

Affleck-Dine Sneutrino Inflation

Jason L. Evans

¹University of Minnesota, FTPI

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Outline

Why Inflation

Quadratic Inflation In SUSY

Sneutrino Chaotic Inflation

Leptogenesis

Horizon and Flatness Problem

► Horizon problem

Visible Universe is Homogenous and Isotropic

CMB is homogenous on super horizon scales

$$\tau = \int_0^a d(\ln a) \frac{1}{Ha} \begin{cases} a & \text{RD} \\ a^{1/2} & \text{MD} \end{cases}$$

► Flatness problem

Universe is quite flat ($\Omega = 1$)

$\Omega = 1$ is unstable fixed point

$$\Omega - 1 = \frac{k}{(aH)^2} \sim k \begin{cases} t^{2/3} & \text{MD } (a \sim t^{2/3}) \\ t & \text{RD } (a \sim t^{1/2}) \end{cases}$$

Inflation: Fixing Flatness and Horizon Problem

- ▶ Flatness/Horizon problem from increasing Hubble radius
- ▶ Hubble radius shrinks during inflation

$$\frac{d}{dt} \left(\frac{1}{Ha} \right) = \frac{1}{H} \frac{d}{dt} \left(\frac{1}{a} \right) < 0$$

- ▶ Comoving horizon τ (i.e. conformal time) shrinks

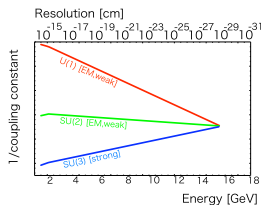
$$\tau = \int_0^a d \ln a \left(\frac{1}{Ha} \right)$$

- ▶ Flat universe becomes attractor

$$\Omega - 1 = -\frac{k}{(aH)^2}$$

Why Supersymmetry

- ▶ Stabilizes the weak scale
 - Some fine tuning is better than a lot of fine tuning
- ▶ Unification of the couplings is virtually automatic



- ▶ Higgs mass $\lesssim 140$ GeV
- ▶ Dark matter candidate
Neutralino LSP

Large Field Inflation: SUGRA

- ▶ Large field inflation requires SUGRA

$$\mathcal{L} = K_i^{j*} g^{\mu\nu} \partial_\mu \phi^i \partial_\nu \phi_j^* - V \quad K_i^{j*} = \frac{\partial^2 K}{\partial \phi^i \partial \phi_j^*}$$

$$V = e^{\frac{K}{M_P^2}} \left[(K^{-1})^i_j \left(W^{*j} + \frac{K^j}{M_P^2} W^* \right) \left(W_i + \frac{K_i}{M_P^2} W \right) - 3 \frac{|W|^2}{M_P^2} \right]$$

- ▶ Canonical Kähler potential

$$K = \phi^* \phi \quad \rightarrow \quad \mathcal{L} = g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi^* - V$$

- ▶ Potential exponentially steep for $\langle \phi \rangle > M_P$

$$V = e^{\frac{|\phi|^2}{M_P^2}} [\dots]$$

- ▶ Majorana superfield create UBF ($W = m\phi^2$)

$$V = e^{\frac{K}{M_P^2}} \left[\dots - 3 \frac{m^2}{M_P^2} |\phi^4| \right]$$

SUGRA Inflation: Shift-Symmetry

- ▶ Canonical shift symmetric Kähler

$$K = \frac{1}{2} |\phi + \phi^\dagger|^2 \quad \rightarrow \quad \mathcal{L} = g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi^* - V$$

- ▶ Exponentially steepening gone for ϕ_I

$$V = e^{\frac{K}{M_P^2}} [\dots] = e^{\frac{\phi_R^2}{M_P^2}} [\dots]$$

- ▶ Stabilizer field prevents UFB ($W = m\phi\chi$)

$$V \simeq e^{\frac{K}{M_P^2}} \left[\dots - 3 \frac{m^2}{M_P^2} |\phi\chi|^2 \right]$$

- ▶ Inflation possible along $\chi, \phi_R = 0$ and $\phi_I \neq 0$ flat direction

$$V \simeq \frac{m^2}{2} \phi_I^2$$

Neutrinos and the seesaw Mechanism

- ▶ Neutrinos oscillations well established
- ▶ Right-handed neutrinos possible explanation

$$W = W_{MSSM} + Y_\nu H_u L N + \frac{1}{2} N^T M_N N$$

- ▶ Seesaw explains small neutrino masses

$$M_N \sim 10^{13} \text{ GeV} \quad \rightarrow \quad Y_\nu \sim 1$$

- ▶ Sneutrino is natural candidate for inflation
Seesaw scale \sim inflation scale
- ▶ Simple models are complicated by SUGRA

$$V \simeq e^{|N_1|^2} \left(M_N |N_1|^2 - 3 \frac{|M_N|^2}{M_P^2} |N_1|^4 \right)$$

