Reheating in an early supersymmetric universe

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Inflation

accelerated expansion of the universe

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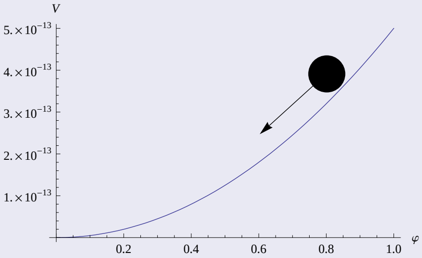
Example

$$V \supset \frac{1}{2} m^2 \varphi^2 \tag{1}$$

φ - inflaton field



Preheating

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very efficient non-perturbative particle production during inflaton oscillations

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Toy model

$$V \supset \frac{1}{2}m^2\varphi^2 + A\varphi^2\chi^2 + Bm\varphi\chi^2 \tag{2}$$

φ - inflaton field, χ - represents the inflaton decay products

$$\omega_{\chi_k}^2 = k^2 + 2A\langle\varphi\rangle^2 + 2Bm\langle\varphi\rangle \tag{3}$$

$$|\tau| \equiv \left|\frac{\dot{\omega}}{\omega^2}\right| > 1 \leftrightarrow \textit{preheating} \tag{4}$$

Preheating and flat directions

Flat direction

- general feature of supersymmetric models
- direction in field-space, along which the scalar potential identically vanishes (when all other field VEVs=0)

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Toy model with a flat direction (Allahverdi, Mazumdar '07)

$$V \supset \frac{1}{2}m^2\varphi^2 + A\varphi^2\chi^2 + Bm\varphi\chi^2 + C\alpha^2\chi^2 \tag{5}$$

α - parameterizes the flat direction

$$\omega_{\chi_k}^2 = k^2 + 2A\langle\varphi\rangle^2 + 2Bm\langle\varphi\rangle + 2C\langle\alpha\rangle^2 \tag{6}$$

The model

Goal

- construct a consistent model of inflation and particle production in a supersymmetric framework
- generate large flat direction VEVs during inflation
  - create a potential for the flat direction $\longrightarrow$ supergravity
  - consider classical evolution of VEVs during inflation

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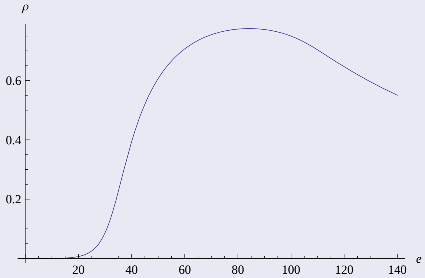
Evolution of flat direction VEV during inflation



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Preheating

- check the impact of large flat direction VEVs on particle production
  - consider excitations around VEVs
  - study the evolution of the mass matrix
  - determine if preheating from the inflaton is possible

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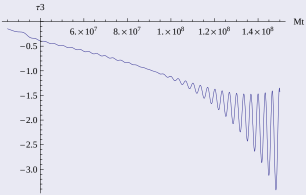
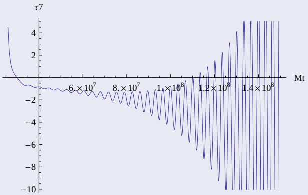
Efficient channel of preheating

the time evolution of light mass eigenvalues connected with the flat direction leads to non-perturbative particle production





Conclusions

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- Such large VEVs can block preheating from the inflaton into certain channels
- Supergravity effects are a source of light, rapidly changing eigenvalues of the mass matrix connected with flat directions. They allow the non-perturbative production of particles from the flat direction and preheating from the inflaton.
- Non-perturbative particle production from the inflaton is likely to remain the source of preheating even in the initial presence of large flat direction VEVs.

