MSSM sector: two-parameter family of anomaly free $U(1)'$

	Q	U	D	L	E	N	H_1	H_2
Y'	$-\frac{1}{3}q_L$	$-q_E - \frac{2}{3}q_L$	$q_E + \frac{4}{3}q_L$	q_L	q_E	$-2q_L - q_E$	$-q_E - q_L$	$q_E + q_L$
R	1	1	1	1	1	1	0	0

- Y: $(q_L, q_E) = (-1, 2)$. $B - L$: $(q_L, q_E) = (-1, 1)$
- Inflation sector:

	Φ	$\bar{\Phi}$	S
Y'	$4q_L + 2q_E$	$-4q_L - 2q_E$	0
R	0	0	2

Coupling the MSSM to F-term inflation

- Superpotential: $W = W_A + W_X + W_I$

- MSSM part: $W_A = H_2 Q Y_U U + H_1 Q Y_D D + H_1 L Y_E E + H_2 L Y_N N$
- Pure F-term inflation part: $W_I = \lambda_1 \Phi \overline{\Phi} S - M^2 S$
- Coupling part : $W_X = \frac{1}{2}\lambda_2 N N \Phi - \lambda_3 S H_1 H_2$

- μ_h-term from $\langle s \rangle \sim M_{\mathrm{SUSY}}$
- RH neutrino masses from $\langle \phi \rangle \sim M \gg M_{\mathrm{SUSY}}$
- All other renormalisable terms forbidden by symmetries
- All B-violating operators forbidden by $U(1)'$ and R

The scalar potential

Study $s, \phi, \overline{\phi}, h_1, h_2$ subspace for $U(1)'$ and $SU(2)\times U(1)$ breaking

- $V(s, \phi, \overline{\phi}, h_1, h_2) = V_F + V_D + V_{\text{soft}} + \hbar \Delta V_1$

- $V_F = \left[\lambda_1^2(|\phi|^2 + |\overline{\phi}|^2) + \lambda_3^2(|h_1|^2 + |h_2|^2)\right] |s|^2 \quad + |\lambda_1 \phi\overline{\phi} - \lambda_3 h_1 h_2 - M^2|^2$

- $V_D = \frac{1}{2} g'^2 \left(q_\Phi(\phi^* \phi - \overline{\phi}^* \overline{\phi}) + q_H(h_1^\dagger h_1 - h_2^\dagger h_2) \right)^2 + \frac{1}{8} g_2^2 \sum_a (h_1^\dagger \sigma^a h_1 + h_2^\dagger \sigma^a h_2)^2 + \frac{1}{8} g_1^2 (h_1^\dagger h_1 - h_2^\dagger h_2)^2$

- No FI-term - unproblematic embedding in supergravity [1]

[1] Komargodski & Seiberg (2009)

The minimum and its geometry

- $V_D = 0$ when $|\phi| = |\overline{\phi}|$, $|h_1| = |h_2|$, $h_1^\dagger h_2 = 0$.
- $V_F = 0$ when $s = 0$, $\lambda_1 \phi\overline{\phi} - \lambda_3 h_1 h_2 = M^2$
- Minimum parameters: angles $\chi \in [0, \pi/2]$, $\varphi \in [0, 2\pi]$, SU(2):

$$\phi = \frac{M}{\sqrt{\lambda_1}} \sin\chi e^{i\varphi}, \quad h_1^T = \left(\frac{M}{\sqrt{\lambda_3}} \cos\chi, 0\right)$$

- Angle φ is associated with U(1)$''$ gauge symmetry generated by $Y'' = Y' - (q_L + q_E)Y$
- Unbroken symmetries :

$\chi = 0$	$\mathrm{U}(1)_{em} \times \mathrm{U}(1)''$	h-vacuum
$0 < \chi < \pi/2$	$\mathrm{U}(1)_{em}$	
$\chi = \pi/2$	$\mathrm{SU}(2) \times \mathrm{U}(1)_Y$	ϕ-vacuum (electroweak)

