# Affleck-Dine Sneutrino Inflation

**Jason L. Evans**

[1]University of Minnesota, FTPI

JLE, Gherghetta, Peloso Phys. Rev. D **92**, no. 2, 021303 (2015)

# 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 $\tau$ (i.e. conformal time) roughly constant

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

- Apparent causal contact, $(Ha)^{-1}$, shrinks
- Flat universe becomes attractor

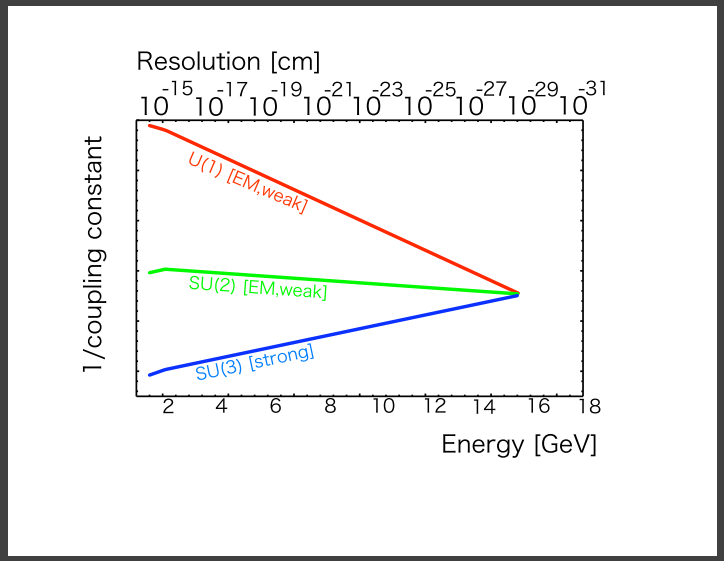
$$\Omega - 1 = -\frac{k}{(aH)^2}$$

# Why Supersymmetry

- Stabilizes the weak scale

  Weak scale is protected from radiative corrections
  Some fine tuning is better than a lot of fine tuning

- Unification of the couplings is virtually automatic
  $SO(10)$ unification right handed neutrinos automatic




- Higgs mass $\lesssim$ 140 GeV
- Dark matter candidate

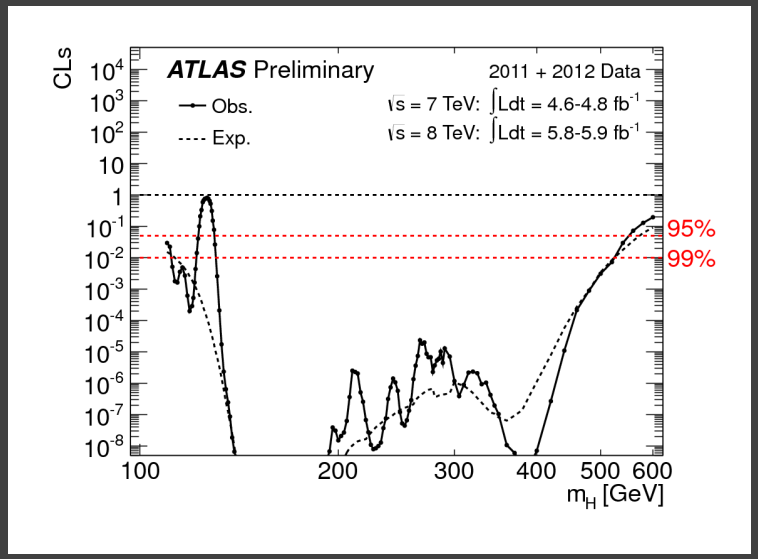
  Neutralino LSP

# Why Supersymmetry

- Stabilizes the weak scale

  Weak scale is protected from radiative corrections
  Some fine tuning is better than a lot of fine tuning

- Unification of the couplings is virtually automatic
  $SO(10)$ unification right handed neutrinos automatic

