SUSY'07

Right-Hand Sneutrino Condensate CDM and the Baryon-to-Dark Matter Ratio

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Baryon-to-Dark Matter Ratio

WMAP 3-year Data => $\Omega_{DM}/\Omega_B = 5.65 \pm 0.58$

In most cases the physics of baryogenesis and of dark matter production is unrelated

Why is the density in baryons within an order of magnitude of that of dark matter?

Either

Remarkable coincidence or undefined anthropic selection mechanism

or

The origin of the baryon asymmetry and dark matter are related

The BDM ratio may be a powerful indicator of the correct particle physics theory

Baryon-to-Dark Matter Ratio Models [BDM models]

It is non-trivial for any particle physics model to have a mechanism to account for the BDM ratio => May serve to select best candidate models

Broadly two classes:

1. Charge conservation based.

e.G . S.Thomas, PLB356 (1995) 256,
K.Enqvist & JMcD, NPB538 (1999) 321,
S.Abel & V.Page, JHEP 05 (2006) 024
L.Roszkowski & O.Seto, hep-ph/0608013

The dark matter particle and baryon number are related by a conserved charge, $Q_B + Q_{cdm} = 0 \Rightarrow n_{cdm} \sim n_B$

$\Rightarrow M_{cdm} \sim m_n n_B / n_{cdm} \sim 1$ GeV [Problem for SUSY]

2. Dynamics based:

The dark matter and baryon densities are related by similar physical mechanisms for their origin

=> Less rigid relation between n_B and n_{cdm} [Can have $n_B >> n_{cdm}$]

Examples of BDM Models

SUSY:

Scalar condensate asymmetry $\phi \rightarrow \tilde{u}dd$ — Thomas, PLB356 (1995) 256

Q-Ball Decay $Q \rightarrow q + \chi$ — Enqvist & JMcD, NPB538 (1999) 321

Affleck-Dine leptogenesis $n_{cdm} \sim L_R = -L_L \sim n_b$ — Abel & Page, JHEP 05 (2006) 024

All imply $n_B \sim n_{cdm}$ => $m_{cdm} \sim 1$ GeV

Q-Ball Decay to axinos $Q \rightarrow q + \tilde{a}$ — Roszkowski & Seto, hep-ph/0608013, Seto & Yamaguchi, hep-ph/0704.0510

$m_{\tilde{a}} \leq 1 GeV$ => Can explain baryon-to-dark matter ratio

Non-SUSY:

Additional $SU(2)_L$ fermions + sphalerons — Barr, Chivukula & Farhi, PLB241 (1990) 387

Additional global U(1) + EW baryogenesis — Kaplan PRL68 (1992) 741

B carrying DM with $\sigma_{X}^{ann} \neq \sigma_{\bar{X}}^{ann}$ — Farrar & Zaharijas, PRL96 (2006) 041302

1 GeV RH neutrinos in $SU(2)_L$ x $SU(2)_R$ — Cosme, Lopez Honorez &Tytgat, PRD72 (2005) 043505

Non-SUSY models generally more complicated than SUSY

SUSY Baryon-to-Dark Matter Ratio Models?

A natural explanation of the baryon asymmetry in SUSY models is Affleck-Dine baryogenesis

Can the dark matter density be related to Affleck-Dine baryogenesis?

Dynamical SUSY BDM Model:

d= 4 $(H_uL)^2$ Affleck-Dine leptogenesis

+

RH Sneutrino Condensate CDM with d=4 non-renormalizable superpotential

RH Sneutrino dark matter originates from a scalar potential lifted by d=4 non-renormalizable terms

If the baryon asymmetry also originates from a condensate along a d=4 flat direction of the MSSM then the mass densities in dark matter and baryons are naturally similar.