The $\mathrm{U}(1)'$ breaking and the see-saw mechanism

- Suppose we are in the ϕ-vacuum.
- Neglecting the soft terms, the breaking of $\mathrm{U}(1)'$ preserves supersymmetry.
- The $\mathrm{U}(1)'$ gauge boson, its gaugino (with one combination of $\psi_{\phi,\overline{\phi}}$) and the Higgs boson form a supermultiplet with mass $m_V = g'\sqrt{v_\phi^2 + v_{\overline{\phi}}^2}$, while the remaining combinations of ϕ, $\overline{\phi}$ and $\psi_{\phi,\overline{\phi}}$, form a massive chiral supermultiplet. Both this multiplet and S have supersymmetric mass $\lambda_1\sqrt{v_\phi^2 + v_{\overline{\phi}}^2}$.
- The large ϕ vev gives RH neutrino masses from the superpotential term $\lambda_2 NN\Phi$, implementing the see-saw mechanism.

SUSY-breaking and the Higgs μ_h-term

- $V_{\text{soft}} = m_{\phi}^2|\phi|^2 + m_{\overline{\phi}}^2|\overline{\phi}|^2 + m_{h_1}^2|h_1|^2 + m_{h_2}^2|h_2|^2 + m_s^2|s|^2 + \rho M^2 M_{\text{SUSY}}(s + s^*) + (h_{\lambda_1}\phi\overline{\phi}s + h_{\lambda_3}h_1 \cdot h_2 s + c.c.)$.
- SUSY-breaking
  - gives μ_h-term ($\langle s\rangle H_1 H_2$)
  - lifts vacuum degeneracy
- μ_h-term: $\langle s\rangle \simeq -\frac{h_{\lambda_1}}{\lambda_1^2} - \frac{M_{\text{SUSY}}\rho}{\lambda_1}$ (in ϕ-vacuum).
- $\langle\phi\rangle^2 - \langle\overline{\phi}\rangle^2 = 2\frac{m_{\overline{\phi}}^2 - m_{\phi}^2}{g'^2 q_{\phi}^2}$ (in ϕ-vacuum)

The ϕ-vacuum and AMSB

Because in fact $v_\phi^2 - v_{\overline{\phi}}^2 = O(m_\phi^2 - m_{\overline{\phi}}^2)$, the $U(1)'$ D-term:

$$V_D = \frac{1}{2} g'^2 \left(q_\Phi(|\phi|^2 - |\overline{\phi}|^2) + q_H(h_1^\dagger h_1 - h_2^\dagger h_2) + \sum q_L |L|^2 + \sum q_Q |Q|^2 \right)^2$$

will solve the AMSB tachyonic scalar problem if we arrange the lepton doublet and singlet $U(1)'$ charges to have the same sign.
Whatever the susy breaking terms, the low energy theory is identical to the MSSM: the scalar component of S gets a small vev from the susy breaking, but the S-quanta get large supersymmetric masses from the $\phi, \overline{\phi}$ vevs.

Lifting the vacuum degeneracy

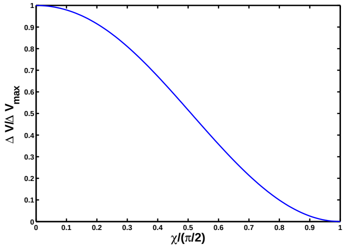
- Define: $v_\phi = \langle|\phi|\rangle/\sqrt{2}$, $v_h = \langle|h|\rangle/\sqrt{2}$, $v_s = \langle|s|\rangle/\sqrt{2}$
- $\chi = \pi/2$: ϕ-vacuum energy: $V_\phi = \frac{M^2}{\lambda_1}\left(m_\phi^2 + m_{\bar{\phi}}^2 - \frac{h_{\lambda_1}^2}{2\lambda_1^2}\right)$
- $\chi = 0$: h-vacuum energy: $V_h = \frac{M^2}{\lambda_3}\left(m_{h_1}^2 + m_{h_2}^2 - \frac{h_{\lambda_3}^2}{2\lambda_3^2}\right)$
- Must have $V_h > V_\phi$ and $V''(\pi/2) > 0$ for electroweak minimum, and $V''(0) < 0$ so Higgs vacuum not a local minimum
- NB V_h, V_ϕ are both $O(M^2 M_{\rm SUSY}^2)$
- Constraint on SUSY-breaking scenarios