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Inflaton sector

M. Kawasaki, M. Yamaguchi, T. Yanagida "'Natural Chaotic Inflation in Supergravity"'

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- shift symmetry in the inflaton superfield in order to avoid the eta problem

$$K \supset \frac{1}{2}(\Phi + \Phi^\dagger)^2 + X^\dagger X, \qquad \Phi = (\eta + i\varphi)/\sqrt{2} \tag{7}$$

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  φ - inflaton field

- auxiliary field X in order to obtain chaotic inflation potential during inflaton domination

$$W \supset mX\Phi \tag{8}$$

$$V \xrightarrow{inflaton\ domination} \frac{1}{2}m^2\varphi^2 \tag{9}$$

The model

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$$W \supset 2hXH_uH_d \tag{11}$$

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- representative flat direction *udd*

$$u_i^{\beta} = d_j^{\gamma} = d_k^{\delta} = \frac{1}{\sqrt{3}}\alpha, \qquad \alpha = \rho e^{i\sigma} \tag{13}$$

The model

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- non-minimal Kähler

$$K \supset \left(1 + \frac{a}{M_4^2} X^\dagger X\right) \left(H_u^\dagger H_u + H_d^\dagger H_d + u_i^\dagger u_i + d_j^\dagger d_j + d_k^\dagger d_k\right) \tag{14}$$

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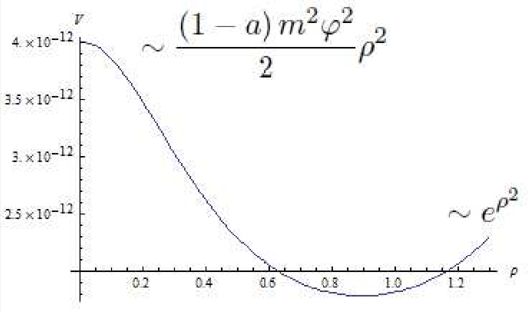

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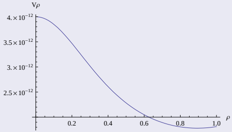

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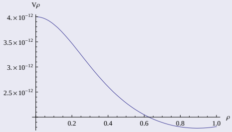
- non-renormalisable terms

$$W \supset \frac{\lambda_\chi}{M_{Pl}} \left(H_u \cdot H_d\right)^2 + \frac{3\sqrt{3}\lambda_\alpha}{M_{Pl}} \left(u_i d_j d_k \nu_R\right) \tag{15}$$



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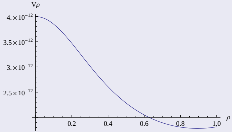

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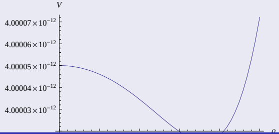

Classical evolution during inflation

Initial conditions

- $\varphi_0 \sim 4M_{Pl}$ allows to study the last $\sim$ 100 e-folds of inflation
- small initial VEVs ($\alpha_0,\ \chi_0 \sim \delta\alpha,\ \delta\chi \sim H$) for *udd* and $H_u H_d$ directions

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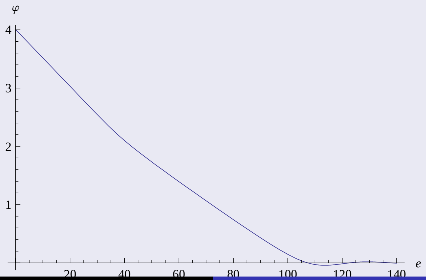
Evolution of the inflaton

$$\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0 \tag{16}$$



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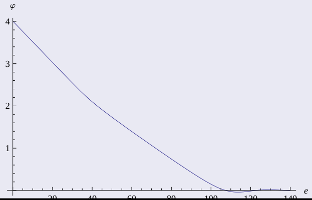

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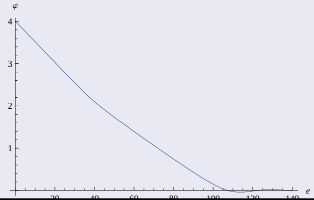