RH Sneutrino condensate dark matter

MSSM with RH Neutrinos:

$$W = W_{MSSM} + W_{\nu}$$

$$W_{\nu} = \lambda_{\nu} N H_u L + \frac{M_N}{2} N^2 \;\; ; \quad \mathrm{N = RH\ Neutrino}$$

If $M_N < m_s \sim 0.1\text{-}1\ TeV$ then the RH sneutrino mass is due to soft SUSY breaking

=> RH sneutrino can be the Lightest SUSY Particle => Dark Matter

Asaka, Ishiwata & Moroi, PRD73 (2006) 051301, PRD75 (2007) 065001

Simplest Case: $M_N = 0$ (e.g. R-symmetry, violated by Planck corrections)

=> Dirac neutrino masses: $m_{\nu} < 0.1\ \mathrm{eV} \Rightarrow \lambda_{\nu} < 10^{-13}$

$\Rightarrow$ N very weakly coupled, out-of-equilibrium, can form a condensate which exists today as dark matter

Oscillating Condensate Dark Matter in SUSY

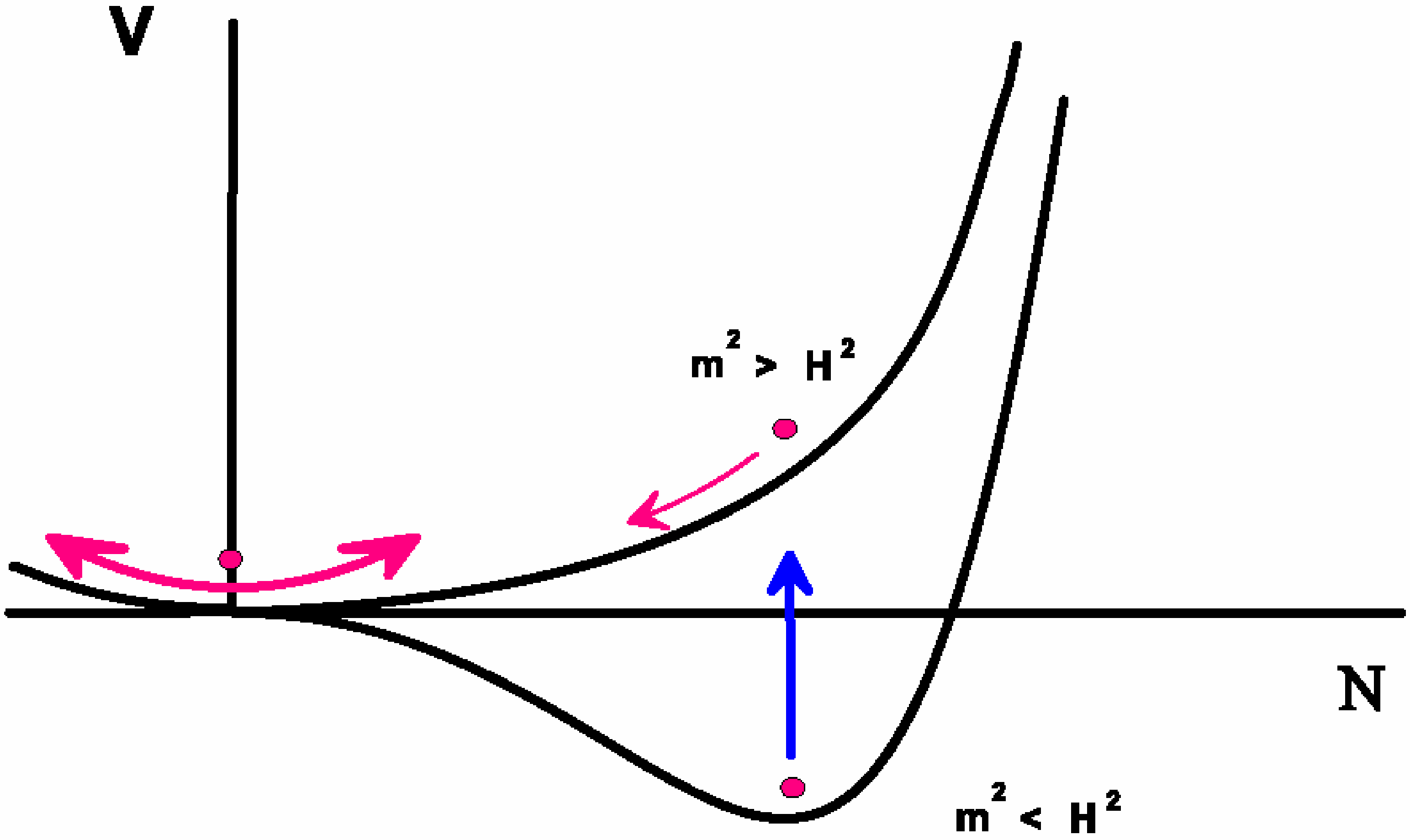
Expect non-renormalizable interactions in a complete theory of Planck-scale physics.