The potential between h and ϕ vacua

$$V(\chi) \simeq -\frac{M^2}{2}\frac{\left(\tilde{h}_{\lambda_1}\sin^2\chi + \tilde{h}_{\lambda_3}\cos^2\chi\right)^2}{\lambda_1\sin^2\chi + \lambda_3\cos^2\chi} + M^2\left(\frac{\bar{m}_\phi^2}{\lambda_1}\sin^2\chi + \frac{\bar{m}_h^2}{\lambda_3}\cos^2\chi\right),$$

where

$$\tilde{h}_{\lambda_1} = \frac{h_{\lambda_1}}{\lambda_1}$$
$$\tilde{h}_{\lambda_3} = \frac{h_{\lambda_3}}{\lambda_3}$$
$$\bar{m}_\phi^2 = m_\phi^2 + m_{\bar{\phi}}^2$$
$$\bar{m}_h^2 = m_{h_1}^2 + m_{h_2}^2$$



Constraints in 3 common SUSY-breaking scenarios

Requiring the ϕ-vacuum be lowest energy leads to:

- Anomaly-mediated Supersymmetry-breaking (AMSB)
  - $\lambda_1 \left(\frac{q_H}{q_\Phi}\right)^2 \lesssim \lambda_3$.
- Gauge-mediated Supersymmetry-breaking (GMSB)
  - $\lambda_1 \left(\frac{q_H}{q_\Phi}\right)^2 \gtrsim \lambda_3$.
- Constrained MSSM (CMSSM)
  - Universal scalar soft mass m_0, universal trilinear coupling A
  - [$2m_0^2 - A^2/2 > 0$ and $\lambda_1 > \lambda_3$] or [$2m_0^2 - A^2/2 < 0$ and $\lambda_1 < \lambda_3$]

SUSY spectrum for AMSB

$m_{\frac{3}{2}}$	40TeV	80TeV	140TeV
(L, e)	$(0, 0.18)$	$(0, 0.72)$	(0,1.96)
$\tilde{g}$	899	1684	2801
$\tilde{t}_2$	536	1001	1629
$\tilde{\tau}_1$	111	280	532
$\tilde{\tau}_2$	223	405	683
$\tilde{\nu}_e$	190	393	689
$\chi_1^{0,\pm}$	132	265	460
h	116	121	125
$H^{\pm}$	419	734	1129
μ_h	603	1111	1852
δa_μ	60×10^{-10}	16×10^{-10}	5.4×10^{-10}

Table: sAMSB spectra (in GeV) and δa_μ for $m_t = 172.9$GeV and different values of (L, e) and $\tan\beta$. NB $\delta a_\mu^{\text{exp}} = 29.5(8.8) \times 10^{-10}$

MHISSM summary

Mass scales:

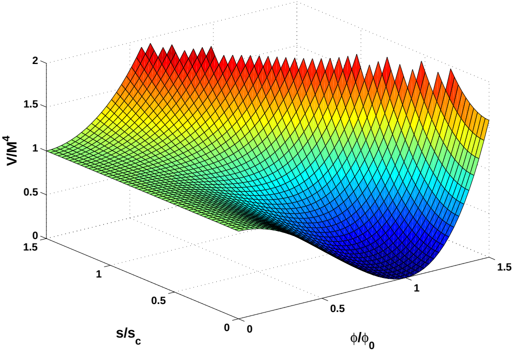
- M U(1)′ breaking scale
- $M_{\rm SUSY}$ supersymmetry breaking scale

Physics:

- Scale M:
  - flat direction in s, $V = M^4$.
  - after U(1)′ breaking, S, Φ, $\bar{\Phi}$ have SUSY masses O(M)
  - Majorana masses for RH neutrinos
- Scale $\sqrt{MM_{\rm SUSY}}$: potential along H_1H_2 “flat" direction
- Scale $M_{\rm SUSY}$: MSSM

Inflationary flat direction.