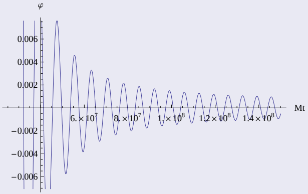

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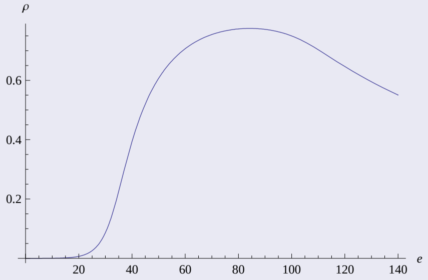

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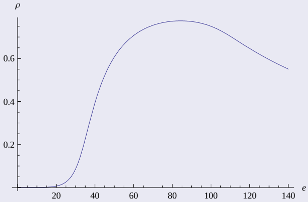

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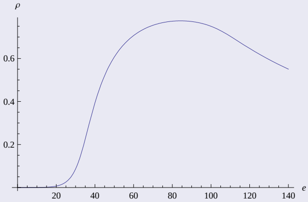

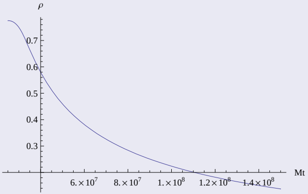

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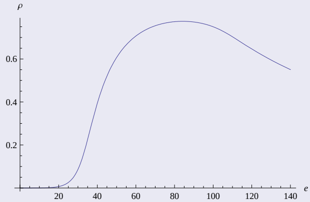

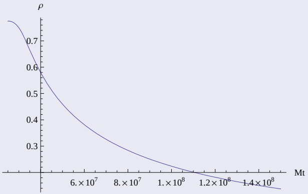

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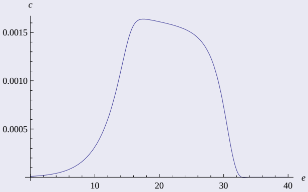

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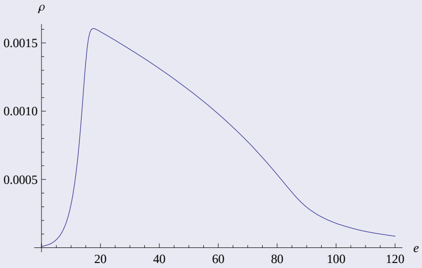

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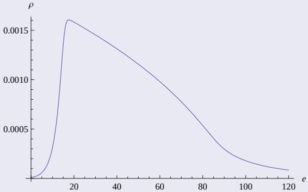

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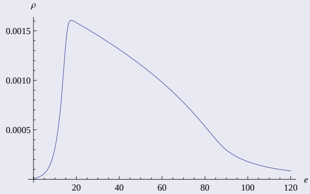

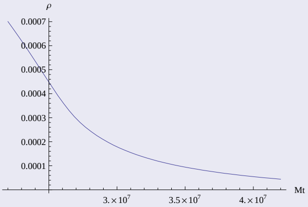

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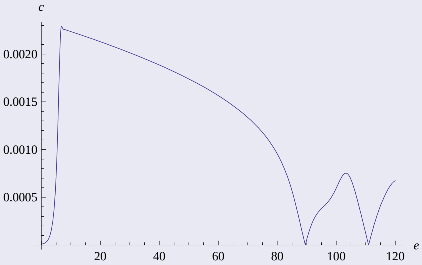

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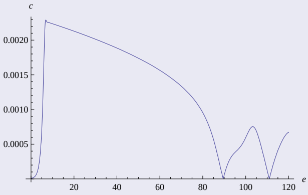

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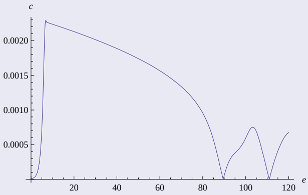