Leading-order Planck-suppressed interaction: d = 4

$$W = \frac{\lambda_N N^4}{4! M} \quad ; \quad M = M_{Pl}/\sqrt{8\pi}$$

=>

$$V(N) = \left(m_N^2 - c_N H^2\right)|N|^2 + \left(A_N \frac{\lambda_N}{4! M} N^4 + h.c.\right) + \frac{|\lambda_N|^2}{3!^2 M^2}|N|^6$$


V
$m^2 > H^2$
N
$m^2 < H^2$

Present energy density in oscillating N field:

$$\rho_{N\ o} = \frac{\sqrt{12}\pi^2}{45}\frac{c_N T_\gamma^3 T_R m_N}{\lambda_N M}$$

Observed dark matter density fixes the reheating temperature:

$$T_R \approx 2.6 \times 10^7\ \frac{\lambda_N}{c_N}\left(\frac{h}{0.7}\right)^2\left(\frac{\Omega_N}{0.23}\right)\left(\frac{100GeV}{m_N}\right)GeV$$

Consistent with the thermal gravitino upper bound:

$T_R \leq 10^{6\text{-}8}$ GeV ⇔ $\lambda_N/c_N \leq 0.1 - 1$

=> Can account for CDM

d=4 $(H_uL)^2$ Affleck-Dine Leptogenesis

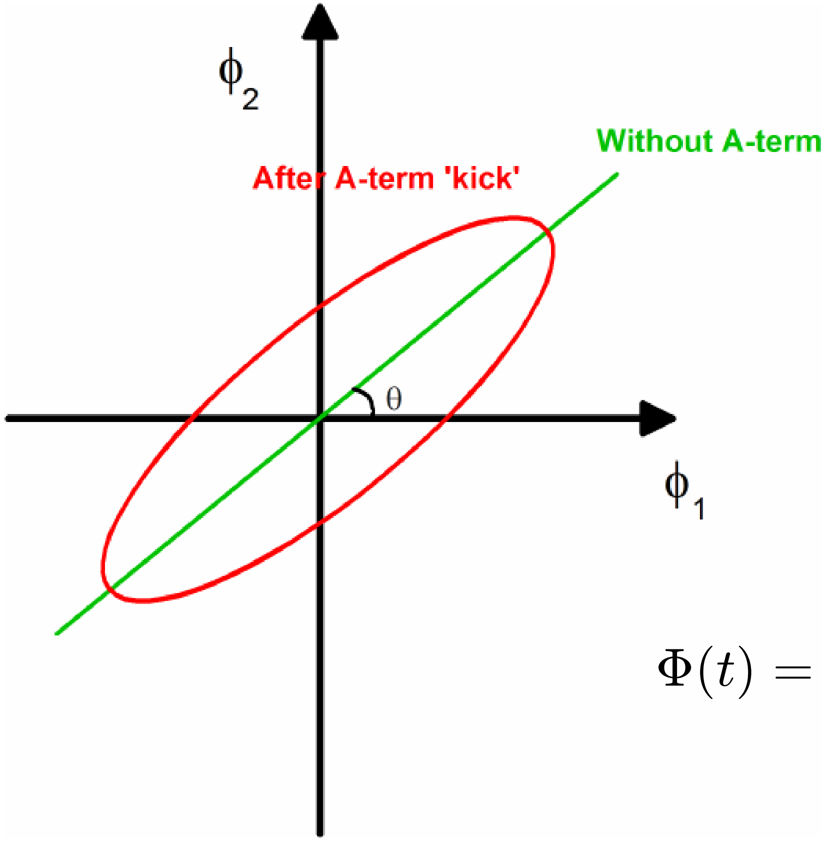
d = 4 flat direction of the MSSM scalar potential:

$$W \sim (H_u L)^2 \equiv \lambda_\phi \Phi^4/(4!M) \qquad \text{(L violating)}$$

$$V(\Phi) = \left(m_\Phi^2 - c_\Phi H^2\right) |\Phi|^2 + \left(A_\Phi \frac{\lambda_\Phi}{4!M} \Phi^4 + h.c. \right) + \frac{|\lambda_\Phi|^2}{3!^2 M^2} |\Phi|^6$$

CP, L violation => Lepton asymmetry in Φ condensate

At $cH^2 \sim m_\Phi^2 \sim m_s^2$, A-term kicks real and imaginary oscillations out of phase



$$\Phi(t) = \left(\phi_1(t) + i\phi_2(t)\right)/\sqrt{2}$$

Φ traces an ellipse in the complex plane
=> Lepton asymmetry in the condensate $\propto$ area

$$n_L = \frac{i}{2}\left(\dot{\Phi}^\dagger\Phi - \Phi^\dagger\dot{\Phi}\right) = \frac{1}{4}m_\Phi\phi^2(t)\sin(2\theta)\sin(\delta)$$

(θ = initial phase of the field, fixed during inflation, δ = phase shift)

Once Φ condensate decays, L is converted to a baryon asymmetry by anomalous B + L violation $n_B = -\frac{8}{23} n_L$ =>

$$n_B \approx \frac{f_A}{4} \frac{\rho_{\Phi\ o}}{m_\Phi}$$ $f_A = \frac{16}{23} \sin(2\theta) \sin(\delta)$ ~ CP violating angle

$\rho_{\Phi\ o} = m_\Phi^2 \phi(t_o)^2/2$ = Present mass density in the d=4
Φ condensate if Φ did not decay

$\Rightarrow$ Baryon number density is directly related to the mass density in a d = 4 condensate

=> Connection between baryon number and dark matter density

Baryon-to-Dark Matter Ratio

$$\rho_{B\ o} = m_n n_B \approx \frac{f_A}{4}\frac{m_n}{m_\Phi}\rho_{\Phi\ o}$$

$$\rho_{N\ o} \propto c_N m_N/\lambda_N \qquad\qquad \rho_{\Phi\ o} \propto c_\Phi m_\Phi/\lambda_\Phi$$

=>

$$\boxed{\frac{\Omega_B}{\Omega_{DM}} \approx \frac{f_A}{4}\frac{m_n}{m_\Phi}\frac{\rho_{\Phi\ o}}{\rho_{N\ o}} = \frac{f_A}{400}\left(\frac{100GeV}{m_N}\right)\frac{c_\Phi}{c_N}\frac{\lambda_N}{\lambda_\Phi}}$$

Dynamics

The observed ratio can be understood with a small hierarchy between λ_Φ and λ_N e.g.

$$\lambda_\Phi \sim 0.01\lambda_N, \;\; f_A \sim 0.5 \;\;, \; c_\Phi \sim c_N, \;\; m_N \sim 100GeV$$

=> $\frac{\Omega_B}{\Omega_{DM}} \approx 1/6$

=>

The puzzle of why $\Omega_B \sim \Omega_{cdm}$ is reduced to a simple hierarchy of couplings

- Requires no additional physics beyond MSSM with neutrino masses

Such a hierarchy of couplings is plausible: if there is also a generational dependence in the non-renormalizable couplings then it is reasonable to have significantly different values of λ_Φ and λ_N

- Model can be tested via collider phenomenology and cosmology

Observational Consequences?