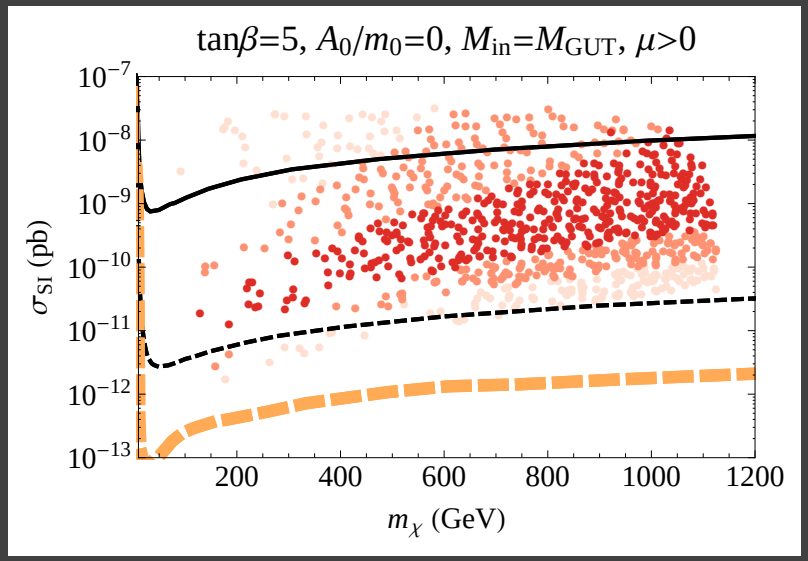



- Higgs mass $\lesssim$ 140 GeV
- Dark matter candidate

  Neutralino LSP

# Why Supersymmetry

- Stabilizes the weak scale
  - Weak scale is protected from radiative corrections
  - Some fine tuning is better than a lot of fine tuning
- Unification of the couplings is virtually automatic
  - $SO(10)$ unification right handed neutrinos automatic




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

# Large Field Inflation: SUGRA

- Large field inflation requires SUGRA

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

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

- Canonical Kähler potential

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

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

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

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

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

# SUGRA Inflation: Shift-Symmetry

- Canonical shift symmetric Kähler

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

- Exponentially steepening gone for $\phi_I$

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

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

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

- 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

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

- Snuetrino 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

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

Murayama, Suzuki, Yanagida, Yokoyama

- Stabilizer field less simply realized

$$W \supset M N_2 N_3 + \frac{1}{2} m N_1^2 \qquad M_N = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & m \end{pmatrix}$$

Murayama, Suzuki, Yanagida, Yokoyama

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

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

# Quadratic chaotic inflation

- Quadratic chaotic inflation

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

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

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

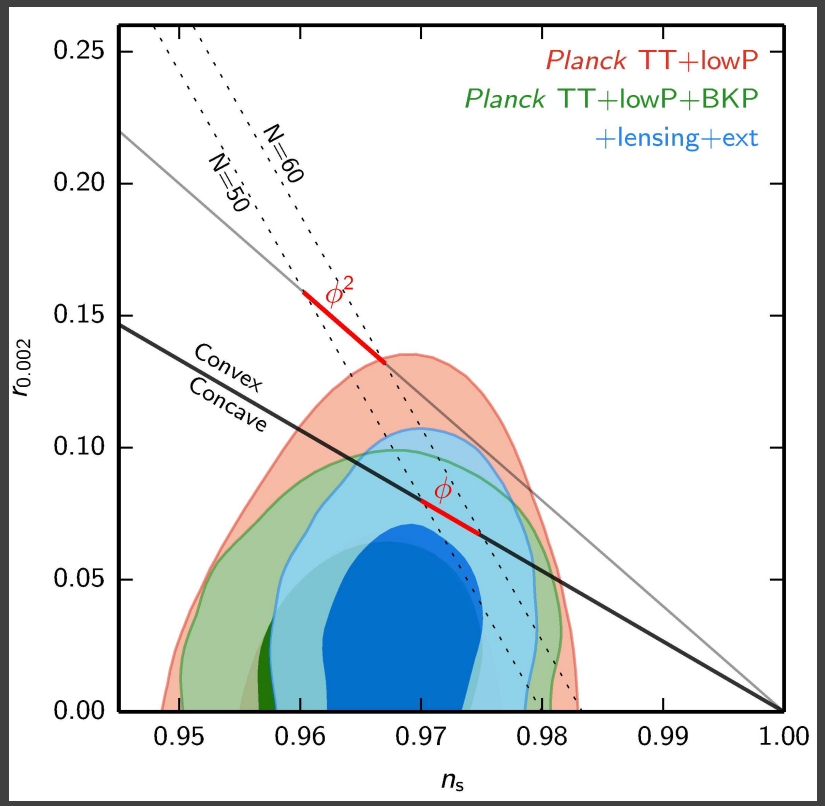
- Power spectrum and spectral index ($m \sim 10^{13}$ GeV)