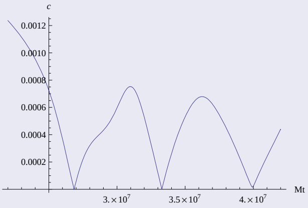

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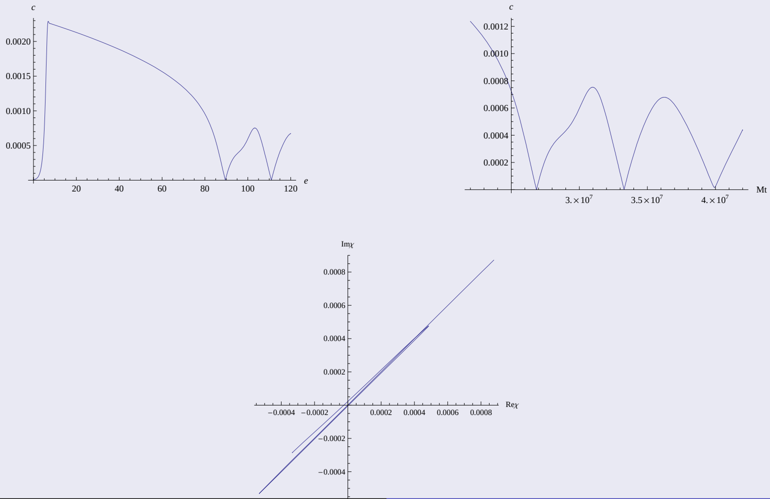
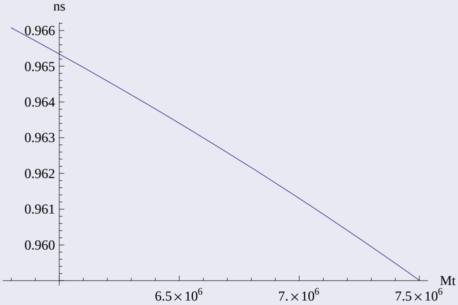


Classical evolution during inflation

Spectral index

values of the spectral index 50-60 e-folds before the end of inflation in the slow-roll approximation



WMAP5: $n_s = 0.960^{+0.014}_{-0.013}$

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$$VEV = 0 \longrightarrow field \sim \delta_a + i\delta_b \tag{18}$$

Constructing the mass matrix

Basbøll '08

- introduce excitations into the Lagrangian

$$L \supset \frac{1}{2}\partial_\mu \Xi^T \partial^\mu \Xi - \frac{1}{2}\Xi^T \underbrace{\left(M_V^2 + M_{kin}^2\right)}_{M^2} \Xi - \dot{\Xi}^T U \Xi, \quad \Xi = (\xi_i, \ \delta_i)^T \tag{19}$$

where U is antisymmetric

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- transformation to the "'inertial frame"' of excitations

$$U = \dot{A}^T A, \ \tilde{\Xi} = A\Xi \ \longrightarrow \ L \supset \frac{1}{2}|\partial_\mu \tilde{\Xi}|^2 - \frac{1}{2}\tilde{\Xi}^T \tilde{M}^2 \tilde{\Xi} \tag{20}$$

$$\tilde{M}^2 = A\left(M^2 - U^2\right)A^T = C M_{diag}^2 C^T \tag{21}$$

Preheating

Analyzing the mass matrix evolution, $\lambda_\alpha \ll \lambda_\chi \sim 1$

$$\tilde{M}^2 = \begin{pmatrix} M^2_{8\times 8}\left[H_u H_d\right] & 0 \\ 0 & M^2_{10\times 10}\left[udd\right] \end{pmatrix} \tag{22}$$

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$M^2_{8\times 8}\left[H_u H_d\right]$ has two different eigenvalues

$$m_1^2 \approx -\frac{m\varphi}{2}\left(2\sqrt{2}h + (a-1)\,m\varphi\right) + \frac{Y^2}{3}\rho^2 + ... \tag{23}$$

$$m_2^2 \approx -\frac{m\varphi}{2}\left(-2\sqrt{2}h + \underbrace{(a-1)\,m\varphi}_{SUGRA}\right) + \frac{Y^2}{3}\rho^2 + ... \tag{24}$$