- SUSY Phenomenology: Non-standard collider phenomenology

- Cosmology: Cold dark matter and baryon isocurvature perturbations

Observation of a combination of non-standard SUSY phenomenology + isocurvature perturbations would strongly support the model

Collider Phenomenology

Collider phenomenology of the RH sneutrino condensate model is similar to the thermal relic RH sneutrino CDM model [Asaka, Ishiwata & Moroi, hep-ph/0512118, 0612211]

Differs in having a wider parameter space of MSSM-LSP:

Thermal relic => $\Omega_N = (m_N/m_{MSSM\text{-}LSP})\Omega_{MSSM\text{-}LSP}$ => $\Omega_{MSSM\text{-}LSP} > \Omega_{cdm}$

Condensate => $\Omega_{MSSM\text{-}LSP} << \Omega_{cdm}$ is possible

RH Sneutrino LSP => Lightest superpartner of MSSM is unstable but long-lived

=> Collider phenomenology like an LSP of the MSSM ['MSSM-LSP']

- MSSM-LSP could be a charged or coloured particle
- Strikingly different phenomenology at colliders cf. MSSM

- If $\tilde{\tau}$ is MSSM-LSP => Can distinguish RH sneutrino LSP from gravitino, axino
  [Buchmuller et al, PLB588 (2004) 90, Brandenburg et al PLB617 (2005) 99]

- An MSSM-LSP neutralino will have different mass and interactions compared with a conventional thermal relic dark matter neutralino LSP
  - Can also distinguish from thermal RH sneutrino model

Stau decay to RH Sneutrino NLSP

- Can trap charged staus and measure lifetime and final states

RH Sneutrino LSP:

Fastest decay via A-term interaction $\tilde{\tau} \to h_u^- + \tilde{N}$

- Lifetime ~ 0.1-10 sec for m_ν ~ 0.1 eV
- Distinctive final state compared with gravitino, axino LSP

Gravitino LSP: $\tilde{\tau} \to \tau + \psi_{3/2}$ [Buchmuller, Hamaguchi, Ratz and Yanagida, PLB588 (2004) 90]

- Lifetime ~ 1-10 years for $m_{3/2}$ ~ 100 GeV [~100 sec for $m_{3/2}$ ~ 0.1 GeV]
- Spin from 3-body decay angular distribution $\tilde{\tau} \to \tau + \psi_{3/2} + \gamma$

Axino LSP: $\tilde{\tau} \to \tau + \tilde{a}$ [Brandenburg, Covi, Hamaguchi, Roszkowski and Steffen, PLB617 (2005) 99]