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

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

# Planck Satellite Results

- Quadratic inflation ruled out
  Need something flatter

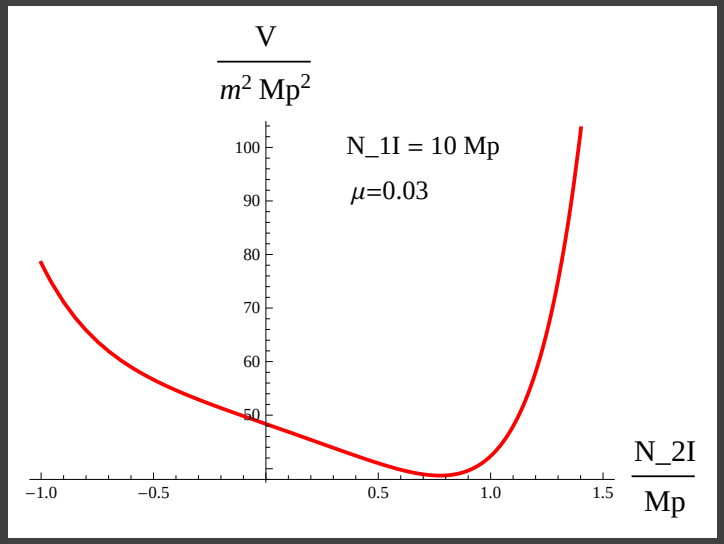


# More Natural Sneutrino Chaotic Inflation

- 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

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

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

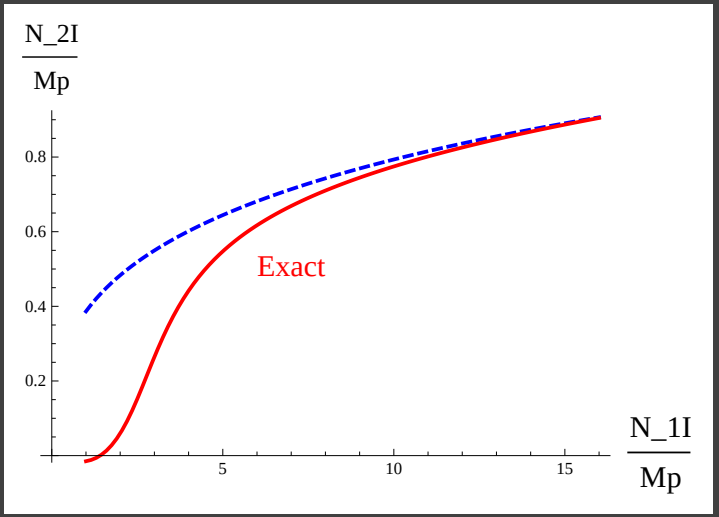


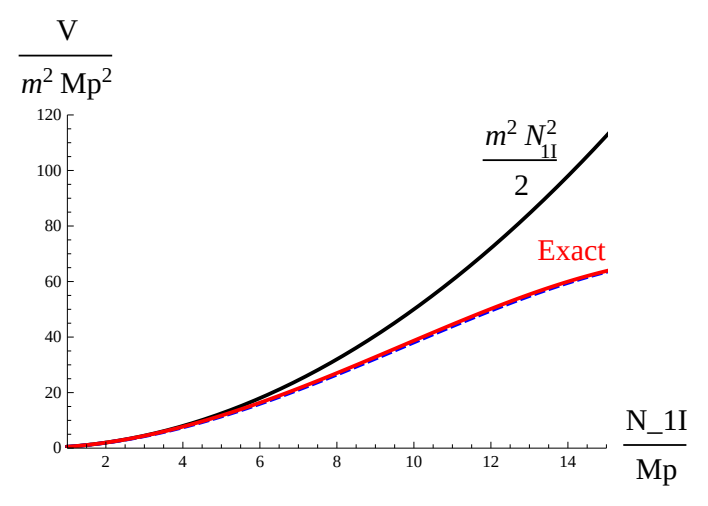

$$V = \frac{m^2}{2} N_{1_I}^2 e^{\frac{N_{2_R}}{M_P^2}} \left[1 + \mu^2 - \frac{3}{8}\frac{\mu^2}{M_P^2} N_{1_I}^2 - \mu\left(1 - \frac{2M_P^2}{N_{1_I}^2}\right) \boxed{\frac{N_{1_I} N_{2_I}}{M_P^2}} + \ldots\right]$$