Sneutrino Chaotic Inflation

- ▶ Shift symmetry simply realized

$$K = \frac{1}{2} |N_3 + N_3^\dagger|^2 + |N_1|^2 + |N_2|^2$$

Murayama, Suzuki, Yanagida, Yokoyama

- ▶ Stabilizer field less simply realized

$$W \supset MN_2N_3 + \frac{1}{2}mN_1^2 \quad M_N = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & m \end{pmatrix}$$

Murayama, Suzuki, Yanagida, Yokoyama

- ▶ Quadratic Inflation along $\text{Im}(N_3)$

$$V \simeq \frac{M^2}{2} \text{Im}(N_3)^2$$

Quadratic chaotic inflation

- ▶ Quadratic chaotic inflation

$$V = \frac{1}{2} m^2 \phi^2$$

- ▶ Slow roll parameters ($\phi(t_I) \simeq 2\sqrt{N}M_P$)

$$\epsilon = \frac{M_P^2}{2} \left(\frac{V_{,\phi}}{V} \right)^2 = \frac{1}{2N} \quad \eta = M_P^2 \frac{V_{,\phi\phi}}{V} = \frac{1}{2N}$$

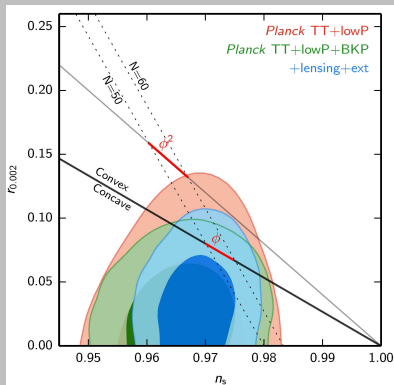
- ▶ Power spectrum and spectral index ($m \sim 10^{13}$ GeV)

$$P_s = \frac{V^{1/2}}{2\sqrt{6}\pi\sqrt{\epsilon}M_P} \simeq \frac{mN}{\sqrt{6}\pi} \quad n_s - 1 = 2\eta - 6\epsilon \simeq -\frac{2}{N}$$

$$r = 16\epsilon \simeq \frac{8}{N}$$

Planck Satellite Results

- ▶ Quadratic inflation ruled out
Need something flatter

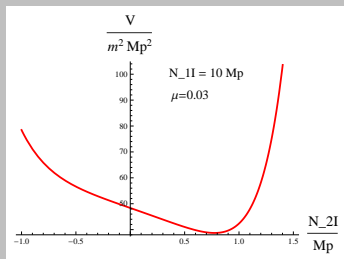


More Natural Sneutrino Chaotic Inflation

- ▶ Generic Majorana mass matrix more natural ($W \supset M_{ij} N_i N_j$)
How does this affect inflation?
- ▶ Simplified two field sneutrino chaotic inflation

$$W = m \left(N_1 N_2 + \frac{\mu}{2} N_1^2 \right) \quad K = \frac{1}{2} \left| N_1 + N_1^\dagger \right|^2 + |N_2|^2$$

- ▶ For $\mu \neq 0$, $N_{2,i} \neq 0 \rightarrow$ two field inflation

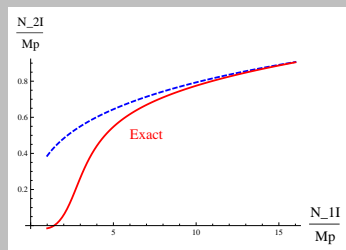
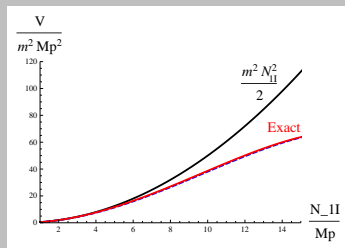


$$V = \frac{m^2}{2} N_{1,i}^2 e^{\frac{N_{2,Pl}}{M_P^2}} \left[1 + \mu^2 - \frac{3}{8} \frac{\mu^2}{M_P^2} N_{1,i}^2 - \mu \left(1 - \frac{2M_P^2}{N_{1,i}^2} \right) \frac{N_{1,i} N_{2,i}}{M_P^2} + \dots \right]$$