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Toy model analogy

$$m_\chi^2 = 2A\left\langle\varphi\right\rangle^2 + 2Bm\left\langle\varphi\right\rangle + 2C\left\langle\alpha\right\rangle^2 \tag{25}$$

Preheating

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$SU(3) \times U(1) \to U(1)$

$$M^2\left[udd\right] = \begin{pmatrix} M^2_{1\times 1}\left[p\right] & & & & \\ & M^2_{3\times 3}\left[f\right] & & & \\ & & M^2_{1\times 1}\left[1\right] & & \\ & & & \dots & \\ & & & & M^2_{1\times 1}\left[6\right] \end{pmatrix} \tag{26}$$

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$$M^2[1] \approx \frac{g^2}{3}\rho^2 + \underbrace{-\frac{m^2\varphi^2}{2}(a-1)}_{SUGRA} + \ldots \tag{27}$$

Preheating

Analyzing the mass matrix evolution, $\lambda_\alpha \ll \lambda_\chi \sim 1$

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the excitation around the phase of the flat direction VEV corresponds also to a naturally light eigenvalue

$$M^2_{1\times 1}[p] \approx \underbrace{(1-a)\frac{m^2\varphi^2}{2} + g(a)\frac{m^2\varphi^2}{2}\rho^2}_{SUGRA} + \ldots \tag{29}$$

Preheating

Analyzing the mass matrix evolution, $\lambda_\alpha \ll \lambda_\chi \sim 1$

the time evolution of both m^2_{abs} and $M^2_{1\times 1}[p]$ leads to non-perturbative particle production

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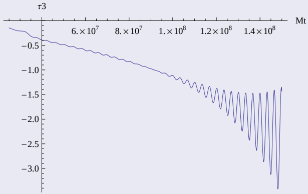

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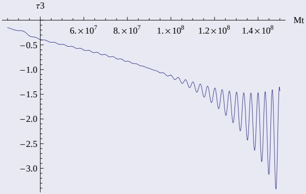

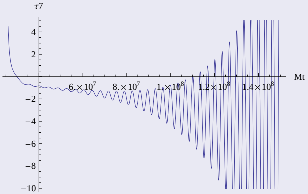

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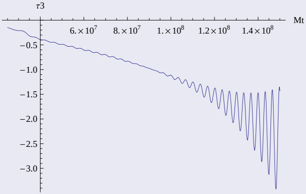

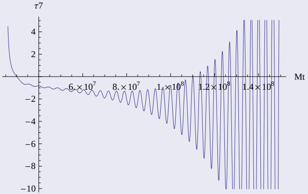

$\longrightarrow$ melting of flat direction VEV and unblocking all other channels of preheating

Preheating

Analyzing the mass matrix evolution, $\lambda_\alpha \sim \lambda_\chi \sim 1$

$SU(3) \times SU(2) \times U(1) \to U(1)$

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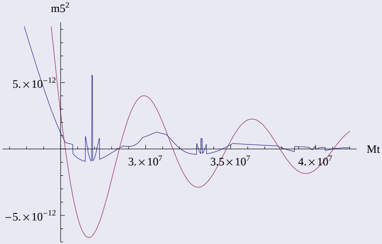
an example of a naturally light eigenvalue corresponding to a combination of excitations around VEVs of complex fields α and χ parameterizing the (quasi) flat directions



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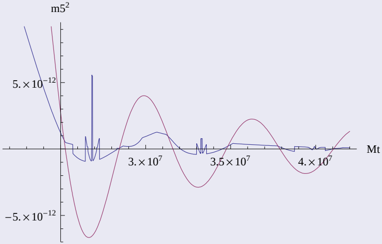

$\longrightarrow$ very efficient preheating into Higgs particles allowed from the beginning of inflaton oscillations