- Charged fields vanish: $|\phi| = |\bar{\phi}| = |h_1| = |h_2| = 0$.
- Flat direction s with $V_F = M^4$ from $W = M^2 S + \cdots$.



The loop-corrected potential

$$V = M^4 + \Delta V_1,$$

$$\begin{aligned}
\Delta V_1 &= \frac{1}{64\pi^2}\mathrm{Str}\left[(M^2(s))^2 \ln(M^2(s)/\mu^2)\right] \\
&= \frac{1}{32\pi^2}\left[(\lambda_1^2 s^2 + \lambda_1 M^2)^2 \ln\left(\frac{\lambda_1^2 s^2 + \lambda_1 M^2}{\mu^2}\right)\right. \\
&+ (\lambda_1^2 s^2 - \lambda_1 M^2)^2 \ln\left(\frac{\lambda_1^2 s^2 - \lambda_1 M^2}{\mu^2}\right) \\
&- \left. 2\lambda_1^4 s^4 \ln\left(\frac{\lambda_1^2 s^2}{\mu^2}\right)\right] + 2\times(\lambda_1 \to \lambda_3)
\end{aligned}$$

For $\lambda_{1,3} s^2 \gg M^2$

$$V(s) \simeq M^4\left[1 + \alpha \ln\frac{2s^2}{s_c^2}\right], \quad \alpha = \frac{\lambda^2}{16\pi^2}, \quad \lambda = \sqrt{\lambda_1^2 + 2\lambda_3^2}, \quad s_c^2 = M^2/\lambda.$$

Predictions from F-term inflation

- Suppose inflation ends with transition to the ϕ-vacuum.
- Predictions: $\mathcal{P}_{\rm s}(k) \simeq \frac{4N_k}{3}\left(\frac{s_c}{m_p}\right)^4, \quad n_s \simeq \left(1-\frac{1}{N_k}\right).$ [2]
- WMAP7, PLANCK:
  $\mathcal{P}_{\rm s}(k_0) = (2.43 \pm 0.11)\times 10^{-9}, n_s = 0.9624 \pm 0.0075$,
- Normalisation: $\frac{s_c}{m_p} \simeq 2.9\times 10^{-3}\left(\frac{27}{N_{k_0}}\right)^{\frac{1}{4}}, \quad N_{k_0} = 27^{+13}_{-7}.$
- 2σ discrepancy with Hot Big Bang: $N_{k_0} \simeq 58 + \ln(T_{\rm rh}/10^{15}\ {\rm GeV})$
- Cosmic strings formed

[2] N_k is number of e-foldings of inflation after $aH = k$

End of inflation and (p)reheating

- $M^2_{\phi,\overline{\phi}} = \lambda_1(\lambda_1|s|^2 \pm M^2)$, $M^2_{h_1,h_2} = \lambda_3(\lambda_3|s|^2 \pm M^2)$
- $\lambda_1 < \lambda_3$:
  - inflation ends at $s^2_{c1} = M^2/\lambda_1$
  - Transition to ϕ-vacuum ($\langle|\phi|^2\rangle = M^2/\lambda_1$)
  - U(1)$''$ symmetry broken: cosmic strings formed
- $\lambda_3 < \lambda_1$:
  - inflation ends at $s^2_{c3} = M^2/\lambda_3$
  - Transition to h-vacuum ($\langle|h_{1,2}|^2\rangle = M^2/\lambda_3$)
  - U(1)$'$ symmetry preserved: no strings formed (yet)
- Reheating time: M^{-1}. Much smaller than expansion time H^{-1}.
- All potential energy $V = M^4$ goes into thermal energy.
- Reheat temperature $T_{\rm rh1} \simeq 2.2\sqrt{\lambda} \times 10^{15}$ GeV, $\lambda = \sqrt{\lambda_1^2 + 2\lambda_3^2}$
- Thermal potential keeps universe in false h-vacuum