# Single Field Approximation

- $N_{2_I}$ can be integrated out

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



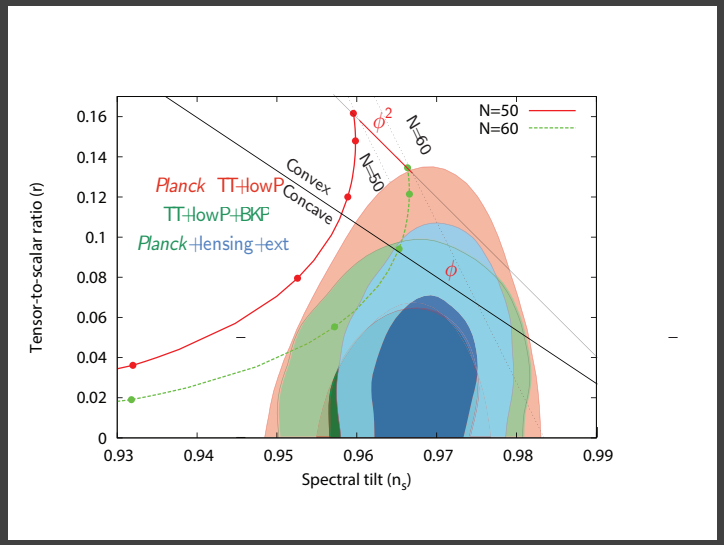

- Effective potential flatter

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

# $r$ and $n_s$ for Generic Sneutrino Inflation

- Flatness of potential $\mu$ dependent

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



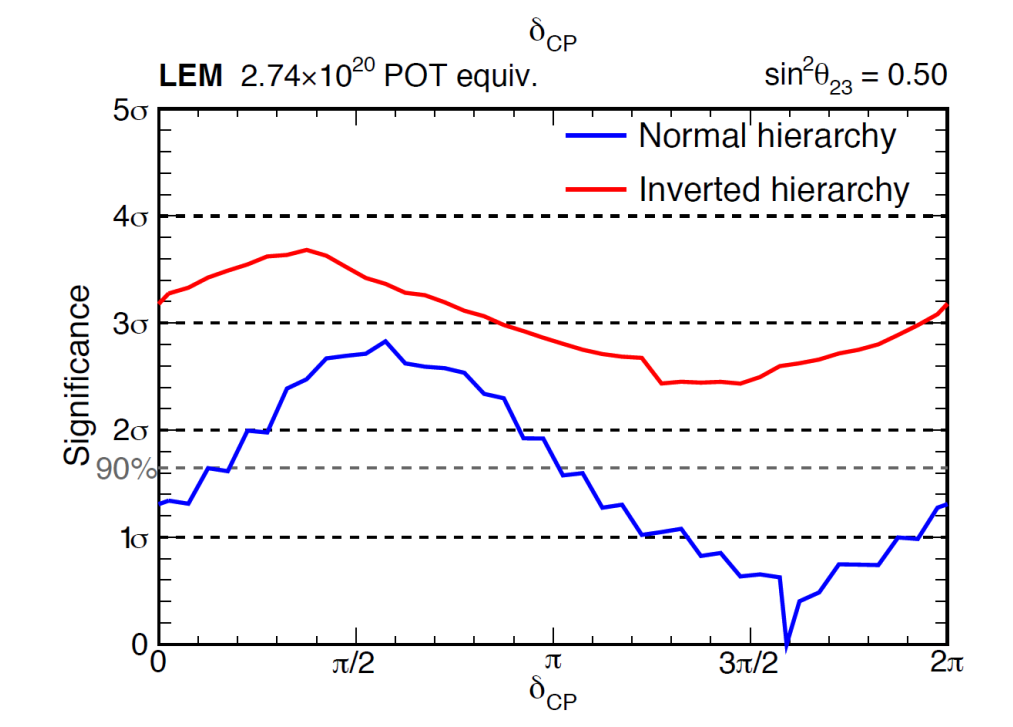