Single Field Approximation

- N_{2I} can be integrated out

$$N_{2I} = \left(2\mu N_{1I} M_P^2 \right)^{1/3} - \frac{1}{6} \mu N_{1I}$$



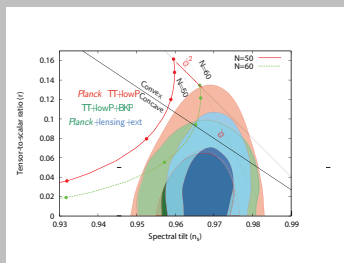
- Effective potential flatter

$$V = \frac{1}{2} m^2 N_{1I}^2 \left[1 - \frac{3}{2^{5/3}} \left(\frac{\mu N_{1I}}{M_P} \right)^{4/3} - \frac{13}{24} \left(\frac{\mu N_{1I}}{M_P} \right)^2 \right]$$

r and n_s for Generic Sneutrino Inflation

- Flatness of potential μ dependent

$$V = \frac{1}{2} m^2 N_{1l}^2 \left[1 - \frac{3}{2^{5/3}} \left(\frac{\mu N_{1l}}{M_P} \right)^{4/3} - \frac{13}{24} \left(\frac{\mu N_{1l}}{M_P} \right)^2 \right]$$



- $\mu = [0, 0.01, 0.02, 0.03, 0.04]$

- $m \simeq 1.5 \times 10^{13}$

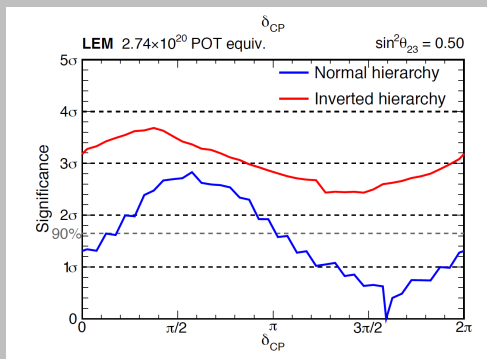
- 3 Neutrinos \rightarrow flatter potential?

CP Violation of the Neutrino Sector

- ▶ Six non-trivial Neutrino CP violating phase
- ▶ Global Fits before Nova experiment

$$\delta = 266_{-63}^{+55} \quad (1.477\pi) \quad \nu\text{fit}$$

- ▶ Nova somewhat confirms these results (Messier Talk)



Leptogenesis

- ▶ Generating the BAU
 - Baryon number violation
 - CP violation
 - Non-equilibrium
- ▶ Neutrino decays violate L (+ Sphaleron) and CP
 - N decay to particles and anti-particles
 - non-trivial phase in neutrino sector
- ▶ Non-equilibrium from inflaton decays
 - Don't produce thermal densities
- ▶ Decay of lightest right handed neutrino generate BAU

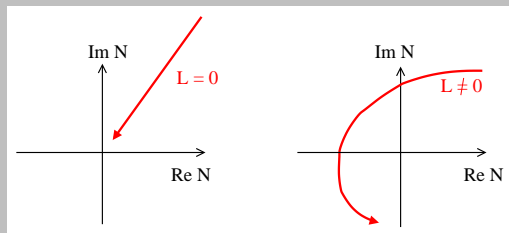
$$M_{N_1} \gtrsim 10^9 \text{ GeV} \quad T_{RH} \gtrsim M_{N_1}$$

- ▶ Works for both sneutrino inflations

Affleck-Dine Baryogenesis

- ▶ CP violation from ϕ^n ($n > 2$ original paper)
- ▶ Lepton number \Leftrightarrow angular momentum
- ▶ The evolution of sneutrino fields can carry lepton number

$$n_L = J_L^0 = i \sum_i \left[N_i^* \frac{dN_i}{dt} - N_i \frac{dN_i^*}{dt} \right] = \sum_i [N_{iR}, N_{iI}, 0] \times \frac{d}{dt} [N_{iR}, N_{iI}, 0]$$



- ▶ Converted to lepton asymmetry by decays to SM fields

Simple Affleck-Dine Leptogenesis

- ▶ Shift symmetry forbids rephasing of N_1

$$K = \frac{1}{2} (N_1 + N_1^\dagger)^2 + \dots$$

- ▶ Rephasing $N_2 \rightarrow$ overall phase of W

$$W = m \left(N_1 N_2 + \frac{|\mu| e^{-i\phi}}{2} N_1^2 \right) \quad N_2 \rightarrow N_2 e^{-i\phi}$$

- ▶ V independent of phase of W

$$V = e^{\frac{K}{M_P^2}} \left[(K^{-1})^i_j \left(W^{*j} + \frac{K^j}{M_P^2} W^* \right) \left(W_i + \frac{K_i}{M_P^2} W \right) - 3 \frac{|W|^2}{M_P^2} \right]$$