The Higgs vacuum

Let us assume $V_h > V_\phi$ but $\lambda_3 < \lambda_1$. The (first period of) inflation ends with transition to the Higgs vacuum and reheating to $T \sim O(M)$, and the universe is trapped there by the thermal potential until the temperature drops below $O(V_h - V_\phi)^{\frac{1}{4}} \sim O(\sqrt{MM_{\mathrm{SUSY}}})$, ie $T \sim 10^9$GeV. A second period of inflation (Higgs Thermal Inflation) follows, with reheating to $T \sim 10^9$GeV.

- Cosmic strings not formed until second transition
- Gravitinos created from first inflation era diluted
- Fewer e-foldings necessary in first inflation era

Thermal inflation

Yamamoto, Binetruy and Gaillard, Lazarindes et al

- Supersymmetric flat direction X
- Lifted by thermal corrections, supersymmetry-breaking and non-renormalisable terms
- $V(X) = V_0 + m_X^2|X|^2 + cT^2|X|^2 + \cdots$
  - NB X-vacuum unstable; $m_X^2 < 0$
- Universe trapped at $|X| = 0$ until $T_c = \sqrt{-m_X^2/c}$.
- Inflation (θ-inflation) (re)starts if potential dominates energy density: $V_0 > \rho(T)$
- Result: $N_\theta \simeq 15$ e-foldings of thermal inflation
- Reduces high scale inflation $N_{k_0} \simeq 42$, so $n_s \simeq 0.976$
- Cosmic strings are light, and μ_{cs} independent of inflaton couplings

Cosmic string constraints on F-term inflation

- U(1)′ symmetry breaking → Nielsen-Olesen vortices: cosmic strings[3] with mass per unit length μ_{cs}
- CMB limit $G\mu_{cs} < 0.42 \times 10^{-6}$ (95%CL)
- Transition to ϕ-vacuum case:
  - $G\mu_{cs} = G \times B(\beta) \times 2\pi v_\phi^2 \simeq 3B(\beta) \times 10^{-6}$ with $\beta = \lambda_1/q_\phi^2 g'^2$
  - $B(\beta) \lesssim 0.1$ means $\lambda_1/q_\phi^2 g'^2 \lesssim 10^{-10}$
  - Small λ_1 (very flat potential) means $n_s \to 1$.
- Thermal inflation case:
  - Cosmic strings have a Higgs condensate, reducing μ_{cs}:
  - $\beta \propto M_{SUSY}^2/v_\phi^2 \sim 10^{-26}$ gives $B \simeq 0.04$
  - $G\mu_{cs} \simeq 10^{-7}$, no constraint on inflaton couplings λ_1, λ_3
  - CMB limit satisfied

[3] Kibble (1976)

Gravitino problem(s) of SUSY cosmology

There are two issues

- Too much Dark Matter
  A gravitino LSP, or if it is not the LSP then the LSP density created by its decay, may mean too much Dark Matter.
  $\Omega_{\rm LSP} h^2 \simeq 6 \times 10^{-3} \frac{m_{\rm LSP}}{100\ \rm GeV} \left(\frac{T_{\rm rh}}{10^9\ \rm GeV} \right) \simeq 0.11$ (WMAP) [(4)]
- Big Bang Nucleosynthesis
  If the gravitino is unstable and its lifetime leads to decay after BBN, then the decay products will photo-dissociate the light elements.
  Lifetime $\tau_{\frac{3}{2}} \sim m_{\rm P}^2 / m_{\frac{3}{2}}^3 \sim 10^8 (100 {\rm GeV}/m_{\frac{3}{2}}\ )^3$ sec
- Gravitino must be stable, heavy, or rare
- Stable gravitino means constraints on NLSP