- Lifetime ~ 10 sec for f_a ~ 10^{11} GeV
- Spin-1/2

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Cosmology

CDM and Baryon Isocurvature Perturbations

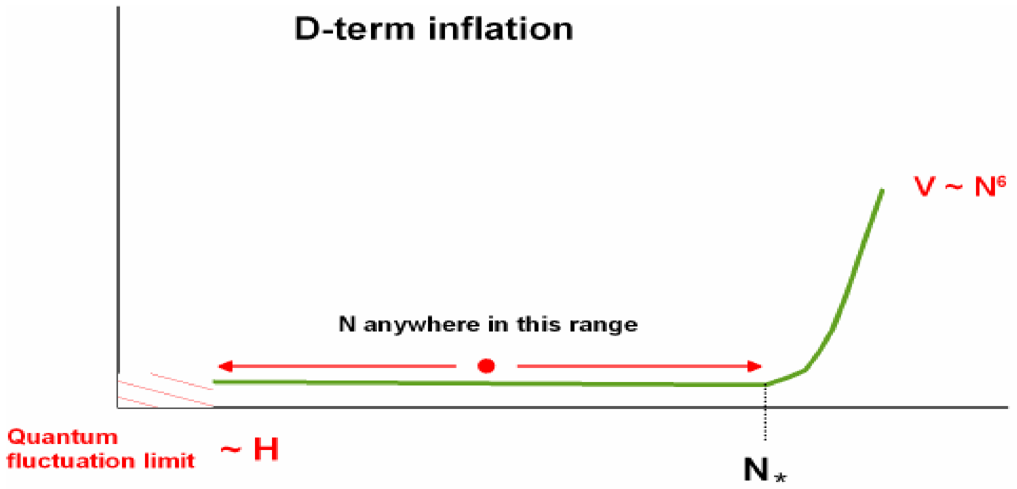
Quantum fluctuations in the amplitude and/or phase of N and ϕ during inflation become isocurvature CDM and baryon density perturbations today

Magnitude of isocurvature perturbation depends on the nature of the SUSY inflation model [eg D-term or F-term]:

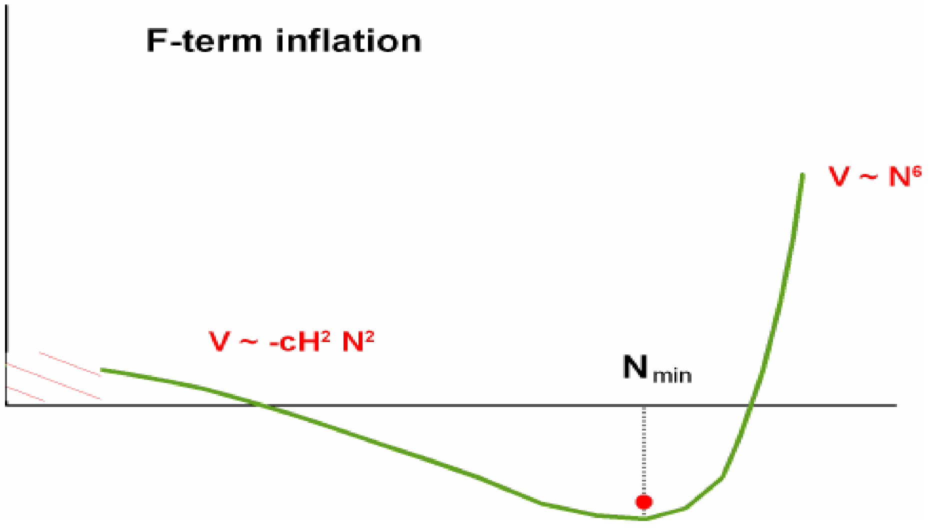
- No order H corrections [D-term inflation]
  => N, ϕ massless during inflation
  => Amplitude/phase fluctuations generate isocurvature perturbations

- N, ϕ mass^2 ~ $-H^2$ during inflation [F-term inflation]
  => N fixed during inflation
  => Phase fluctuations generate isocurvature perturbations
  if no H corrections to A-terms [e.g. via inflaton S ⇔ -S]

Flat direction potential during inflation



$N_* \Rightarrow V'' = H^2$



CDM isocurvature perturbations

Since inflaton and RH sneutrino quantum fluctuations are independent, adiabatic and isocurvature perturbations are uncorrelated:

$$C_l = (1-\alpha)C_l^{ad} + \alpha C_l^{iso}$$ CMB multipoles

$$\boxed{\alpha \approx \frac{H_I^2}{\pi^2 P_{\mathcal{R}} N_I^2}}$$

$$(P_{\mathcal{R}}^{1/2} = 4.8 \times 10^{-5})$$

3-year WMAP limit: $\alpha < \alpha_{lim} = 0.26$ [Bean, Dunkley and Pierpaoli, hep-ph/0606685]

- D-term Inflation can have large isocurvature perturbations since $N_I << N_*$ is possible