- $\mu = [0, 0.01, 0.02, 0.03, 0.04]$
- $m \simeq 1.5 \times 10^{13}$
- 3 Neutrinos $\rightarrow$ flatter potential?

# CP Violation of the Neutrino Sector

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

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

- 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

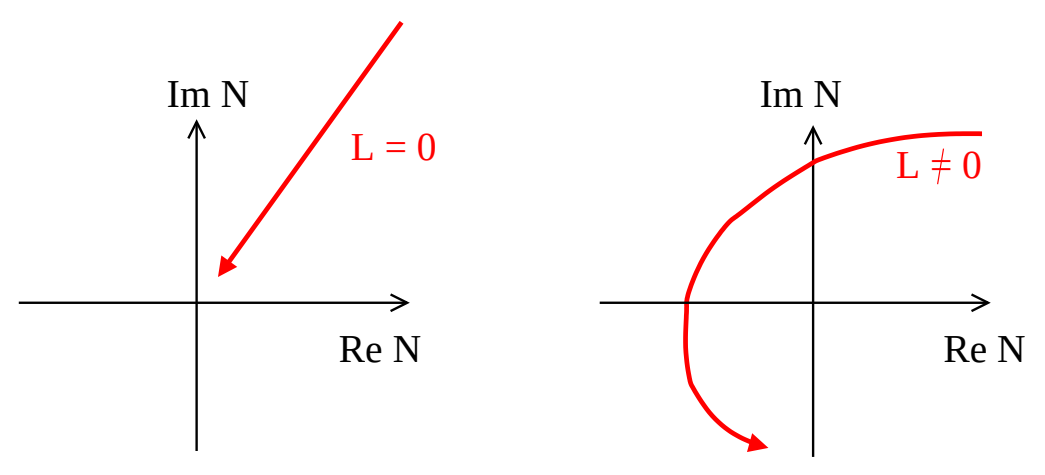
$$M_{N_1} \gtrsim 10^9 \mathrm{GeV} \qquad T_{RH} \gtrsim M_{N_1}$$