(4) see e.g. Kawasaki et al (2008)

Gravitino problem becomes gravitino solution

- During θ inflation: Universe cools from $T_\mathrm{i} \sim \sqrt{v_\phi M_\mathrm{SUSY}}$ to $T_\mathrm{c} \sim M_\mathrm{SUSY}$.
- e-foldings: $N_\theta \simeq \frac{1}{2} \ln \left(\frac{v_\phi}{M_\mathrm{SUSY}} \right) \simeq 15 - \ln \left(\frac{M_\mathrm{SUSY}}{1\ \mathrm{TeV}} \right)$
- Gravitinos from high-scale inflation diluted
- Gravitinos regenerated by reheating to $T_\mathrm{rh2} \simeq 10^9 \left(\frac{M_\mathrm{SUSY}}{1\ \mathrm{TeV}} \right)^{\frac{1}{2}}$ GeV
- Gravitinos are either LSP, or decay into LSP
- $\Omega_\mathrm{LSP} h^2 \simeq 6 \times 10^{-3} \frac{m_\mathrm{LSP}}{100\ \mathrm{GeV}} \left(\frac{T_\mathrm{rh2}}{10^9\ \mathrm{GeV}} \right)$

Gravitino constraints and supersymmetry-breaking

$$\Omega_{\mathrm{LSP}} h^2 \simeq 6 \times 10^{-3} \omega_{\tilde{G}} \frac{m_{\mathrm{LSP}}}{100\ \mathrm{GeV}} \left(\frac{M_{\mathrm{SUSY}}}{1\ \mathrm{TeV}} \right)^{\frac{1}{2}} \simeq 0.11 \text{ (WMAP)}$$

$$\begin{aligned} \Delta V &= v_\phi^2 M_{\mathrm{SUSY}}^2 = M^2 \left(\frac{\tilde{h}_{\lambda_1}^2}{2\lambda_1} - \frac{\tilde{h}_{\lambda_3}^2}{2\lambda_3} - \frac{\bar{m}_\phi^2}{\lambda_1} + \frac{\bar{m}_h^2}{\lambda_3} \right) \\ &= v_\phi^2 \left(\frac{1}{4} \left[\tilde{h}_{\lambda_1}^2 - \tilde{h}_{\lambda_3}^2 \frac{\lambda_1}{\lambda_3} \right] - \frac{1}{2} \left[\bar{m}_\phi^2 - \bar{m}_h^2 \frac{\lambda_1}{\lambda_3} \right] \right). \end{aligned}$$

In the three benchmark supersymmetry-breaking schemes:

- $$M_{\mathrm{SUSY}}^2 \simeq \begin{cases} m_{\frac{3}{2}}^2 \left(\frac{g'^2}{16\pi^2} \right)^2 \mathrm{Tr}(Y'^2) \left[q_\phi^2 - q_H^2 \left(\frac{\lambda_1}{\lambda_3} \right) \right], & \text{(AMSB)}, \\ \Lambda_s^2 \frac{\lambda_1}{\lambda_3} \left(\frac{g'^2}{16\pi^2} \right)^2 \left[q_H^2 \left(\frac{\lambda_1}{\lambda_3} \right) - q_\phi^2 \right] & \text{(GMSB)}, \\ \frac{1}{2}(m_0^2 - A^2/4) \left[\frac{\lambda_1}{\lambda_3} - 1 \right] & \text{(CMSSM)}. \end{cases}$$

Gravitino constraints (AMSB)

$$\Omega_{\rm LSP} h^2 \simeq 6 \times 10^{-3} \frac{m_{\rm LSP}}{100\ {\rm GeV}} \left(\frac{M_{\rm SUSY}}{1\ {\rm TeV}}\right)^{\frac{1}{2}} \simeq 0.11$$