- F-term Inflation => N_I is fixed at $N_{min} \sim N_*$

Baryon isocurvature perturbations

Fluctuations in the phase θ of the Affleck-Dine field ϕ
=> Fluctuations in the number of baryons, $\delta n_B \; \alpha \; \delta\theta$

- Contribution of the baryon isocurvature perturbation to CMB indistinguishable from CDM isocurvature perturbation

- Can be distinguished from CDM isocurvature by observing 21cm background [Barkana & Loeb, astro-ph/0502083, Lewis & Challinor, astro-ph/0702600]

Contribution of baryon isocurvature perturbation is of same form as CDM case:

$$C_l = (1-\alpha)C_l^{ad} + \alpha C_l^{iso}$$

$$\alpha_{BI} = \left(\frac{\Omega_B}{\Omega_{DM}}\right)^2 \frac{f_\theta^2 H_I^2}{4\pi^2 P_{\mathcal{R}} \phi_I^2}$$

$$f_\theta = \frac{2}{\tan 2\theta} \sim 1$$

=>

$$\boxed{\frac{\alpha_{BI}}{\alpha_{CDI}} = \frac{f_\theta^2 N_I^2}{4\phi_I^2}\left(\frac{\Omega_B}{\Omega_{CDM}}\right)^2 \approx 8 \times 10^{-3} f_\theta^2 \left(\frac{N_I}{\phi_I}\right)^2}$$

Ratio of baryon to CDM isocurvature perturbation

Summary of Isocurvature Perturbation Results

CDM isocurvature perturbation: Observable in D-term Inflation if

$$H_I \gtrsim \left(\frac{48}{5}\right)^{1/2} \frac{\pi^2 P_{\mathcal{R}} M \alpha_{lim}}{\lambda_N} \equiv 4.4 \times 10^{11} \left(\frac{0.1}{\lambda_N}\right) \left(\frac{\alpha_{lim}}{0.26}\right) \left(\frac{N_I}{N_*}\right)^2 GeV$$

- Comparable with values of H_I in D-term Hybrid Inflation $\left(H_I \approx 1.1 \times 10^{13} g\ GeV\right)$
  => Realistic prospect of observing a CDM isocurvature perturbation

- Similar result for F-term inflation

Ratio of Baryon to CDM isocurvature perturbation: $\frac{\alpha_{BI}}{\alpha_{CDI}} \propto \left(\frac{N_I}{\phi_I}\right)^2$

F-term Inflation: ϕ_I and N_I are fixed at the minimum of their potentials

=> $$\frac{\alpha_{BI}}{\alpha_{CDI}} \approx 8 \times 10^{-3} f_\theta^2 \left(\frac{c_N}{c_\phi}\right)^{1/2} \frac{\lambda_\phi}{\lambda_N} \sim 10^{-3} - 10^{-4}$$

D-term Inflation: Since ϕ_I and N_I are undetermined, the baryon isocurvature perturbation can be large if $\phi_I \lesssim 0.1 N_I$

The ratio of the baryon to CDM isocurvature perturbation probes
the nature of SUSY inflation in the RH Sneutrino condensate BDM model

Conclusions

- d=4 Affleck-Dine leptogenesis combined with d=4 RH sneutrino condensate dark matter can plausibly account for the baryon-to-dark matter ratio

- Unlike models based on conserved total charge, the mechanism is dynamical => Freedom to account for $n_B \sim 100\ n_{CDM}$

- Based on MSSM with neutrino masses: no additional physics

- Clear observational consequences:

NLSP could be a squark, slepton or non-thermal relic neutralino $\tilde{\tau}$ NLSP => Can identify LSP

Observable cold dark matter and/or baryon isocurvature perturbations are possible. Ratio => Nature of SUSY inflation.

Combined observation of SUSY, non-standard MSSM-LSP and isocurvature perturbations would strongly support the RH sneutrino condensate BDM model