- ▶ Gravitino mass prevent removal of phase

$$W = m_{3/2} M_P^2 + m e^{-i\phi} \left(N_1 N_2 + \frac{|\mu|}{2} N_1^2 \right)$$

Affleck-Dine From CP Violating Mass

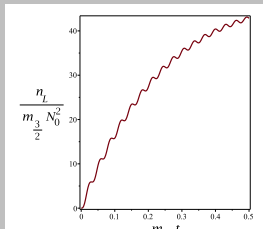
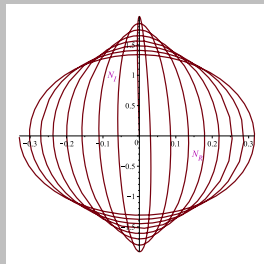
- Fairly accurate toy model

$$V = m^2 |N|^2 + mm_{3/2} (N^2 + N^{*2})$$

- Initial Conditions (End of inflation)

$$\dot{N}_R = \mathcal{O}(m_{3/2} N_0) \quad \dot{N}_I = \mathcal{O}(m N_0)$$

$$N_R = N_I = 0$$



- Lepton asymmetry oscillates
($m_{3/2} \ll m$)

$$\frac{n_L}{N_0} = m_{3/2} \sin(2mt) + m \sin(m_{3/2}t)$$

- Freq. \pm mass eigenvalues

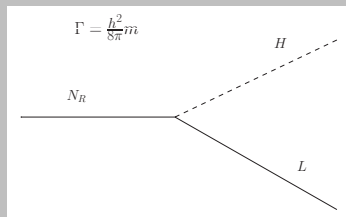
Affleck-Dine From CP Violating Mass

- ▶ $\langle N \rangle < m$, mass term dominates evolution
- ▶ $M_{N_{1I}} \neq M_{N_{1R}} \rightarrow$ different osc. frequencies for N_{iI} and N_{iR}
- ▶ Lepton asymmetry oscillates (Toy Model)
- ▶ Frequency of oscillation differences of masses $\Delta m \propto \mu$
- ▶ Decay width \gg slow oscillation frequency
- ▶ Prompt decay suppresses n_L

$$\frac{n_L}{s} \simeq \frac{n_B}{s} \simeq \frac{\mu_I}{27\mu_R^{2/3}} \frac{m_{3/2}}{m} \sqrt{\frac{M_P}{\Gamma}}$$

$$m_{3/2} = 3.6 \text{ GeV} \frac{\mu_R}{\mu_I} \left(\frac{0.02}{\mu_R} \right)^{1/3} \frac{h}{0.1} \left(\frac{m}{10^{13} \text{ GeV}} \right)^{3/2}$$

Reheating and Gravitino Problem



- ▶ $Y_{N_R} \sim 0.1$ set by inflaton mass
- ▶ High Reheat temp., $H \sim \Gamma$

$$T_R \simeq 4 \times 10^{13} \text{GeV} \frac{h}{0.1} \sqrt{\frac{m}{10^{13} \text{GeV}}}$$

- ▶ Thermal bath overproduces gravitinos

$$Y_{3/2} = 2.3 \times 10^{-9} \left(\frac{T_R}{10^{13} \text{GeV}} \right)$$

- ▶ Gravitino decay to LSP overclose universe

$$\omega_{LSP} h^2 = 64 \left(\frac{T_R}{10^{13} \text{GeV}} \right) \left(\frac{m_{\tilde{\chi}_1^0}}{100 \text{GeV}} \right)$$

Preventing Overclosure

- ▶ Really light DM can fix problem.

$$\omega_{LSP} h^2 = 6.4 \times 10^{-2} \left(\frac{T_R}{10^{13} \text{GeV}} \right) \left(\frac{m_{\tilde{\chi}_1^0}}{100 \text{MeV}} \right)$$

- ▶ R -parity violation makes LSP unstable

$$W = \lambda_{ijk} \bar{U} \bar{U} \bar{D} + \lambda'_{ijk} L \cdot L \bar{E} \dots$$

- ▶ Gravitino decays before LSP freezeout

$$m_{3/2} \gtrsim 10^7 \text{ GeV} \left(\frac{m_{LSP}}{100 \text{ GeV}} \right)^{2/3}$$

Conclusions

- ▶ Inflation solves Cosmological fine tuning
- ▶ Most inflation models have no contact with low scale
Seesaw sneutrino scale similar to inflation scale
- ▶ Quadratic chaotic inflation is basically ruled out
More general/natural W revives the model
- ▶ BAU connected to inflation
- ▶ Additional possibilities for Leptogenesis
Standard Leptogenesis scenario works fine
AD baryogenesis also possible
- ▶ Reheat problem unavoidable, but ...