- AMSB empirical formula: $m_{\rm LSP} \simeq 3.3 \times 10^{-3} m_{\frac{3}{2}}$ [5]
- $M_{\rm SUSY}^2 \simeq m_{\frac{3}{2}}^2 \left(\frac{g'^2}{16\pi^2}\right)^2 {\rm Tr}(Y'^2) \left[q_\phi^2 - q_H^2 \left(\frac{\lambda_1}{\lambda_3}\right)\right]$
- Correct μ_h-parameter (EW vacuum): $q_\phi^2 g'^2 \simeq \frac{\lambda_3}{\lambda_1}$
- Hence $m_{\frac{3}{2}} \simeq 350 \left(\frac{q_\phi}{\sqrt{{\rm Tr}(Y'^2)}} \frac{\lambda_3}{\lambda_1}\right)^{\frac{1}{3}}$ TeV
- Allowed range: $150\ {\rm TeV} \lesssim m_{\frac{3}{2}} \lesssim 240\ {\rm TeV}$
- Higgs mass 125 GeV with $m_{\frac{3}{2}} = 140$ TeV

[5] Hindmarsh, Jones (2012)

Gravitino constraints (GMSB)

$$\Omega_{\rm LSP} h^2 \simeq 6 \times 10^{-3} \frac{m_{\rm LSP}}{100\ \rm GeV} \left(\frac{M_{\rm SUSY}}{1\ \rm TeV}\right)^{\frac{1}{2}} \simeq 0.11$$

- Lightest supersymmetric particle is gravitino
- $M_{\rm SUSY}$ is controlled by gaugino masses
- Gravitino constraint: $\left(\frac{m_{\frac{3}{2}}}{1\ \rm TeV}\right)^2 \simeq 5\sqrt{N_{\rm mi}}\sqrt{\frac{\lambda_3}{\lambda_1}}\left(\frac{M_2}{1\ \rm TeV}\right)^{-1}$
- (SU(2) gaugino mass M_2, messenger index $N_{\rm mi}$)
- OK for e.g. $m_{\frac{3}{2}} \sim 1$ TeV, $M_{\rm gaugino} \sim$ few TeV.
- **But** messenger mass constrained by NLSP decays during BBN[6]
- $\left(\frac{m_{\frac{3}{2}}}{1\ \rm TeV}\right)^3 \lesssim 0.5\sqrt{N_{\rm mi}}\sqrt{\frac{\lambda_3}{\lambda_1}}$

[6] Gherghetta, Giudice, Riotto (1998)

Gravitino constraints (CMSSM)

$$\Omega_{LSP} h^2 \simeq 6 \times 10^{-3} \frac{m_{LSP}}{100\ \text{GeV}} \left(\frac{M_{SUSY}}{1\ \text{TeV}} \right)^{\frac{1}{2}} \lesssim 0.11$$

- Dark matter can be neutralino produced by standard freeze-out
- Density constraint on thermally-produced gravitinos:

$$\left(m_0^2 - A^2/4\right)^{\frac{1}{2}} \lesssim 5 \times 10^2 \left(\frac{\lambda_1}{\lambda_3} - 1 \right)^{-\frac{1}{2}} \left(\frac{m_{LSP}}{100\ \text{GeV}} \right)^{-2}\ \text{TeV}.$$

- $T_{rh2} \simeq 10^9$ GeV means $m_{\frac{3}{2}} \gtrsim$ (few) TeV to avoid BBN constraints

Summary

- Simplest way of coupling F-term inflation and MSSM gives ...
- ... minimal hybrid inflationary supersymmetric standard model (MHISSM)
- Mechanisms for Higgs μ_h-term and RH neutrino masses
- Two phases of inflation: (a) F-term at 10^{15} GeV and (b) Higgs thermal at 10^9 GeV
- DM from decays of thermally produced gravitinos (AMSB,CMSSM)
- Cosmic string $G\mu_{cs} \simeq 10^{-7}$ satisfies CMB constraints
- Reduced e-foldings of F-term inflation: $n_s \simeq 0.976$
- Temperature high enough for leptogenesis
- Higgs thermal inflation is generic when inflaton $\rightarrow \mu_h$-term