- Works for both sneutrino inflations

# Affleck-Dine Baryogenesis

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

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




- Converted to lepton asymmetry by decays to SM fields

# CP Violation for AD Baryogenesis

- Shift symmetry forbids rephasing of $N_1$

$$K = \frac{1}{2}\left(N_1 + N_1^\dagger\right)^2 + \ldots$$

- Rephasing $N_2 \to$ overall phase of $W$

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

$$N_2 \to N_2 e^{-i\phi}$$

- $V$ independent of phase of $W$

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

- 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

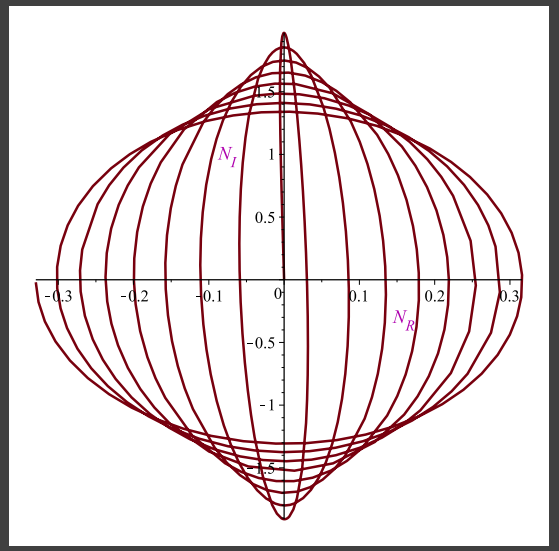
- Fairly accurate toy model

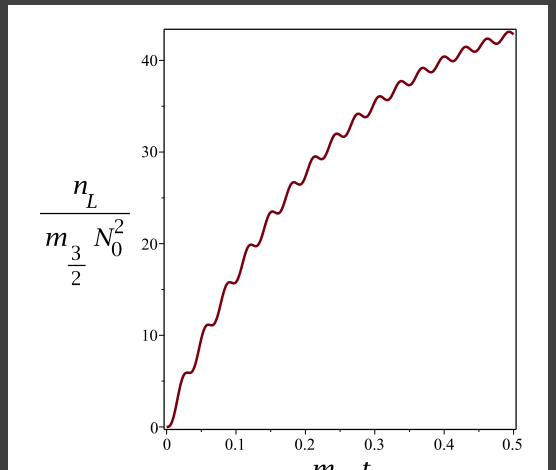
$$V = m^2|N|^2 + m m_{3/2}\left(N^2 + N^{*2}\right)$$

- Initial Conditions (End of inflation)

$$\dot{N}_R = \mathcal{O}(m_{3/2}N_0) \qquad \dot{N}_I = \mathcal{O}(mN_0)$$

$$N_R = N_I = 0$$




- 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

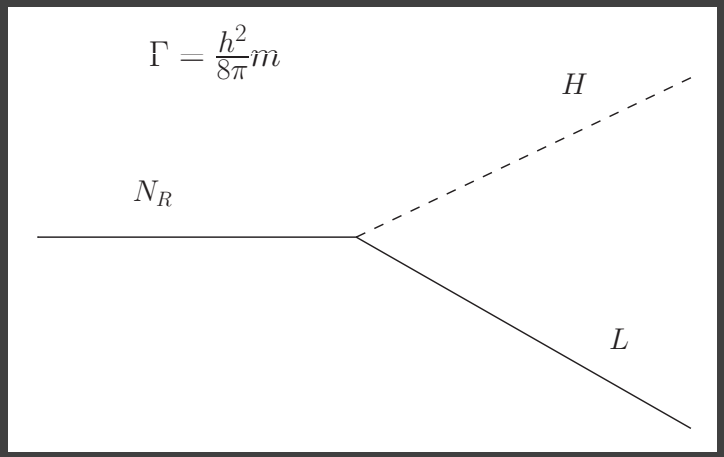
# Affleck-Dine From CP Violating Mass

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

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

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

# Reheating and Gravitino Problem




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

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

- Thermal bath overproduces gravitinos

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

- Gravitino decay to LSP overclose universe

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

# Preventing Overclosure

- Really light DM can fix problem.

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

- $R$- parity violation makes LSP unstable

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

- Gravitino decays before LSP freezeout

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

# 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 ...